UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

GLOBALFOUNDRIES U.S. INC. AND GLOBALFOUNDRIES INC.,

Petitioners,

v.

OAK IP, LLC.

Patent Owner.

Case No. IPR2025-01052

Patent No. 9,905,691

Title: METHOD FOR DEPINNING THE FERMI LEVEL OF A SEMICONDUCTOR AT AN ELECTRICAL JUNCTION AND DEVICES INCORPORATING SUCH JUNCTIONS
Issue Date: February 27, 2018

DECLARATION OF DR. E. FRED SCHUBERT IN SUPPORT OF PETITION FOR *INTER PARTES* REVIEW OF U.S. PATENT NO. 9,905,691

TABLE OF CONTENTS

I. INTRODUCTION

I, E. Fred Schubert, Ph.D., a resident of Troy, NY over 18 years of age, hereby declare as follows:

1. I have personal knowledge of all of the matters about which I testify in this declaration.

2. Covington & Burling LLP retained me on behalf of Petitioners GlobalFoundries U.S., Inc. and GlobalFoundries Inc. ("Petitioners" or "GF") to provide my technical opinions and testimony about Claims 5-12, 14-19, 21, 23-24, and 26-29 of U.S. Patent 9,905,691 (Ex. 1001, "the '691 Patent"), assigned to Oak IP, LLC ("Patent Owner" or "Oak IP"). I refer to those claims as the "Challenged Claims." The full text of the Challenged Claims appears in **Appendix A** to my declaration.

3. I am being compensated for my work in this proceeding at my usual consulting rate of $600/hour and receiving reimbursement for expenses incurred in the course of my work. My compensation is not contingent in any way on either the opinions I have reached or the outcome of this case.

II. BASES FOR OPINION

4. I have reviewed and considered the documents listed below in Section III in light of my specialized knowledge provided by my education, training, research, and experience, as summarized in Section IV and described in detail in my CV, which is attached to this declaration as **Appendix C.** My analysis of those documents,

combined with the specialized knowledge and practical hands-on experience that I have obtained over the course of my education and career, form the bases for my opinions in this declaration.

III. MATERIALS CITED

5. I have reviewed, analyzed, and relied upon the documents listed in **Appendix B** in reaching my opinions in this matter. I have also reviewed and analyzed the exhibits cited in this declaration.

6. At the direction of the attorneys for the Petitioners, I have reviewed certain portions of the Petition in arriving at my opinions. I reference those portions of the Petition in the declaration as relevant.

7. Where my declaration cites an exhibit by a page number, I have used the page numbers that Petitioners have added to that exhibit instead of citing to the original pagination. Where my declaration cites a patent, I have cited to the column and line of the patent. Where my declaration cites an exhibit that has paragraph numbers, I have cited to the paragraph number. Finally, where there is emphasis in a quotation, I have added that emphasis unless I indicate otherwise.

IV. EDUCATION AND EXPERIENCE

A. Overview

8. I am currently an active tenured full Professor in the Department for Electrical, Computer, and Systems Engineering at the Rensselaer Polytechnic Institute (RPI) located in Troy, New York.

9. I received a Master's Degree in Electrical Engineering from the University of Stuttgart, Germany, in 1981. I received a Ph.D. degree in Electrical Engineering from the University of Stuttgart, while working at the Max Planck Institute for Solid-State Research, in Stuttgart, from 1981 to 1985.

10. Subsequent to my education, starting in 1985, I worked in industry at AT&T Bell Laboratories in Holmdel and Murray Hill, New Jersey, for ten years.

11. In 1995, I joined academia. My first position was at Boston University (Boston, MA), where I worked as a full professor for seven years.

12. In 2002, I joined RPI as a distinguished professor, the Wellfleet Senior Constellation Professor and Head of the Future Chips Constellation with appointments in the Department for Electrical, Computer, and Systems Engineering and the Department for Physics, Applied Physics and Astronomy. I am the founding Director of the Smart Lighting Engineering Research Center that was funded by the U.S. National Science Foundation at a volume of $40 million for over 10 years.

13. I am named as co-inventor in more than 35 U.S. patents and have co-authored more than 300 publications. I authored the books *“Doping in III-V Semiconductors”* (1993), *“Delta Doping of Semiconductors”* (1996), *“Physical Foundations of Solid-State Devices”* (2015) and the first, second and third editions of *“Light-Emitting Diodes”* (2003, 2006 and 2018); the latter book is known as a standard textbook in the field of LEDs, and the book has been translated into Russian, Japanese and Korean. My publications have been well recognized by the technical community as illustrated by the more than 45,000 citations that my publications have received.

14. I received several awards for my technical contributions. They include: Senior Member IEEE (1993); Literature Prize of Verein Deutscher Elektrotechniker for my book *“Doping in III-V Semiconductors”* (1994); Fellow SPIE (1999); Alexander von Humboldt Senior Research Award (1999); Fellow IEEE (1999); Fellow OSA (2000); Boston University Provost Innovation Award (2000); Discover Magazine Award for Technological Innovation (2000); R&D 100 Award for RCLED (2001); Fellow APS (2001); RPI Trustees Award for Faculty Achievement (2002 and 2008); honorary membership in Eta Kappa Nu (2004); 25 Most Innovative Micro- and Nano-Products of the Year Award of R&D Magazine (2007); and Scientific American 50 Award (2007).

15. My general expertise is in the field of electrical engineering and applied physics including semiconductor materials, processing, and devices. My specific

expertise is in the field of semiconductor devices, semiconductor integrated circuits, ohmic and Schottky contacts, and optoelectronic devices such as light-emitting diodes (LEDs). My work has included the design, growth, fabrication, and testing of semiconductor devices as well as the employment of these devices in a variety of applications. I have made pioneering contributions to the following technical fields that are relevant to the present matter: Delta-doping of semiconductors, monolayer doping of semiconductors, integrated circuit fabrication processes, Schottky contacts, ohmic contacts, polarization-enhanced ohmic contacts, delta-doped ohmic contacts, non-alloyed ohmic contacts, fabrication technologies of ohmic contacts, and the theory of ohmic and Schottky contacts.

B. Specific Experience with Metal-Semiconductor Junctions

16. The ’691 Patent generally relates to metal-semiconductor junctions that have a metal oxide layer and a passivating dielectric tunnel barrier layer between the metal and the semiconductor. (Ex. 1001 [’691 Patent] at 1:25-29.) There are two main types of metal-semiconductor junctions: rectifying contacts, also known as Schottky contacts; and low-resistance contacts, also known as ohmic contacts. (*Id.* at 1:36-42; Ex. 1023 [Rhoderick] at 1.) The ’691 claims and specification focus on low resistance contacts. (Ex. 1001 [’691 Patent] at 4:19-22, 5:10-19.)

17. I have extensive experience related to ohmic contacts for semiconductor devices, both with silicon-based semiconductors and Group III-V semiconductors.

This includes the fabrication of ohmic contacts, the assessment of specific contact resistance, the design of ohmic contacts, and the theory of ohmic contacts.

18. I have written several publications on the topic of ohmic contacts to semiconductors. My publications on ohmic contacts to semiconductors include:

- E. F. Schubert, J. E. Cunningham, W. T. Tsang, and T. H. Chiu, "Delta-doped ohmic contacts to n-GaAs," Applied Physics Letters 49, 292 (1986) and Applied Physics Letters 49, 984 (1986).
- Y.-L. Li, E. F. Schubert, J. W. Graff, A. Osinsky, and W. F. Schaff, "Low-resistance ohmic contacts to p-type GaN," Applied Physics Letters 76, 2728 (May 2000).
- T. Gessmann, Y.-L. Li, E. L. Waldron, J. W. Graff, and E. F. Schubert, "Ohmic contacts to p-type GaN mediated by polarization fields in thin InGaN capping layers," Applied Physics Letters 80, 986 (Feb. 2002).
- T. Gessmann, Y.-L. Li, E. L. Waldron, and E. F. Schubert, "Novel type of ohmic contacts to p-doped GaN using polarization fields in thin InGaN capping layers," Journal of Electronic Materials 31, 416 (May 2002).
- T. Gessmann, J. W. Graff, Y.-L. Li, E. L. Waldron, and E. F. Schubert, "Ohmic contact technology in III-V nitrides using polarization effects in cap layers," Proceedings of the Lester Eastman conference on high-speed devices (Sept. 2002).
- T. Gessmann, J. W. Graff, Y.-L. Li, E. L. Waldron, and E. F. Schubert, "Ohmic contacts to III-V nitrides using polarization effects of cap layers," Journal of Applied Physics 92, 3740 (October 2002).

- Seung Cheol Han, Jae-Kwan Kim, Jun Young Kim, Dong Min Lee, Jae-Sik Yoon, Jong-Kyu Kim, E. F. Schubert, and Ji-Myon Lee, "Ohmic contacts to N-face p-type GaN using Ni/Au for the fabrication of polarization inverted light-emitting diodes," Journal of Nanoscience and Nanotechnology 13, 5715 (Aug. 2013).
- Dissertation by E. F. Schubert, "Modern Schottky gate field-effect transistors based on III-V semiconductors" (University of Stuttgart, Germany, 1986).
- "Physical Foundations of Solid-State Devices" (Book, Google Books, Mountain View CA, 2015).
- H.-J. Gossmann and E. F. Schubert, "Delta doping in silicon" CRC Critical Reviews in Solid State and Materials Sciences 18, 1 (1993).

19. I am an inventor on U.S. patents that are specifically directed to ohmic contacts for semiconductors. My patents related to ohmic contacts to semiconductors include:

- J. E. Cunningham, E. F. Schubert, and W. T. Tsang, "Delta doped ohmic metal to semiconductor contacts" U.S. Patent No. 4,772,934, issued on September 20, 1988.
- J. E. Cunningham, E. F. Schubert, and W. T. Tsang, "Field-effect transistor having a delta-doped ohmic contact" U.S. Patent No. 4,780,748, issued on October 25, 1988.

20. Further, at RPI, I regularly teach on the subject of Schottky contacts and ohmic contacts for group-IV and group-III-V semiconductors, including the theory of

ohmic contacts. In my research laboratories, we routinely measure the properties of ohmic contacts, including the contact resistance, the specific contact resistance and the transfer length. We also assess structural aspects of semiconductor devices, including ohmic contacts, by assessment techniques such as SIMS (secondary ion mass spectrometry), AES (auger electron spectroscopy), SEM (scanning electron microscopy), EDXS (energy dispersive x-ray spectroscopy), and ellipsometry.

C. Curriculum Vitae

21. In addition to the summary I have provided here, I describe my education and experience in greater detail in my CV, which is attached to this declaration as **Appendix C**.

V. LEGAL STANDARDS

22. The attorneys for Petitioners have explained to me the legal standards that apply in this case. My understanding of those standards is described below. I am not an attorney, and although I hold several patents, I do not have formal training in the law regarding patents. I have used my understanding of the following legal principles set forth in this section in reaching my opinions.

A. Anticipation

23. I understand that to anticipate a claim of a patent, a prior art reference must disclose, either expressly or inherently, all limitations of a claim as those limitations are arranged in the claim. I understand that if a prior art reference discloses

a species of a genus (e.g. one specific element of a category of elements) then a patent's claim limitation claiming the genus is satisfied by the prior art reference.

24. I understand that for a reference to anticipate a claim, the reference must disclose the relevant technology in a manner such that a person of ordinary skill in the relevant art would be able to carry out or utilize the technology that the reference describes without having to undertake undue experimentation. I also understand that prior art references are presumed to be enabling.

25. I understand that a limitation is disclosed inherently in a reference only if it is necessarily present in the process or product described in the prior art reference. I understand that probabilities or possibilities are insufficient to show that a prior art reference inherently discloses something beyond what it discloses explicitly.

B. Obviousness

26. I understand that under 35 U.S.C. § 103, "[a] patent may not be obtained through the invention is not identically disclosed or described as set forth in section 102, if the differences between the subject matter sought to be patented and the prior art are such that the subject matter as a whole would have been obvious at the time the invention was made to a person having ordinary skill in the art to which said subject matter pertains."

27. I understand that I must consider whether the claimed subject matter as a whole would have been obvious to a person of ordinary skill in the art at the time of the invention in light of the following:

- The scope and content of the prior art;
- Any differences between the prior art and the claim;
- The level of ordinary skill in the pertinent art; and
- Any evidence of secondary indicia of non-obviousness (if available).

28. I understand that in the case where the claimed ranges "overlap or lie inside ranges disclosed by the prior art" a prima facie case of obviousness exists. I further understand that such an overlap creates a presumption of obviousness, and that the burden of production falls upon the patentee to come forward with pertinent evidence that the overlapping range would not have been obvious in light of the prior art.

29. It is my understanding that there must be a nexus between any secondary indicia of non-obviousness and the claimed subject matter. Further, I understand that evidence of secondary indicia of non-obviousness must be commensurate with the scope of the claimed subject matter.

C. Priority

30. I understand that for a claim to receive a priority date of an earlier parent application, the earlier application must both (1) provide adequate written description of the claimed subject matter; and (2) enable the claimed subject matter.

31. I understand that for a claim to obtain the benefit of the filing date of an earlier application via a chain of parent applications, each application in the chain leading back to the earlier application must both (1) provide adequate written description of the claimed subject matter; and (2) enable the claimed subject matter. I discuss my understanding of those two requirements below.

1. Written Description Requirement

32. I understand that the test for sufficiency of written description is whether the disclosure of the application relied upon reasonably conveys to those skilled in the art that the inventor had possession of the claimed subject matter as of the filing date. I further understand that a disclosure in a parent application that merely renders the later-claimed invention obvious does not satisfy the written description requirement; instead, the disclosure must describe the claimed invention with all its limitations.

33. I understand that the abstract, specification, figures, and originally-filed claims of a patent application are considered part of the application's written description. I understand that other patents or patent applications incorporated by

reference in the patent application at issue must be considered in assessing whether that patent application provides adequate written description.

34. I understand that a sufficient description of a genus requires the disclosure of either a representative number of species falling within the scope of the genus or structural features common to the members of the genus so that a person of ordinary skill in the art can visualize or recognize the members of the genus. I further understand that describing a single species is not sufficient to support claims to a genus when the evidence indicates ordinary artisans could not predict the operability in the invention for the remainder of the species other than the one disclosed.

2. Enablement Requirement

35. I understand that to enable a patent claim, the patent's disclosure must teach ordinarily skilled artisans how to make and use the full scope of the claim without undue experimentation.

36. I understand that the following factors are typically considered in assessing whether a patent's disclosure enables a person of ordinary skill in the art to make and use the full scope of the claimed invention without undue experimentation: (1) the quantity of experimentation necessary, (2) the amount of direction or guidance presented, (3) the presence or absence of working examples, (4) the nature of the invention, (5) the state of the prior art, (6) the relative skill of those in the art, (7) the predictability or unpredictability of the art, and (8) the breadth of the claim. But, I

understand that not all of those factors need to be reviewed to determine whether a disclosure is enabling. Instead, those factors are illustrative, but not mandatory. In some instances, the breadth of the claim alone may indicate that the claim is not enabled.

D. Claim Construction

37. I understand that in this proceeding, the claims are construed according to their ordinary and customary meaning in light of the specification and file history of the patent in which those claims appear. I understand that this is the same claim construction approach used in district court litigation.

VI. OVERVIEW OF THE '691 PATENT

A. Technical Background

1. Metal-Semiconductor Junctions

38. The '691 Patent generally relates to metal-semiconductor junctions, which are basic electronic components. (Ex. 1001 ['691 Patent] at 1:25-29.) "In these junctions, a metal (such as aluminum) is brought in contact with a semiconductor (such as silicon)." (*Id.* at 1:34-36.) Thus, metal-semiconductor junctions are also commonly known as metal-semiconductor contacts. (*E.g.*, Ex. 1029 [Schroen] at 1:7-15; Ex. 1023 [Rhoderick] at 1.)

39. The two principal types of metal-semiconductor junctions are (1) rectifying contacts, which are also called Schottky contacts or Schottky diodes; and (2)

low-resistance contacts, also known as ohmic contacts. (Ex. 1023 [Rhoderick] at 1, 11.) Rectifying contacts "tend to conduct current in one direction more favorably than in the other direction." (Ex. 1001 ['691 Patent] at 1:38-39.) Ohmic contacts, on the other hand, display low resistance regardless of the direction of current flow. (*Id.* at 1:39-42; Ex. 1023 [Rhoderick] at 11.)

40. "A Schottky barrier . . . is characterized by an impedance due to the barrier height and width, which must be minimized in the formation of ohmic contacts." (Ex. 1029 [Schroen] at 1:33-37; Ex. 1001 ['691 Patent] at 3:6-9.) The energy barrier impedes the flow of charge carriers at the interface between the metal and the semiconductor. (Ex. 1001 ['691 Patent] at 1:46-48; Ex. 1023 [Rhoderick] at 1.) The width of the barrier is the width of the depletion region created when electrons deplete from the semiconductor and transition to the metal. (Ex. 1029 [Rhoderick] at 1; Ex. 1024 [Chang] at 545-546.)

41. The barrier's width depends on the doping concentration of the semiconductor, among other factors. (Ex. 1024 [Chang] at 545.) Increasing the doping concentration generally reduces the barrier's width, which facilitates the flow of charge carriers (electrons or holes) across the barrier via quantum tunneling. (*Id.*) "Thus, even a high barrier contact can become ohmic if the barrier is thin enough such that tunneling dominates the carrier transport process . . . ." (*Id.*) Consistent with Chang's disclosure that increasing doping can improve the flow of charge carriers across a

barrier, the ’691 Patent admits that a known approach to reducing the specific contact resistance of a metal-semiconductor junction was to increase the doping concentration of the semiconductor. (Ex. 1001 [’691 Patent] at 18:10-13.)

42. The height of the barrier depends on, among other factors, the type of semiconductor used, the type of metal used, and the properties of the interface between the metal and the semiconductor. (Ex. 1001 [’691 Patent] at 2:4-3:3; Ex. 1025 [Goodnick] at 949; Ex. 1023 [Rhoderick] at 2-3.)

43. One important property of the interface that affects the barrier height is the presence of electron states at the interface. (Ex. 1001 [’691 Patent] at 2:63-3:3.) Electron states include electron orbitals and chemical bonds (including dangling bonds), which can be occupied by an electron (filled state) or unoccupied (empty state).

44. The ’691 Patent identifies two main types of states that affect barrier height: (1) states at the surface of the semiconductor, which are also called Bardeen states; and (2) metal-induced gap states, which are abbreviated as MIGS. (Ex. 1001 [’691 Patent] at 2:4-3:3.)

45. The first type of electron states, Bardeen states, are states that arise from dangling bonds at the surface of the semiconductor. (Ex. 1001 [’691 Patent] at 2:4-16.) Fig. 1 of the ’691 Patent depicts an example of dangling bonds (reference number 120) at a silicon surface:

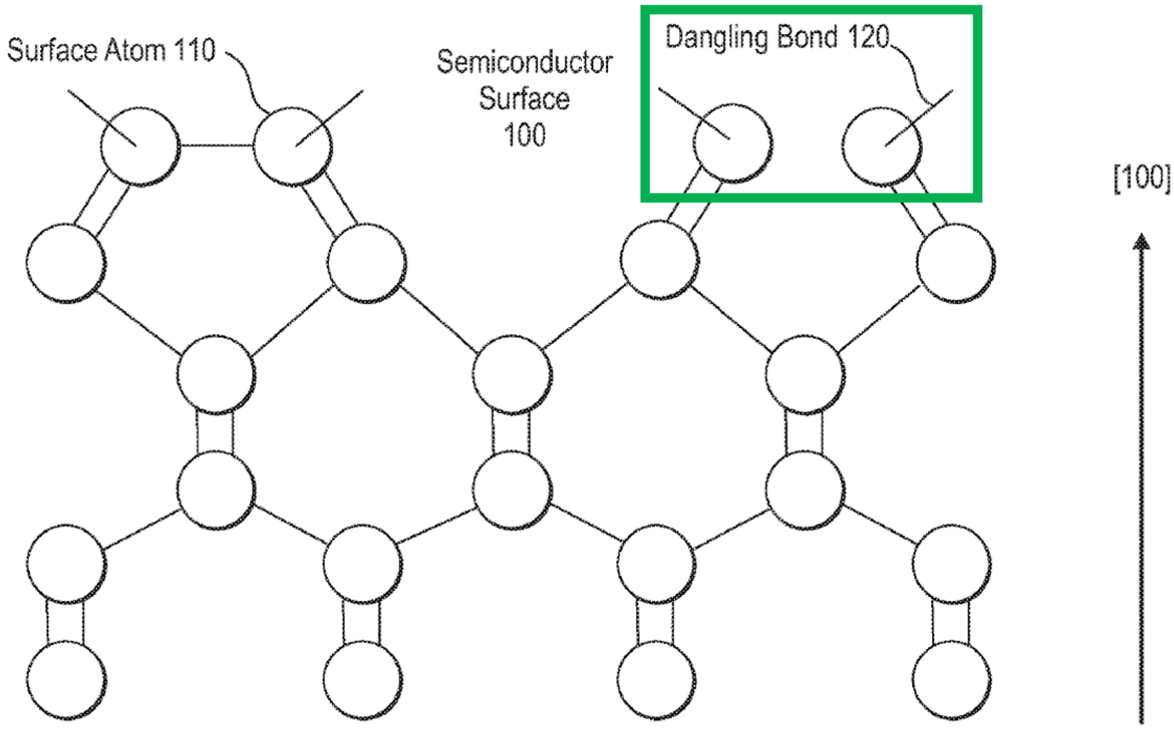


Fig. 1

(*Id.* at Fig. 1 (annotation added).)

46. As can be seen in Fig. 1, some, but not all, of the silicon atoms at the surface have a bonding partner. (Ex. 1001 ['691 Patent] at 2:4-18.) The unsatisfied chemical bonds of those silicon atoms without a bonding partner are called dangling bonds because they freely dangle at the surface of the silicon. (Ex. 1023 [Rhoderick] at 2.) A dangling bond "can either give up its electron, acting as a donor, or accept another, acting as an acceptor." (*Id.*) Either way, the surface states give rise to a net charge that modifies the barrier height. (*Id.* at 2-3.)

47. The second type of electron states, metal-induced gap states (MIGS), originate in the metal, but induce electron states within the semiconductor. (Ex. 1023 [Rhoderick] at 3.) More specifically, metal-induced gap states "are energy states in the bandgap of the semiconductor that become populated due to the proximity of the metal. That is, the wave functions of the electrons in the metal do not terminate abruptly at the surface of the metal, but rather decay in proportion to the distance from that surface (*i.e.*, extending inside the semiconductor)." (Ex. 1001 ['691 Patent] at 2:41-48.)

2. Fermi-Level Pinning in Metal-Semiconductor Junctions

48. Early attempts to model barrier heights at metal-semiconductor junctions did not account for Bardeen states (from dangling bonds) or metal-induced gap states (from the proximity of the metal). (Ex. 1001 ['691 Patent] at 1:49-58.) In 1938, Schottky theorized that the barrier height of a metal-semiconductor junction was determined solely by the difference between the work function of the metal and the electron affinity of the semiconductor:

> In this model, the height of the barrier (as measured by the potential necessary for an electron to pass from the metal to the semiconductor) was postulated as the difference between the work function of the metal (the work function is the energy required to free an electron at the Fermi level of the metal, the Fermi level being the highest occupied energy state of the metal at $T = 0$) and the electron affinity of the semiconductor (the electron affinity is the difference between the energy of a free electron and the conduction band edge of the semiconductor).

(Ex. 1001 [’691 Patent] at 1:49-58.)

49. Subsequent experimental observations of the barrier heights for metal-semiconductor junctions did not agree with Schottky’s theory. (Ex. 1001 [’691 Patent] at 1:64-2:3; Ex. 1023 [Rhoderick] at 2.) The ’691 Patent summarizes those observations:

> If the theory is correct, one should be able to observe direct variations in barrier heights for metals of different work functions when put in contact with a common semiconductor. What is observed, however, is not direct scaling, but instead only a much weaker variation of barrier height with work function than implied by the model.

(Ex. 1001 [’691 Patent] at 1:65-2:3.)

50. Bardeen later attributed that “much weaker variation of barrier height with work function than implied by the model” to surface states arising from dangling bonds. (Ex. 1001 [’691 Patent] at 2:4-25; Ex. 1023 [Rhoderick] at 2.)

51. Later, Heine and Tersoff developed and refined a model that incorporated metal-induced gap states to explain why the barrier height of metal-semiconductor junctions did not always vary with the work function of the metal. (Ex. 1001 [’691 Patent] at 2:26-61, 7:44-48.)

52. Bardeen states and metal-induced gap states were believed to be (and still are believed to be) the main causes of a phenomenon referred to as Fermi-level pinning, in which the Fermi level is “pinned” within the bandgap of the semiconductor,

typically near the middle of the bandgap. (Ex. 1001 ['691 Patent] at 2:4-61, 5:24-27, 7:44-48.) Fig. 7a of the '691 Patent shows an example of Fermi-level pinning for a metal-semiconductor junction with no interface layer:

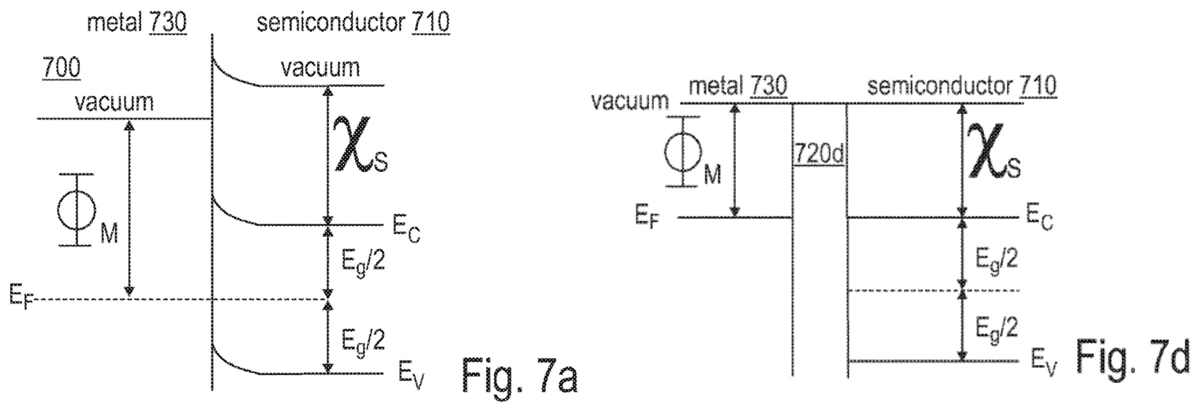


Fig. 7a Fig. 7d

(*Id.* at Fig. 7a and 7d, 16:52-55, 16:67-17:12.)

53. Fig. 7a (above on left) depicts that the pinned Fermi level E_F is not aligned with the conduction band edge E_C of the semiconductor at the interface. However, as Fig. 7d (above on right) depicts, "when the interface layer 720d is sufficient to both eliminate or reduce the effect of MIGS and to passivate the semiconductor surface, we see the Fermi level of the metal aligning with the conduction band of the semiconductor" and "vacuum level is now continuous as there is no charged dipole at the interface." (*Id.* at 16:67-17:12.)

54. For a junction between a metal and an n-type semiconductor, where there is a difference between the Fermi level and the conduction band edge of the semiconductor (labeled E_c in the figure above), a barrier forms "that blocks further

transfer of electrons into or out of the semiconductor." (Ex. 1001 ['691 Patent] at 7:27-29.) Referring to the example barrier between a metal and n-type silicon shown in Fig. 4 (excerpted below), if the Fermi level is pinned at E_F, the height Φ_b of that barrier is the difference between the Fermi level E_F and the conduction band edge of the semiconductor E_c at the interface:

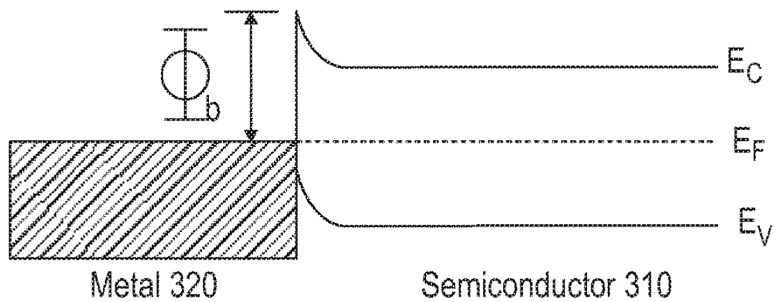


Fig. 4
(Prior Art)

Id. at Fig. 4.

55. As the '691 Patent notes, "[t]he importance of the barrier height at a metal-semiconductor interface is that it determines the electrical properties of the junction. Thus, if one were able to control or adjust the barrier height of a metal-semiconductor junction, one could produce electrical devices of desired characteristics." (Ex. 1001 ['691 Patent] at 3:4-8.) The '691 Patent also describes that depinning the Fermi level is one way to control or adjust barrier height. (*Id.* at 16:23-44.)

3. Techniques for Depinning a Fermi Level

56. Techniques for depinning the Fermi level of a metal at a metal-semiconductor junction were well-known before the earliest possible priority date of

the ’691 Patent of August 12, 2002. As discussed in the background and elsewhere in the ’691 Patent, it was believed that the two principal causes of Fermi-level pinning are (1) Bardeen states arising from dangling bonds at the surface of the semiconductor; and (2) metal-induced gap states arising from the proximity of the metal to the semiconductor. (Ex. 1001 [’691 Patent] at 2:4-61, 5:24-27, 7:44-48.)

57. It had also been known since at least the 1980s that an interface layer disposed between the metal and the semiconductor could satisfy dangling bonds to reduce Bardeen states and displace the metal from the semiconductor to reduce the effects of metal-induced gap states.

58. The Goodnick reference from April 1981 provides an example of using an interface layer to depin a Fermi level at a metal-semiconductor junction. “The presence of a thin interfacial oxide at metal-silicon interfaces may have a profound effect on the formation of Schottky barriers.” (Ex. 1025 [Goodnick] at 949.) “[A]n oxide layer that is sufficiently thin may sustain considerable current via tunneling.” (*Id.*) “A thin interfacial oxide also may significantly reduce the density of interface states by satisfying silicon dangling bonds. As a result, the Fermi level at the surface may become unpinned and the barrier height is more directly determined by the metal work function.” (*Id.*) Thus, Goodnick discloses using a thin interfacial oxide to satisfy silicon dangling bonds, which reduces the Bardeen states that contribute to Fermi-level pinning.

59. Rhoderick, an article from 1982, provides an overview of the "present knowledge of metal-semiconductor contacts." (Ex. 1023 [Rhoderick] at Abstract.) Rhoderick analyzed both "real" contacts (i.e., contacts between a metal and semiconductor with a thin layer of interfacial oxide between the two) and "intimate" contacts (i.e., metal-semiconductor contacts devoid of an interfacial layer). (*Id.* at 3.) Rhoderick reported: "'Real' contacts . . . are rather better understood than intimate contacts because the oxide tends to reduce the importance of interdiffusion, and also because, to a certain extent, it 'decouples' the electron states in the semiconductor from the influence of the metal, and so they can be analyzed more simply." (*Id.*) Thus, Rhoderick described that an interfacial oxide in a metal-semiconductor junction decouples the electron states in a semiconductor from the effects of a metal. An ordinarily skilled artisan would have understood that Rhoderick's description of decoupling electron states in the semiconductor from the influence of the metal referred to reducing the effects of metal-induced gap states in the semiconductor.

60. Sobolewski, an article from 1989, discloses that "[a] thin (< 30 Å) insulating layer present at a metal-semiconductor interface" changes the barrier height of a metal-semiconductor junction: "the barrier height of such a metal-insulator semiconductor (MIS) Schottky barrier will in general differ from that obtained in the absence of the insulating layer." (Ex. 1026 [Sobolewski] at 971.) Sobolewski also discloses that the thin insulating layer produces that change in barrier height by

passivating the semiconductor and reducing the penetration of metal wave functions into the semiconductor: "[t]his can be attributed either to a passivation of semiconductor interface states by the insulating layer, to a reduction of the penetration of metal wave functions into the semiconductor, to the chemistry of the metal-insulator interface, or to some combination of these effects." (*Id.*)

61. It was also well-known before 2002 that an interfacial oxide in a metal-semiconductor junction could reduce the Schottky barrier height of the junction.

62. Risko, a U.S. patent issued in 1978, discloses that an oxide layer disposed between a metal and a silicon substrate reduces the Schottky barrier height. "The deposition of the Schottky metal upon an oxide adjacent a silicon substrate has heretofore produced inferior Schottky barriers." (Ex. 1027 [Risko] at 1:43-45.) "Hence, a production of a Schottky barrier on an oxide coated substrate is known to produce a Schottky barrier with a substantially lowered barrier height." (*Id.* at 1:47-50.)

63. Taubenblatt 1984 describes that an interfacial oxide reduces the pinning ability of interface states in the silicon:

> The effect of interfacial oxides on barrier height has been explained by Turner and Rhoderick as being due to a reduction in Si interface states due to oxygen bonding to Si. ***This results in a reduction, in turn, of the pinning ability of the states,*** so that the barrier behaves more like

> an ideal Schottky barrier, with low work function metals having high (low) barriers to p-type (n-type) silicon.

(Ex. 1028 [Taubenblatt 1984] at 897.)

64. Similarly, it was well-known before 2002 that interposing an interface layer between a metal and a semiconductor at a metal-semiconductor junction could reduce specific contact resistance.

65. The Schroen patent, which issued in 1976, is one example. Its abstract states that the specific contact resistance that could be obtained by using a thin insulating interfacial layer between a metal and a semiconductor was "far smaller than the resistance one would observe in a structure consisting only of the semiconductor and metallization layer because the resistance of the structure is dominated by the resistance of the Schottky barrier formed at the metal-semiconductor interface." (Ex. 1029 [Schroen] at Abstract.)

66. Kim, a patent issued in 1989, is another example. Kim describes an interface layer formed by titanium reducing silicon dioxide:

> It is believed that during the sintering step titanium in the conductor 27 at the interface between the conductor 27 and the silicon conductive members 15, 17 and 16 reacts with native silicon dioxide present on the exposed portions of these conductors to form silicon and titanium dioxide, a semiconductor, thereby reducing the interface resistance.

(Ex. 1030 [Kim] at 4:63-5:1.)

67. Kim further describes achieving a specific contact resistance as low as 8 Ω-μm^2. (Ex. 1030 [Kim] at 5:27-30.)

68. Iwaguro is a more recent example. Iwaguro describes a 0.3 nm to 2.25 nm silicon sub-oxide layer between a metal and a semiconductor. (Ex. 1032 [Iwaguro] at [0005]-[0006], [0012]-[0014].) Iwaguro particularly discloses that "[b]y bringing a metal film into contact with this sub silicon oxide film, an ohmic junction exhibiting favorable low contact resistance can be obtained." (*Id.* at [0006].) And Iwaguro describes that the interface layer it used had 14.3% lower specific contact resistance than an otherwise identical contact that did not employ an interface layer. (*Id.* at [0013].) Furthermore, Figure 3 of Iwaguro compares a contact with a 1.5 nm thick interfacial oxide film (curve B in Iwaguro's Figure 3) to a contact without an interfacial oxide film (intimate contact, curve C in Iwaguro's Figure 3). The interfacial-oxide contact has an ohmic current-voltage characteristic, whereas the intimate contact has a Schottky-type rectifying current-voltage characteristic. The difference in the magnitude of current flowing through the two contacts (near zero voltage), and thus the difference in specific contact resistance, is at least a factor of a hundred, as indicated by the differences in the slopes of curve B and curve C near zero voltage.

B. Prosecution History

69. I have reviewed the prosecution history of the '691 Patent, as well as the prosecution histories of the patent and patent applications in its priority chain. (Exs.

1002-1020.) In addition, I have reviewed **Section VII.C** of the Petition that provides a summary of the file history and partial family tree of the family of the ’691 Patent, and I concur with that section. To the extent the file histories of the ’691 Patent or any of its parent applications affect my analysis, I have addressed those file histories below.

C. Litigation History

1. District Court

70. I understand that on February 4, 2025, Oak IP, LLC (“Oak IP”) filed a complaint in the District Court for the District of Delaware against GlobalFoundries Inc. and GlobalFoundries U.S., Inc. (“GF”) asserting, among other patents, the ’691 Patent. (Ex. 1095 [Oak IP Complaint], ¶¶ 60-69.) (“Oak IP/GF Litigation”) I refer to Oak IP as the Patent Owner or the current Patent Owner.

71. I understand that on October 23, 2019, Acorn Semi, LLC (“Acorn”) filed a complaint in the District Court for the Eastern District of Texas against several Samsung entities (“Samsung”) asserting, among other patents, the ’691 Patent. (Ex. 1038 [Acorn Complaint] ¶¶ 108-117) (“Acorn/Samsung Litigation”). I refer to Acorn as the prior Patent Owner or the Patent Owner during the Acorn/Samsung Litigation.

2. IPR Petitions

72. I understand that Samsung filed the following two petitions for *inter partes review* of the ’691 Patent. I served as an expert in both IPRs, provided declarations and was deposed.

a) IPR2020-01206 (Grupp '483 IPR)

73. I have reviewed **Section VII.D.2** of the Petition and concur with the summary of the Grupp '483 IPR.

b) IPR2020-01279 (Goodnick-Jammy IPR)

74. I have reviewed **Section VII.D.2** of the Petition and concur with the summary of the Goodnick-Jammy IPR.

VII. CLAIM CONSTRUCTION

75. For all claim terms, I have applied the ordinary and customary meaning of those terms as understood by one of ordinary skill in the art in light of the specification and prosecution history of the '691 Patent.

76. I understand that the district court in the Eastern District of Texas issued a *Markman* order on October 16, 2020 and has construed several terms of the Challenged Claims in the Acorn/Samsung Litigation. (Ex. 1100 [Acorn/Samsung Markman Order]). I also understand that in the prior *inter partes* reviews filed by Samsung, the Board also has construed the terms "specific contact resistivity" and "specific contact resistance" to be interchangeable. (Ex.1091, 8-9; Ex. 1097, 8.)

77. I understand that the term "specified contact resistivity" that appears in Claim 21 has not been construed. In my opinion, the term "specified contact resistivity" is not commonly used in the art. However, it is my opinion that a POSITA would have understood the term "specified contact resistivity" in Claim 21 as "specific contact

resistance" or "specific contact resistivity" in the context of the '691 Patent. The specification of the '691 Patent never uses the phrase "specified contact resistivity," but it does discuss "specific contact resistance" in the context of the purported invention in Claim 21. (Ex.1001, 17:41-54.) That is, the '691 Patent discloses that "the present junction can be fabricated with a much thinner interface layer as compared to the thickness of the silicide layer used previously" (in other words, "the dielectric tunnel barrier layer has a thickness less than that which would exist for a silicide layer at a contact junction between the metal electrical contact and the semiconductor region" as recited in Claim 21) and that "[t]he thinner interface layers provided by the present invention permit higher current across the junction (i.e., lower junction specific contact resistance)." (Ex.1001, 17:43-46, 17:52-54.) Thus, a POSITA would have understood the term "specified contact resistivity" in Claim 21 to refer to "specific contact resistance" or "specific contact resistivity."

78. Some of the key terms and their constructions that I have applied in my analysis are listed below:

Term	**Claims**	**Construction**
"a metal oxide layer, and a passivating dielectric tunnel barrier layer"	1	"a metal oxide layer, and a distinct dielectric tunnel barrier layer that terminates all or substantially all dangling bonds that may be present at the surface of the semiconductor region

Term	Claims	Construction
		without the layer present"
"interface layer"	25-30	Plain and ordinary meaning
"the interface layer comprising a metal oxide separation layer and a semiconductor oxide passivation layer"	25-30	"the interface layer comprising a metal oxide separation layer and a distinct layer of a semiconductor oxide that terminates all or substantially all dangling bonds that may be present at the surface of the semiconductor without the layer present"
"configured to"	20	Plain and ordinary meaning
"specific contact resistivity"	18, 26-29	"specific contact resistance"
"specified contact resistivity	21	"specific contact resistance"

(Ex. 1100 [Acorn/Samsung Markman Order] at 27-31; Ex.1091, 8-9; Ex. 1097, 8.)

VIII. PRIORITY DATE OF THE CHALLENGED CLAIMS

79. I have reviewed **Sections X.A, X.B, X.C, X.D, and X.E** of the Petition that lists the priority dates of the Challenged Claims, and I concur with that section. I summarize the priority of the Challenged Claims below:

Challenged Claims	Priority Date	Scope of Claims
6-12, 15-19, 23-24, and 26-29	Feb. 19, 2016	Require "oxide of titanium"
5, 9, and 14	Feb. 19, 2016	Require "a stack of metals deposited on the interface layer"
18 and 26-29	Feb. 19, 2016	Require a specific contact resistivity "less than 1 $\Omega \cdot \mu m^2$"
21	Feb. 7, 2011	Depends upon a claim that requires "metal oxide"
23-24	Feb. 19, 2016	Require "metal electrical contact" comprise an "oxide of titanium"

IX. LEVEL OF ORDINARY SKILL IN THE ART

80. I understand that written description and enablement are considered from the perspective of a person of ordinary skill in the art (or a POSITA).

81. My analysis and my opinions in this declaration for Claims 6-12, 15-19, 23-24, and 26-29 (i.e., claims that require an "oxide of titanium") are from the perspective of a person of ordinary skill in the art as of 2016.

82. My analysis and my opinions in this declaration pertaining to Claims 5, 9, 14 (i.e., claims that require an "a stack of metals deposited on the dielectric tunnel barrier layer") are from the perspective of a person of ordinary skill in the art as of 2016.

83. My analysis and my opinions in this declaration pertaining to Claims 18 and 26-29 (i.e., claims that require "a specific contact resistivity . . . less than 1 Ω-μm^2") are from the perspective of a person of ordinary skill in the art as of 2016.

84. My analysis and my opinions in this declaration pertaining to Claims 21 (i.e., a claim that requires a "metal oxide" because it depends from Claim 1 but does not require an "oxide of titanium") are from the perspective of a person of ordinary skill in the art as of 2011.

85. My analysis and my opinions in this declaration pertaining to Claims 23-24 (i.e., claims that require an the "metal electrical contact" comprise an "oxide of titanium") are from the perspective of a person of ordinary skill in the art as of 2016.

86. I understand that several factors are considered in determining the level of ordinary skill in the art, including the educational level of active workers in the field, the types of problems encountered in the art, the nature of prior art solutions to those problems, prior art patents and publications, the activities of others, the sophistication of the technology involved, and the rapidity of innovations in the field.

87. I have reviewed **Section IX** of the Petition that lists the skill of a person of ordinary skill in the field of the '691 Patent, and concur with that level of skill. I offered the same opinion and the prior IPR petitions involving the '691 Patent, and I understand that the Board concurred with the above mentioned qualifications of a person of ordinary skill. (Ex.1090, 10; Ex.1098, 10-11.)

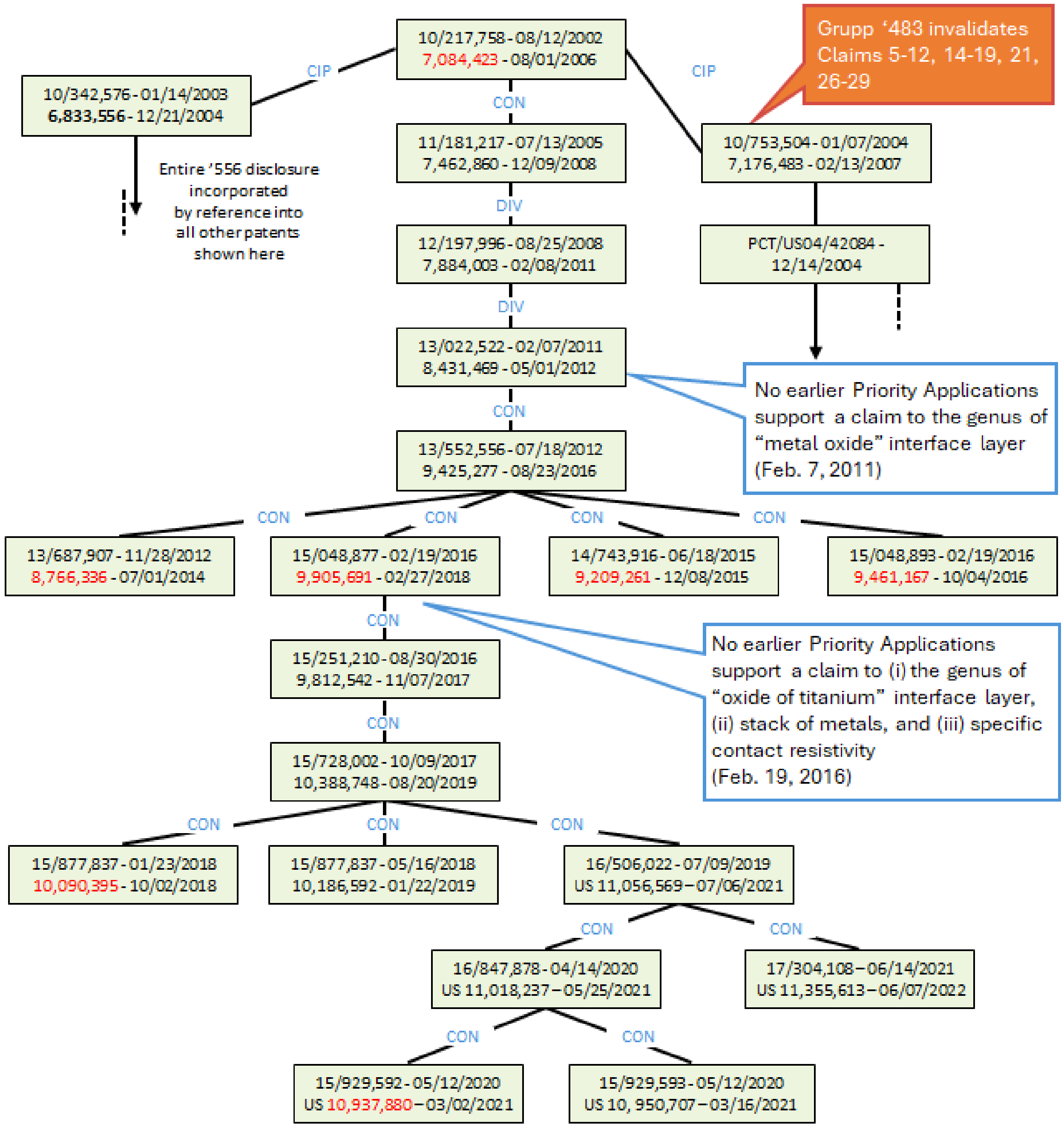
88. I understand that Patent Owner may contend that the priority date of the Challenged Claims is August 12, 2002. Although a person of ordinary skill in the art would have been aware of any additional developments in the field between August 2002 and February 2016, the level of ordinary skill in the art would have been essentially the same in August 2002, February 2011, or February 2016. Thus, the perspective of a person of ordinary skill in the art would have been essentially the same in August 2002, February 2011, or February 2016, and my opinions providing the perspective of a person of ordinary skill in the art would remain the same whether the Challenged Claims are given a priority date of August 2002, February 2011 or February 2016.

89. I had enough education and experience to have qualified as a person of ordinary skill in the art in 2002, 2011 and 2016.

X. SUMMARY OF OPINIONS

90. It is my opinion that Claims 6-12, 15-19, 23-24, and 26-29 (i.e., claims that require an "oxide of titanium") cannot claim priority prior to February 19, 2016. It is also my opinion that Claims 5, 9, and 14 (i.e., claims that require "a stack of metals deposited on the dielectric tunnel barrier layer") cannot claim priority prior to February 19, 2016. It is also my opinion that Claims 18 and 26-29 (i.e., claims that require "a specific contact resistivity . . . less than 1 Ω-μm^2") cannot claim priority prior to February 19, 2016. It is also my opinion that Claim 21 (i.e., a claim that requires "a

metal oxide" but not "an oxide of titanium") cannot claim priority prior to February 7, 2011. It is also my opinion that Claims 23 and 24 (i.e., claims that require metal electrical contact" comprise an "oxide of titanium") cannot claim priority prior to February 19, 2016. Thus, Grupp '483, which issued in 2007, is prior art to all challenged claims (Claims 5-12, 14-19, 21, 23-24, and 26-29) of the '691 Patent. Further, Wu, which was filed on Dec. 17, 2007 and issued on June 1, 2010, is prior art to Claims 23 and 24. Thus, Grupp '483 (Ex. 1021) anticipates all of these claims except Claims 23 and 24 (i.e., Claims 5-12, 14-19, 21, and 26-29) but Grupp '483 in view of Wu (Ex.1126) renders them obvious, as I explain below in **Section XI.C**. This is summarized below with the aid of a family tree:


Grupp '483 invalidates Claims 5-12, 14-19, 21, 26-29
10/217,758 - 08/12/2002
7,084,423 - 08/01/2006
CIP
10/342,576 - 01/14/2003
6,833,556 - 12/21/2004
CIP
10/753,504 - 01/07/2004
7,176,483 - 02/13/2007
Entire '556 disclosure incorporated by reference into all other patents shown here
CON
11/181,217 - 07/13/2005
7,462,860 - 12/09/2008
DIV
12/197,996 - 08/25/2008
7,884,003 - 02/08/2011
PCT/US04/42084 - 12/14/2004
DIV
13/022,522 - 02/07/2011
8,431,469 - 05/01/2012
No earlier Priority Applications support a claim to the genus of "metal oxide" interface layer (Feb. 7, 2011)
CON
13/552,556 - 07/18/2012
9,425,277 - 08/23/2016
CON
CON
CON
CON
13/687,907 - 11/28/2012
8,766,336 - 07/01/2014
15/048,877 - 02/19/2016
9,905,691 - 02/27/2018
14/743,916 - 06/18/2015
9,209,261 - 12/08/2015
15/048,893 - 02/19/2016
9,461,167 - 10/04/2016
CON
15/251,210 - 08/30/2016
9,812,542 - 11/07/2017
No earlier Priority Applications support a claim to (i) the genus of "oxide of titanium" interface layer, (ii) stack of metals, and (iii) specific contact resistivity (Feb. 19, 2016)
CON
15/728,002 - 10/09/2017
10,388,748 - 08/20/2019
CON
CON
CON
15/877,837 - 01/23/2018
10,090,395 - 10/02/2018
15/877,837 - 05/16/2018
10,186,592 - 01/22/2019
16/506,022 - 07/09/2019
US 11,056,569 – 07/06/2021
CON
CON
16/847,878 - 04/14/2020
US 11,018,237 – 05/25/2021
17/304,108 – 06/14/2021
US 11,355,613 – 06/07/2022
CON
CON
15/929,592 - 05/12/2020
US 10,937,880 – 03/02/2021
15/929,593 - 05/12/2020
US 10, 950,707 – 03/16/2021

XI. OPINIONS

A. The parent applications of the ’691 Patent do not adequately describe a metal oxide layer or a metal oxide separation layer that comprises an “oxide of titanium”

91. My analysis and conclusions in this Section are applicable to the Claims 6-12, 15-19, and 26-29 of the ’691 Patent.[1]

1. The specification of ’691 Patent and its parent applications describe only a TiO_2 spacer layer

92. Claims 6-12, 15-19 and 26-29 of the ’691 Patent recite or depend on a claim that recites a “metal oxide layer compris[ing] an oxide of titanium” or a “metal oxide separation layer compris[ing] an oxide of titanium.” I have been asked to consider whether the parent applications of the ’691 Patent provide written description support for “metal oxide layer compris[ing] an oxide of titanium” or a “metal oxide separation layer compris[ing] an oxide of titanium” as recited in Claims 6-12, 15-19 and 26-29.

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[1] Claims 23-24 also recite “an oxide of titanium,” but in these claims, “the metal electrical contact comprises an oxide of titanium.” The ancestor applications do not disclose a metal electrical contact comprising any oxide, let alone an oxide of titanium. Thus, the priority date of Claims 23-24 cannot be earlier than February 19, 2016 for this reason alone and discussed separately in **Section I**.

93. It is my opinion that the ancestor applications and patents to which the ’691 Patent claims priority (“Priority Applications”) do not provide sufficient disclosure regarding which specific “oxides of titanium” would be encompassed by the claimed “metal oxide compris[ing] an oxide of titanium” or a “metal oxide separation layer compris[ing] an oxide of titanium.” And, importantly, the Priority Applications do not provide sufficient disclosure regarding which of these “oxides of titanium”—other than TiO_2—were in the inventors’ possession at the time of the Priority Applications.

94. To reach this conclusion, I have reviewed each of the Priority Applications. Those patent applications and patents are listed in the table below, with each row for each application and its corresponding patent:

Application	Citation	Issued Patent	Citation
10/217,758	Ex. 1002, at 5-52	7,084,423	Ex. 1003
11/181,217	Ex. 1006, at 3-42	7,462,860	Ex. 1007
12/197,996	Ex. 1008, at 8-48	7,884,003	Ex. 1009
13/022,522	Ex. 1010, at 14-51	8,431,469	Ex. 1011
13/552,556	Ex. 1012, at 6-46	9,425,277	Ex. 1013

95. I observe that those ancestor applications and issued patents (i.e., Priority Applications) have the same specifications and figures as the ’691 Patent. Thus, I

principally address the ’691 Patent’s specification and figures herein, with the understanding that the specifications and figures of the parent applications of the ’691 Patent are identical. But, the abstracts and claims differ somewhat. I have also considered those abstracts and claims and address them to the extent they affect my analysis.

96. While the ’691 Patent and its ancestor applications do describe a TiO_2 spacer layer—“[s]pacer layers may be used with lower barriers (e.g., TiO_2 has a barrier of less than 1 eV)”—no other oxides of titanium are described for use as “metal oxide compris[ing] an oxide of titanium” or a “metal oxide separation layer compris[ing] an oxide of titanium” in the specification of either the ’691 Patent or its parent applications. (*E.g.,* Ex. 1001 [’691 Patent] at 17:60-62.)

97. I have also reviewed U.S. Patent No. 6,833,556 (Ex. 1005) and the application from which that patent issued. (Ex. 1004 at 4-44.) I understand that U.S. Patent No. 6,833,556 is incorporated by reference in each of the parent applications of the ’691 Patent.

98. None of the ancestor applications before U.S. Patent App. No. 15/048,877 describes a “metal oxide compris[ing] an oxide of titanium” or a “metal oxide separation layer compris[ing] an oxide of titanium,” i.e., that the genus of titanium oxide can comprise or be ***any*** oxide of titanium. The originally-filed claims of U.S. Patent App. No. 15/048,877 are the first instance in any of the parent

applications of ’691 Patent where the patentee described a generic “oxide of titanium.” (Ex. 1020 [File History of U.S. Patent No. 9,905,691] at 62.) U.S. Patent App. No. 15/048,877 was filed on February 19, 2016. (*Id.* at 1.) Though claim 18 of U.S. Patent No. 9,425,277 recites the term “a titanium oxide,” the originally-filed claims submitted along with U.S. Patent App. No. 13/022,522 do not recite the term “a titanium oxide.” (Ex. 1012 [File History for U.S. Patent No. 9,425,277] at 38-39.) The “a titanium oxide” was added on June 5, 2014 as part of a new claim in the response to a non-final office action dated February 26, 2014. (*Id.* at 152-173, 176-178.)

99. Further, although U.S. Patent No. 6,833,556 (incorporated by reference into the ’691 patent) does describe both a generic metal oxide and specific examples of zinc oxide, aluminum oxide, zirconium oxide, and hafnium oxide (Ex. 1005 [U.S. Patent No. 6,833,556] at 7:60-8:22, 13:44-14:20), that patent does not provide any further disclosure about oxides of titanium. Further, the metal oxides in U.S. Patent No. 6,833,556 are used to prevent the flow of current between a transistor’s gate and the transistor’s channel so as to electrically isolate the gate from the channel. (Ex. 1005 [U.S. Patent No. 6,833,556] at 7:60-8:5.) That patent does not describe using any of those metal oxides as a “metal oxide compris[ing] an oxide of titanium” or a “metal oxide separation layer compris[ing] an oxide of titanium” through which current flows as is described and claimed in the ’691 Patent. (Ex. 1001 [’691 Patent] at 14:45-52.)

100. Thus, the only example of an "oxide of titanium" suitable as "metal oxide compris[ing] an oxide of titanium" or a "metal oxide separation layer compris[ing] an oxide of titanium" described in either the '691 Patent or its parent applications is the TiO_2 spacer layer described in the '691 Patent and its parent applications: "[s]pacer layers may be used with lower barriers (e.g., TiO_2 has a barrier of less than 1 eV)." (*E.g.,* Ex. 1001 ['691 Patent] at 17:60-62.) But, neither the specification of the '691 Patent nor the specifications of its parent applications equate spacer layers with "lower barriers" to the genus of oxides of titanium. The lone example of TiO_2 spacer layer in the priority applications and a passing mention of a spacer layer presenting a "barrier of less than 1 eV" does not reflect the variation across the genus of oxide of titanium, and cannot support claims to the entire genus of "oxide of titanium." I also note that Acorn (i.e., Patent Owner during the Acorn/Samsung Litigation) has itself alleged that inserting an insulating interface layer between a metal and a semiconductor was "counter-intuitive" because "an insulating interface layer was not generally considered to be a solution for applications where the goal was to reduce resistance in a design. This is because adding an insulating layer between a metal and a semiconductor typically ***increases*** resistance in the design. The idea of ***adding*** an insulating layer to ***reduce*** resistance is counterintuitive." (Ex. 1038 [Acorn Complaint] ¶ 48 (emphasis in original); *see also* Ex. 1095 [Oak IP Complaint], ¶¶ 37, 38.) I also understand that

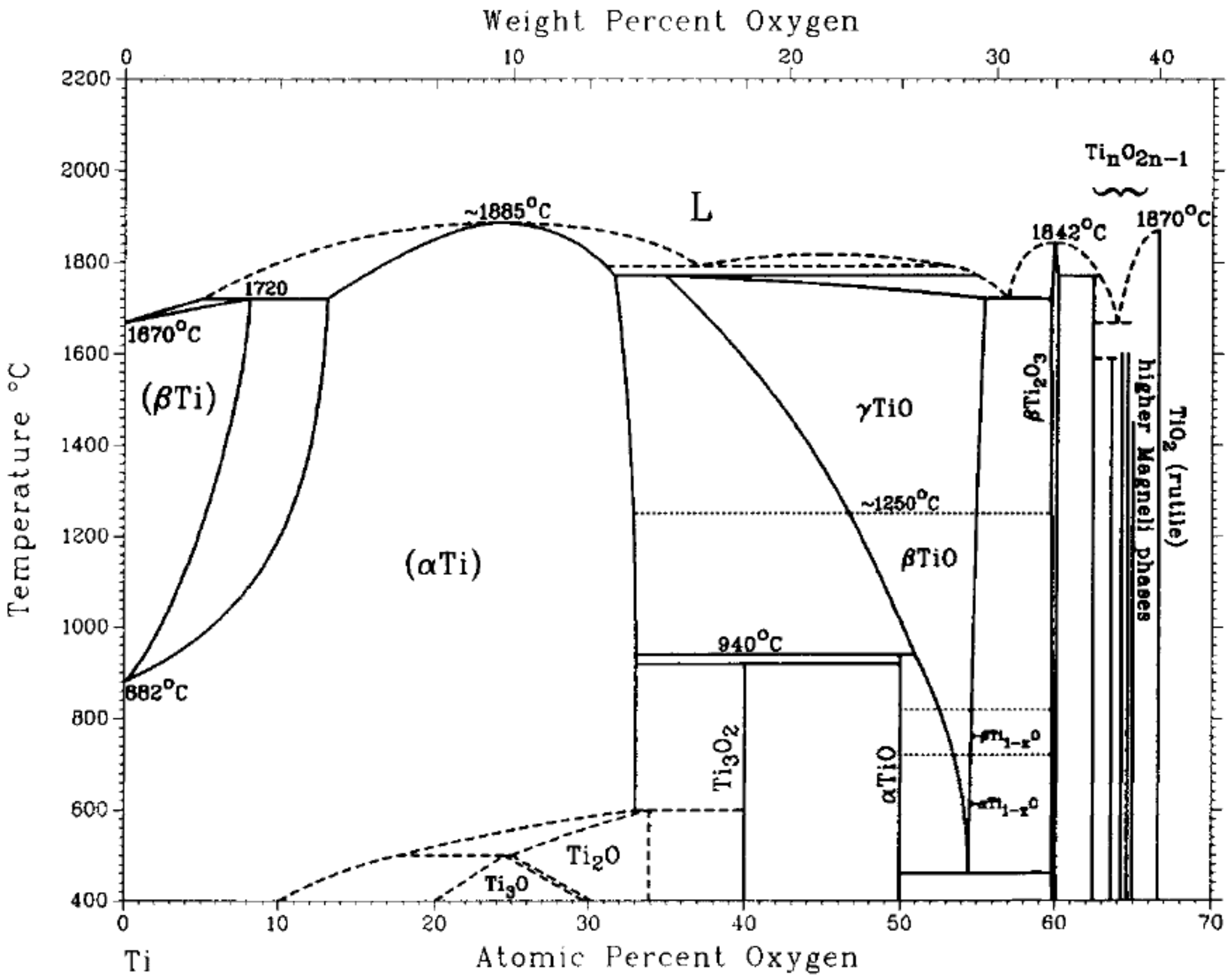
Oak's Complaint also alleges that the inventors found this result "remarkable." (Ex.1095 [Oak IP Complaint], ¶¶ 37-39.)

2. Genus of "oxide of titanium" includes numerous species that include oxygen and titanium atoms

a) Genus of "oxide of titanium" includes numerous stoichiometric and non-stoichiometric binary compounds containing oxygen and titanium

101. The term "oxide of titanium" describes a very broad genus with a very large number of binary compounds of oxygen and titanium, i.e., compounds containing only oxygen and titanium atoms. The breadth of the "oxide of titanium" genus is exacerbated because the genus of "oxide of titanium" does not include only stoichiometric compound species but also non-stoichiometric compound species.

102. The "stoichiometric compounds" have compositions where the atom ratios are given by integers. For example, titanium oxide has multiple equilibrium compound forms, including but not limited to: TiO, Ti_2O, Ti_3O, TiO_2, Ti_2O_3, Ti_3O_5, and Ti_4O_7. (Ex. 1056 [1987-Murray] at Fig. 1.) 1987-Murray shows these variations of titanium oxide in Figure 1:



(*Id.*)

103. But the genus of "oxide of titanium" is not limited to equilibrium compounds in this area of technology. The "non-stoichiometric compounds" have compositions where the atom ratios are not given by integers. In the field of semiconductors, both stoichiometric and non-stoichiometric forms of titanium oxide are commonly used. (Ex. 1056 [1987-Murray].) These non-stoichiometric compounds are generally considered to be non-equilibrium—that is, they are not at the lowest possible energy state due to being non-stoichiometric with some bonds being

unsatisfied. For example, as opposed to stoichiometric compounds, such as TiO (atom ratio is 1-to-1) and TiO_2 (atom ratio is 1-to-2), TiO_{1-x}, or TiO_{2-x} are non-stoichiometric (having a non-integer atom ratio) and thus non-equilibrium compounds. Non-stoichiometric variations of titanium oxide thereby include compounds such as TiO_{1-x} or TiO_{2-x}. Non-stoichiometric variations of titanium oxide (such as TiO_{1-x}, or TiO_{2-x}) can form when using a non-stoichiometric deposition technique such as PVD. (Ex. 1048 [Dr. Kuhn's Deposition Transcript from 7-6-2021] at 50:25-51:13 ("Q: Each metal oxide has multiple species; correct? A: That's a more complicated question that it sounds. You can have various equilibrium compounds for a metal oxide. So, for example, titanium oxide might have TiO_2 or Ti_2O_3 or Ti_3O_5, something like that. Those are equilibrium stable compounds. But in the semiconductor industry, you can also have nonequilibrium compounds because these products are fabricated in nonequilibrium conditions. So there are potential for many more possibilities within a family than the traditional stable equilibrium compounds.").) For example, oxides of titanium that can form may not be stoichiometric compounds, such as Ti_2O_3, but can have oxygen deficiency variations such as Ti_2O_{3-y}, depending on the conditions under which those metal oxides are formed. Indeed, when depositing a titanium oxide in an oxygen-deficient environment leaves no choice but to form an oxygen-deficient non-equilibrium species of a titanium oxide. Such compounds are referred to as non-equilibrium compounds because they will continue to oxidize over long periods of time until they reach a stable stoichiometric composition.

b) Genus of "oxide of titanium" includes numerous ternary compounds containing oxygen, titanium and another element

104. The term "oxide of titanium" describes a very broad genus with a very large number of underlying species if the genus includes compounds of oxygen, titanium, and another element, such as silicon. In addition to compounds of $TiSi_xO_y$ (titanium silicate) discussed below in **Section XI.A.3.a)**, examples of ternary oxides of titanium include but are not limited to the following:

- TiN_xO_y (titanium oxynitride). (*See* Ex. 1077 [1999-Gwo] at 1092 ("We suggest a formation of **TiN_xO_y** graded oxide layer in the near surface region.").)
- TiOC (titanium oxycarbide). (*See* Ex. 1073 [1984-Shikama] at 197 ("preferential removal of carbon and the formation of **titanium oxycarbide** when titanium carbide (TiC) was sputtered by argon ions in the presence of oxygen").)
- $TiGeO_4$ (titanium germanate). (*See* Ex. 1072 [1991-Glebov] at 59 ("**Titanium-germanate** glasses and waveguides feature the high refractive indices (n = 1.77).").)
- $Ti_xCr_{2-x}O_3$ (titanium chromium oxide). (*See* Ex. 1071 [2013-Rangel-Kuoppa] at 23 ("Among the novel metal-oxide semiconductors, **$Ti_xCr_{2-x}O_3$**

(TiCrO) is one whose electrical properties and the formation of ohmic contacts on it have not been explored extensively.").)

- $SrTiO_3$ (strontium titanate). (*See* Ex. 1067 [2000-Pontes] at Abstract ("**$SrTiO_3$** thin films were prepared by the polymeric precursor method and deposited by spin-coating onto Pt/Ti/SiO2/Si(100) substrates.").)
- TiAlO (titanium aluminate). (*See* Ex. 1070 [2003-Nguyen] at Abstract ("In this report, we attempt to address and improve the methodology of the ellipsometric application to this class of materials by investigating, in particular, metal oxides of hafnium aluminates and **titanium aluminates**.").)
- $BaTiO_3$ (barium titanate). (*See* Ex. 1060 [1992-Roy] at Abstract ("Thin films of **$BaTiO_3$** were deposited on platinum coated silicon substrates by excimer laser (248 nm) ablation at 600 °C or *ex situ* crystallized at about the same annealing temperature.").)
- Mg_2TiO_4 (magnesium titanate). (*See* Ex. 1065 [1993-Imai] at Abstract ("Formation of **Mg_2TiO_4** occurs at the interface between the MgO layer and the TiOx layer and/or at the grain boundary of the superlattice.").)
- Ca_2TiO_4 (calcium titanate). (*See* Ex. 1061 [2000-Hao] at Abstract ("We found that the dielectric constants of 1-µm-thick **$CaTiO_3$** films are very close to that observed in the bulk materials.").)
- $Li_{0.5}TiO_2$ (lithium titanate). (*See* Ex. 1064 [2001-van-de-Krol] at 2235 ("Special attention will be devoted to the properties of **$Li_{0.5}TiO_2$**.").)

105. As depicted in the list above, ternary titanates are three-element compounds that include titanium, oxygen and one other element. I estimate that the

number of possible species to be at least 10 but more likely to be more than 20. Like the binary compounds of titanium and oxygen discussed above, there are variations in the properties of ternary compounds. Each ternary titanate genus is a species of the "oxide of titanium" genus with different characteristics making them of interest for multiple applications. (Ex. 1068 [2014-Doeff] at 5 (noting that "ternary titanates, particularly those belonging to the Na-Ti-O system, have diverse structural and physical characteristics making them of particular interest for use in batteries, as well as other applications.").)

3. Patent Owner agrees that the "oxide of titanium" genus includes numerous species that include oxygen and titanium atoms

a) Patent Owner interprets the "oxide of titanium" genus to include silicon besides oxygen and titanium

106. I have reviewed **Section XI.A.2.a)** of the Petition and concur that Oak IP and Acorn have alleged that the "oxide of titanium" encompasses other elements besides oxygen and titanium, such as silicon.

107. As discussed in **Section XI.A.4** *infra*, there are numerous different ternary compounds in the genus of "oxide of titanium," which renders the scope of the genus of "oxide of titanium" extremely broad.

b) Acorn interpreted the "oxide of titanium" genus to include non-stoichiometric, non-equilibrium compounds with varying levels of oxygen

108. I have reviewed **Section XI.A.2.a** of the Petition and concur that Acorn has alleged that all compounds of titanium, silicon and oxygen fall within this genus of "oxide of titanium" irrespective of the level of oxygen content.

109. Oak IP's and Acorn's infringement allegations make clear that they interpret the term "oxide of titanium" to be a very broad genus with a very large number of underlying species containing varying amounts of titanium, silicon and oxygen.

4. Different species in the "oxide of titanium" genus can have different electrical and structural properties

110. The genus of "oxide of titanium" includes not only dielectric compounds (i.e., insulators) but also metallic compounds and semiconductive compounds. The '691 Patent does not provide any guidance regarding which species of the genus are suitable to form an metal oxide layer that comprises an oxide of titanium. This is because different types of "oxide of titanium" can have vastly different electrical and structural properties.

111. There are many different properties that affect the characteristics of the compound and the applications for which the compound may be employed. For example, a non-limiting list of such properties include: (a) electrical (tunneling and bulk) conductivity (*or* resistivity); (b) barrier height; (c) electron affinity; (d) bandgap

energy; (e) dielectric constants; (f) structural characteristics; (g) melting point; and (h) optical transparency. I note that the melting point is indicative of high-temperature structural stability which is of interest for reliability considerations. I also note that the optical transparency gives an indication of the bandgap energy, with opaque materials having a lower bandgap energy, and transparent materials having a higher bandgap energy. I finally note that changes in the chemical composition of a material cause changes in the bandgap energy, which in turn cause changes in the electrical properties.

112. As discussed below, ranges of these properties in the genus of "oxide of titanium" demonstrate that some species of "oxide of titanium" are not suitable for the metal oxide layer that comprises an oxide of titanium. Moreover, relevant properties of some species are not known.

a) Electrical Conductivity (or resistivity)

113. Electrical conductivity measures how easily electricity flows through a material. I understand that the Board has noted that "[t]he electrical conductivity of a metal oxide is an important property for the recited genus because electrical conductivity directly affects the specific contact resistance of a junction, which is important property for the '691 patent's disclosure." (Ex. 1091 [Grupp '483 IPR], at 20 n.3.). Fig. 8 of the '691 Patent depicts a graph of interface-specific contact resistance versus interface thickness. (Ex.1001 ['691 Patent] at 14:29-31.). When discussing the graph of Fig. 8, the '691 Patent notes the importance of resistance

when it states that "[t]he present inventors have discovered that this competition results in an optimum thickness, as shown in the illustration, ***where the resistance is a minimum***." (*Id.* at 14:31-53.)

114. The electrical conductivity of an "oxide of titanium" used in a metal oxide layer in a metal-semiconductor junction is important because it directly affects the specific contact resistivity of the junction. Specifically, carrier transport through an "oxide of titanium" layer in a metal oxide layer may proceed through tunneling and/or thermionic emission. Whereas tunneling is expected to dominate for high barriers (such as Si-Al_2O_3), thermionic emission is expected to be a factor for lower barriers (such as Si-TiO_2). The genus of "oxide of titanium" exhibits such a wide range of properties such that a person of ordinary skill cannot discern a common property for all the species in the genus. For example, TiO (Titanium monoxide) has metallic properties, and would not pose any tunnelling barrier. TiO_2 is considered a semiconductor (due to its bandgap energy value of about 3 eV) and it has a low tunneling barrier (around 1 eV) when used as a metal oxide layer in a metal-interface layer-silicon structure.

115. It is common in the art to categorize materials based on their electrical conductivity (or electrical resistivity, which is the reciprocal of electrical conductivity) into three categories:[2]

- Conductive materials that include metals and metallic materials have high electrical conductivity (10^4 to 10^8 /Ω cm) and low electrical resistivity (10^{-8} to 10^{-4} Ω cm).
- Semi-conductive materials that include semiconductors, such as silicon, have medium electrical conductivity (10^{-7} to 10^3 /Ω cm]) and medium electrical resistivity (10^{-3} to 10^7 Ω cm).
- Non-conductive materials that include insulators and dielectric have low electrical conductivity (10^{-18} to 10^{-8} Ω cm) and high electrical resistivity (10^8 to 10^{18} Ω cm).

[2] Conductors, semiconductors, non-conductors: Conductors have electrical resistivity on the order of 10^{-8} to 10^{-4} Ω cm, whereas insulators have electrical resistivity on the order of 10^8 to 10^{18} Ω cm. Semiconductors have an electrical resistivity value between those of conductors and insulators, approximately 10^{-3} to 10^7 Ω cm. (*See* Ex. 1115 at 1.)

116. It was well-known to a POSITA that many factors may affect electrical conductivity of an oxide of titanium (as interpreted by the Patent Owner), such as the composition, environmental conditions, growth (deposition) conditions, and oxygen content. Thus, these factors may determine whether a species of oxides of titanium is conductive (metallic), semi-conductive, or non-conductive (insulative). Each of these factors is explained in detail below.

(1) Composition of an oxide of titanium

117. ***First***, it was known that the chemical composition of an oxide of titanium may affect its electrical conductivity. Especially, it was well-known that conductivity of an oxide of titanium depends on its oxygen content. For example:

- **Conductive (Metallic)**: TiO (titanium monoxide), which has an atomic oxygen content of 50%, is an oxide of titanium with metallic properties. TiO has an electrical resistivity (ρ)[3] of 2.0×10^{-6} to 2.5×10^{-6} **Ω** m which has been characterized as metallic and is a good conductor. (*See* 1063 [1966-Denker] at 142, 145-149; *see also* Ex. 1083 [U.S. 4,912,286 (Clarke)] at 2:29-34 ("invention also provides a structure which comprises a titanium-sub-oxide of formula TiO_x in which x is less than 2, which is in a form suitable for use as an electrical conductor.").) The properties of Ti_3O and Ti_2O are not well known, yet are expected to exhibit metallic properties

[3] Electrical conductivity is the reciprocal of electrical resistivity.

(because the content of Titanium in Ti_3O and Ti_2O is even higher than the content of Titanium in TiO).

- **Semi-conductive**: TiO_2 (titanium dioxide) is an oxide of titanium with semi-conductive properties (which may vary depending on the impurity content). TiO_2 has an electrical resistivity (ρ) ranging from 1×10^4 to 1×10^7 Ω m. (*See* Ex. 1078 [1978-Takeuchi] at 88).
- **Non-conductive (Insulator)**: $TiSiO_4$ (titanium silicon oxide), which has an atomic oxygen content of 66%, is an oxide of titanium (containing a third element of silicon) with insulating properties. As discussed above, Patent owner interprets the genus of "oxides of titanium" to contain a third element such as silicon. $TiSiO_4$ has an electrical resistivity (ρ) of 10^8 to 10^{10} Ω m. (*See* Ex.1035 [2005-Brassard] at 054912-6).

Accordingly, the genus of "oxides of titanium," as understood by Patent owner, spans about 15 orders of magnitude in electrical resistivity and includes metallic, semi-conductive, and insulating properties.

118. It was also well-known that conductivity of an oxide of titanium depends on its oxygen content, even among the species that are composed of the same elements. For example, in case of an oxide of titanium that is composed of titanium, silicon, and oxygen, i.e., $TiSi_xO_y$, it was well-known that conductivity of the compound varies widely depending on the level of oxygen content of the compound. Brassard et al. showed that the electrical properties of $TiSi_xO_y$ changed considerably depending upon the level of oxygen content in the compound. Fig. 6(c) of 2005-Brassard (shown

below) demonstrates "a strong correlation between the [electrical] resistivity of the [] titanium silicate films and their oxygen content." (*Id.* at 054912-7) "[T]he resistivity of the titanium silicate films is seen to vary in a strikingly exponential way" from a low of 10^{-2} Ω cm to a high of 10^{12} Ω cm (almost as wide as 14 decades) as the level of oxygen content is increased. (*Id.*; *see also* Ex. 1083 [U.S. 4,912,286 (Clarke)] at 4:14-16 (noting that the "conductivity of the electrical conductor of the invention is dependent inter alia on the value of x in the titanium sub-oxide TiO_x in the structure.").

119. Fig. 6(c) of 2005-Brassard (shown below) further shows that titanium silicates ($TiSi_xO_y$) with high levels of oxygen content are insulating. For example, consider $TiSiO_4$. The atomic oxygen content of this compound is 66.6%, and its oxygen ratio (x-axis in Fig. 6(c)) is 2.0.[4] Fig. 6(c) of 2005-Brassard shows that the

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[4] The atomic oxygen content is calculated by the number of oxygen atoms divided by the total number atoms: for example, for $TiSiO_4$, [O] / ([Ti] + [Si] + [O]) = 4 / (1 + 1 +4) = 4/6 = 66.6%. The oxygen ratio is calculated by the number of oxygen atoms divided by the sum of the number of silicon (Si) atoms and the number of titanium (Ti) atoms: for example, for $TiSiO_4$, [O] / ([Si] + [Ti]) = 4 / (1+1) = 2.0. The rectangular brackets […] indicate the atomic concentration of the element. (*See* Ex. 1033 [2004-Brassard].)

resistivity of $TiSiO_4$ is about 10^{12} Ω cm, which confirms that $TiSiO_4$ is an insulator. (Ex. 1035 [2005-Brassard] at 054912-6; Ex. 1033 [2004-Brassard] at 2306.)

120. On the other hand, titanium silicates ($TiSi_xO_y$) with lower levels of oxygen content are conductors and behave like metallic compounds. Consider $TiSiO_2$. The atomic oxygen content of this compound is 50%, and its oxygen ratio is 1. (Ex. 1033 [2004-Brassard].) Although there is sparse technical literature describing the resistivity of $TiSiO_2$, its resistivity can be estimated by considering a 1:1 mixture of TiO and SiO—which, like $TiSiO_2$, has 25% Ti, 25% Si, and 50% O. It is well established that TiO has metallic properties, (Ex. 1063 [1966-Denker] at 149), and SiO is a semiconductor with a bandgap energy of 2.25 eV. 1984-Al-Ani reported that SiO has a bandgap energy of 2.25 eV (experimental value), (Ex. 1057 [1984-Al-Ani] at 1740), and 2020-Chen reported that SiO has a bandgap energy of 1.52 eV (calculated value). (Ex. 1088 [2020-Chen] at Abstract.) Because $TiSiO_2$ can be considered a mixture of a metallic compound (TiO) and a semiconducting compound (SiO), it is reasonable to expect that $TiSiO_2$ will have a conductivity that is somewhere between metallic and semiconducting. Fig. 6(c) of 2005-Brassard, after extrapolation, confirms that at the oxygen ratio of 1, the electrical resistivity is approximately 10^{-6} Ω cm, which confirms that $TiSiO_2$ is a conductor. (Ex. 1035 [2005-Brassard] at 054912-6, Fig. 6(c).)

121. Low levels of oxygen content in a titanium silicate layer results in a layer with sufficiently low resistivity that the layer is suitable as a conductor. (Ex. 1053 [1984-Robb] at 2906 (noting that "resistances as low as 1 Ω / ϒ have been obtained on titanium silicide films containing 5% oxygen"). (Ex. 1082 [1989-Hallock] at 191 (noting that resistivity of titanium silicide films was acceptable when deposited using a sputtering gas composition of 25% oxygen and 75% Argon).) 1989-Hallock suggests that an atomic oxygen content of 36% is acceptable for titanium silicide serving as a conductor.

122. In other words, the genus of "oxides of titanium" is highly diverse with respect to electrical resistivity with no commonality among the different species. And given the vast number of compositions of compounds in the "oxides of titanium" genus, a POSITA may not have been able to find sufficient scientific literature to categorize the conductivity of some oxides of titanium.

(2) Environmental Conditions

123. ***Second***, it was known that environmental conditions may affect electrical conductivity of an oxide of titanium. For example, it was known that Ti_3O_5, a species of oxides of titanium, is a semiconductor at room temperature but becomes conductive at elevated temperatures. (Ex. 1062 [1987-Shveikin] at 21 ("The semiconductor-metal phase transition accompanied by a sharp change of electric, magnetic, structural, and other characteristics, occur in Ti_3O_5 oxide at 450 K.").)

(3) Growth (Deposition) Conditions

124. ***Third***, it was known that growth (deposition) conditions of an oxide of titanium may affect its electrical conductivity. For example, the electrical conductivity of titanium silicate[5] ($TiSi_xO_y$) change considerably —from a metal to an insulator— depending upon their growth conditions (e.g., film deposition conditions), including oxygen pressure and deposition temperature.

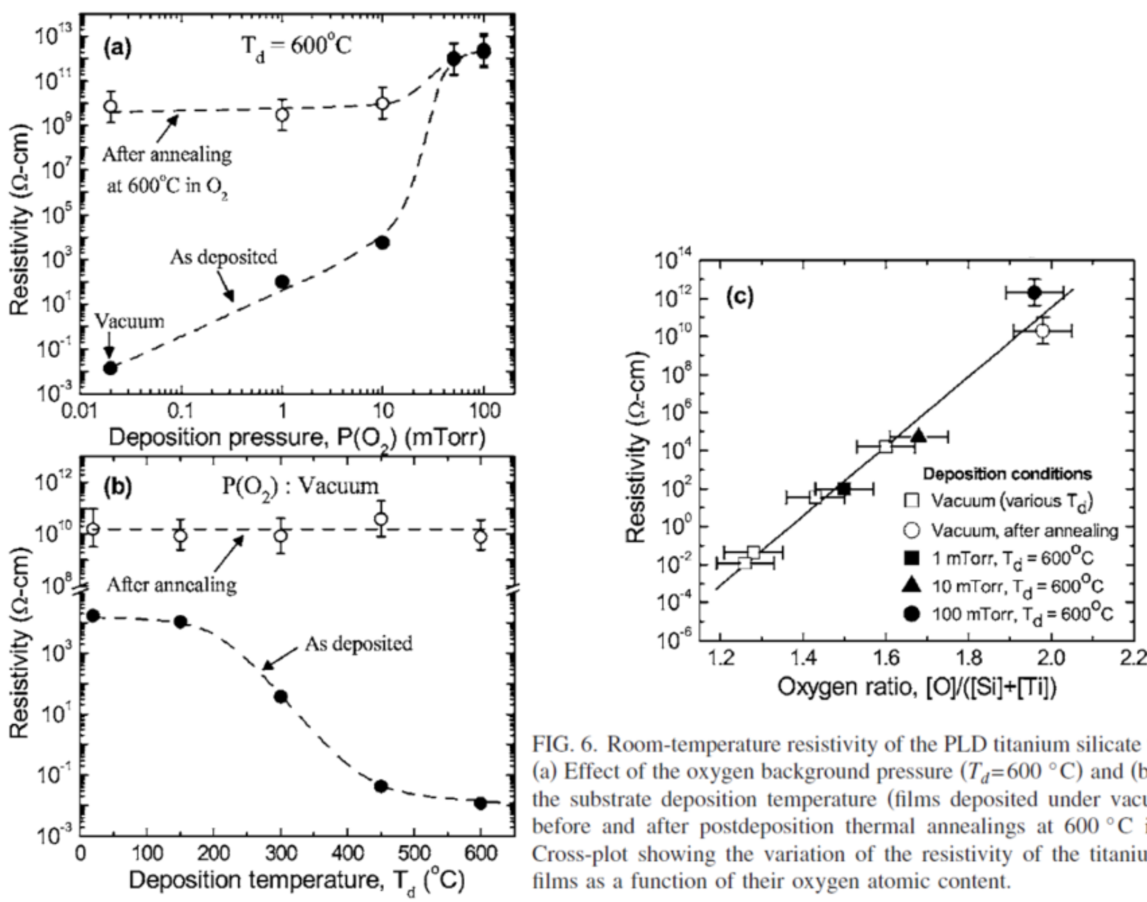

FIG. 6. Room-temperature resistivity of the PLD titanium silicate thin films. (a) Effect of the oxygen background pressure (T_d=600 °C) and (b) effect of the substrate deposition temperature (films deposited under vacuum) both before and after postdeposition thermal annealings at 600 °C in O_2. (c) Cross-plot showing the variation of the resistivity of the titanium silicate films as a function of their oxygen atomic content.

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[5] As discussed supra Section XI.A.3, ternary compounds of titanium oxide are also "oxides of titanium" under Patent Owner's interpretation.

(Ex. 1035 [2005-Brassard] at 054912-6, Fig. 6.)

125. **Oxygen Pressure:** The electrical conductivity of an oxide of titanium may depend on the oxygen pressure during deposition. Fig. 6(a) of 2005-Brassard shows the effect of oxygen pressure ($P(O_2)$) on the electrical resistivity (i.e., the reciprocal of electrical conductivity) of titanium silicate thin films. (Ex. 1035 [2005-Brassard] at 054912-6; *see also* Ex. 1033 [2004-Brassard] at 2306.) When the oxygen pressure was low when the film was deposited, "the resistivity is found to be surprisingly low for $P(O_2) < 50$ mTorr (ρ as low as 1.2×10^{-2} Ω cm)." (Ex. 1035 [2005-Brassard] at 054912-7.) "On the other hand, the [electrical] resistivity is seen to increase rapidly when $P(O_2)$ is increased," and "highly insulating films with a resistivity of about 10^{12} Ω cm are obtained for $P(O_2) \geq 50$ mTorr." (*Id.*)

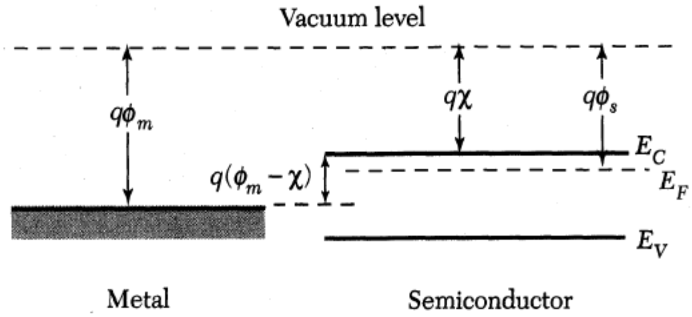
126. **Deposition Temperature:** The electrical conductivity of an oxide of titanium may depend on the deposition temperature. For example, Brassard et al. showed that electrical resistivity (inverse of electrical conductivity) of a $TiSi_xO_y$ film changes significantly with the deposition temperature (T_d) of the film. Fig. 6(b) of 2005-Brassard shows that "the [electrical] resistivity of the [titanium silicate] films deposited under vacuum is shown to decrease from 1.6×10^4 to 1.2×10^{-2} Ω cm when the T_d is increased from 20 to 600° C." (*Id.*)

127. In light of the broad range of variation in conductivity within the genus of oxide of titanium depending on the composition, environmental conditions, and

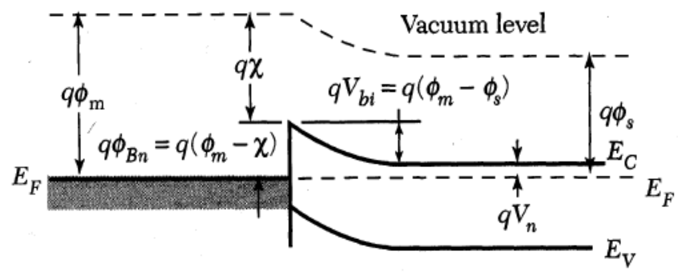
growth (deposition) conditions, the disclosure of "TiO_2" with "a barrier less than 1 eV" alone does not convey to a POSITA that the inventors had possession of the entire genus of oxide of titanium.

b) Barrier Height

128. In a metal-semiconductor junction, the barrier height represents the energy an electron needs to overcome to move from the semiconductor to the metal or vice versa. Thus, barrier height influences the electrical characteristics of the junction, and impacts current flow. (Ex. 1107 [Sze Textbook] at 72-24.) Fig. 2(a) from the Sze Textbook (excerpted below) is the energy band diagram of an isolated metal adjacent to an isolated n-type semiconductor and Fig. 2(b) from the same textbook is a diagram for a metal-semiconductor junction:



(a)



(b)

(Ex. 1107 [Sze Textbook], Figs. 2(a), 2(b), and 226.) The concept of barrier height is related to work function and electron affinity, and as shown in Fig. 2(b), barrier height ($q\varphi_{Bn}$) in a metal-semiconductor junction is the difference between the metal's work function and the semiconductor's electron affinity:

$$q\varphi_{Bn} = q\varphi_m - q\chi$$

(Ex. 1107 [Sze Textbook] at 226.) The electron affinity $q\chi$ is the energy difference between the conduction band edge E_c and the vacuum level in the semiconductor (i.e., level at which an electron has no potential energy). (*Id.*) The work function $q\varphi_s$ is the energy difference between the Fermi level E_F and the vacuum level in the semiconductor. (*Id.*) The work function of a metal $q\varphi_m$ is an inherent property of the metal and does not vary. Thus, the barrier height varies along with the electron affinity $q\chi$. As shown in Fig. 2(b) (above), the choice of metal and the semiconductor to form the junction influences barrier height, which in turn influences the specific contact resistance. In the case of metal-to-semiconductor junctions, Bardeen states and metal-induced gap states play an additional role in determining the barrier height. In the case of semiconductor-to-dielectric junctions, these metal-specific contributions are absent.

129. The ’691 Patent provides limited guidance regarding the barrier height of an “oxide of titanium.” It merely states that “[s]pacers layers may be used with lower barriers (e.g., TiO_2 has a barrier less than 1 eV).” (Ex. 1001 [’691 Patent] at 17:60-62.)

130. However, species of the “oxide of titanium” genus do not necessarily fall within the characterized range of having a barrier less than 1 eV. For example, several ternary titanate compounds that fall within the genus of “oxide of titanium” (as interpreted by the current and prior Patent Owner) exhibit a barrier height that is equal to 1 eV or higher than 1 eV. For example, a thesis published in 2003 reported that “[t]he barrier height of titanium aluminate [TiAlO] escalates with the aluminum concentration.” (Ex. 1094 [2003-Luo] at 164.) Specifically, this study observed that “the barrier heights of titanium aluminates with 15, 30, and 50 atomic % aluminum concentrations over Al Fermi-level are about 1 eV, 1.1 eV, and 1.5 eV respectively, as shown in Figure 4.25.” (Ex. 1094 [2003-Luo] at 164.) Figure 4.25 from 2003-Luo is excerpted below:

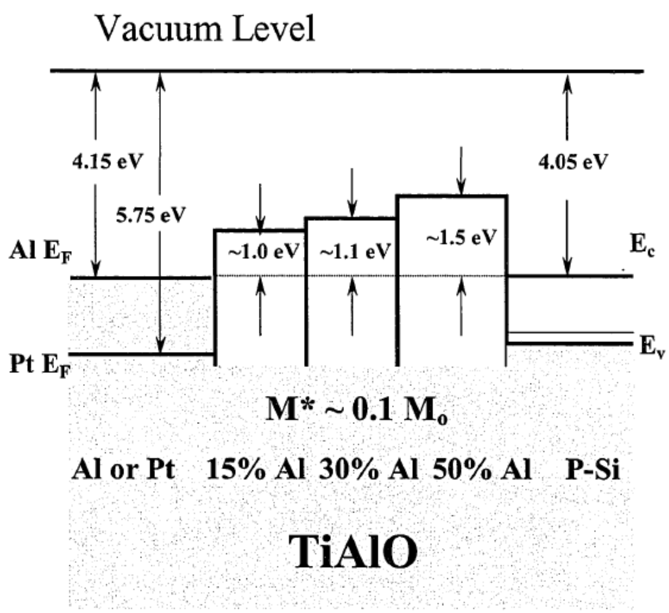


Figure 4.25 Band diagrams of titanium aluminates with 15, 30, and 50 atomic % aluminum concentrations.

(Ex. 1094 [2003-Luo] at 166, Fig. 4.25.)

131. The barrier heights of TiAlO relative to the silicon conduction band are also higher than or equal to 1 eV and not less than 1 eV, as calculated from data present in Figure 4.25. In Figure 4.25, 2003-Luo reports the barrier heights of TiAlO relative to the Fermi level of aluminum. According to Figure 4.25, E_F for aluminum is 4.15 eV below the vacuum level and E_C for silicon is 4.05 eV below the vacuum level. (Ex. 1094 [2003-Luo] at 165, Fig. 4.24.) Barrier height for TiAlO (50% Al) is 1.5 eV. Thus, the barrier height of TiAlO (50% Al) relative to silicon would be 1.5 eV – (E_F – E_C) = 1.4 eV. Similarly, the barrier heights of TiAlO (30% Al) relative to the silicon conduction band will be 1.0 eV. Thus, in some of these instances, the barrier heights

of titanium aluminates relative to silicon conduction band (or the aluminum Fermi level) are higher than or equal to 1 eV and not less than 1 eV.

132. Claim 1 of the ’691 Patent requires the “passivating dielectric tunnel barrier layer [that] comprises a semiconductor oxide” to be in contact with the semiconductor substrate and with the “metal oxide layer.” Similarly, Claim 25 requires the “semiconductor oxide passivation layer” of the “interface layer” to be in contact with the semiconductor. When the semiconductor substrate is in contact with the semiconductor oxide layer or the passivation layer, the silicon-to-“passivation layer” boundary or the silicon-to-“semiconductor oxide layer” has a barrier height that is particularly high for the Si-SiO_2 interface. The barrier height for the Si-HfO_2 and Si-ZrO_2 interface is also high. However, the barrier height is low for the Si-TiO_2 interface (“less than 1 eV”).

133. However, metallic compounds such as TiO (and likely Ti_3O and Ti_2O) do not form such a silicon-dielectric interface barrier (e.g., Si-HfO_2 and Si-ZrO_2) because these titanium compounds are not dielectrics but rather metals.[6] When electrons flow out of the silicon towards the metal oxide layer, they encounter a barrier

[6] Titanium compounds such as TiO are metallic compounds, that is, they are metal-like. Such metallic compounds are occasionally referred to as “metals” in the field of semiconductor technology.

for dielectrics such as SiO_2, HfO_2, ZrO_2, and TiO_2. The electrons do not encounter a barrier when they flow towards a layer made of metallic compounds, such as TiO, Ti_2O and Ti_3O. Accordingly, the metallic species of the genus "oxide of titanium" cannot be characterized as fitting the description of having "a barrier of less than 1 eV."

134. In light of the broad range of variation in the bandgap energy within the genus of oxide of titanium, the disclosure of "TiO_2" with "a barrier less than 1 eV" alone does not convey to a POSITA that the inventors had possession of the entire genus of oxide of titanium.

c) Electron Affinity

135. As discussed above, in a metal-semiconductor junction, electron affinity $q\chi$ is the energy required to move an electron from the bottom of the semiconductor's conduction band to the vacuum level. Electron affinity, along with the work function of a metal $q\varphi_m$, determines the barrier height of the junction and the resistance of the junction.

136. The electron affinity can be compared to the ionization energy of an atom. It takes the ionization energy to remove an electron from an atom (such as a hydrogen atom) and, similarly, it takes the electron affinity to remove an electron from a solid material (such as silicon material). Within the framework of energy band diagrams, the electron affinity is the energy difference between the conduction band edge and the vacuum level.

137. The electron affinity of a metal oxide used in an metal oxide layer is important because the electron affinity determines the alignment of the bands; for example, how the conduction band of an insulator aligns with the Fermi level of a metal.

138. Compounds in the "oxide of titanium" genus have different electron affinities that affect the characteristics of the compound and the applications for which the compound may be employed.

139. Different compounds in the "oxide of titanium" genus have different electron affinities. If, in terms of electrical conductivity, the "oxide of titanium" behaves like a metal, its properties are more appropriately described by a metal work function. For example, TiO, which has metallic properties, is more appropriately described by the work function, (Ex. 1063 [1966-Denker] at 149); the electron affinity of TiO_2 (a semiconductor) is 4.0 eV, (Ex. 1087 [2017-Marques] at 506); the electron affinity of Ti_2O_3 is not well understood in the current literature, (Ex. 1076 [1982-Hong] at 214). Finally, electron affinity of $TiSiO_4$ may not be known.

140. In light of the broad range of variation in the electron affinity within the genus of oxide of titanium, the disclosure of "TiO_2" with "a barrier less than 1 eV" alone does not convey to a POSITA that the inventors had possession of the entire genus of oxide of titanium.

d) Bandgap Energy

141. The bandgap energy is the gap between the bottom of the conduction band and top of the valence band ($E_c - E_v$). (Ex.1107 at 29.) Fig. 15 from the Sze Textbook shows the conduction band and the valence band that are formed by bringing isolated silicon atoms together:

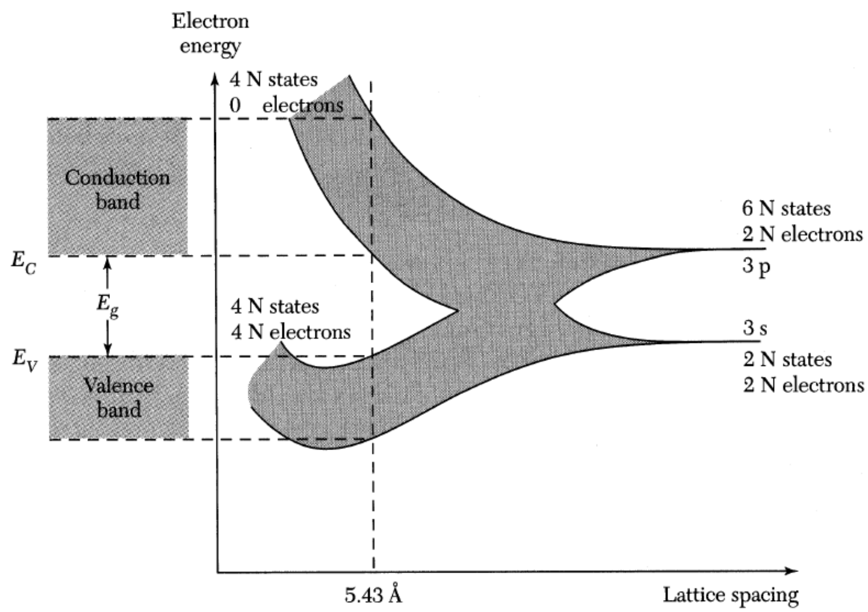


Fig. 15 Formation of energy bands as a diamond lattice crystal is formed by bringing isolated silicon atoms together.

(Ex. 1107 [Sze Textbook] at 30.) E_g is the energy required to break a bond in the semiconductor to free an electron to the conduction band and leave a hole in the valence band. *Id.* Higher bandgap energy E_g implies higher resistivity and smaller bandgap implies lower resistivity. Thus, the bandgap energy is a key factor in determining a material's electrical conductivity—that is, a material's electrical conductivity is inversely related to its bandgap energy.

142. Insulators usually have wider bandgap energies (for example, 4 eV to 9 eV), semiconductors have narrower bandgap energy (for example, 0.25 to 4 eV), and conductors (metals) usually have no bandgap energies.

143. The band alignment between two materials in a metal-semiconductor junction, such as the band alignment between the metal's Fermi level and the metal oxide layer's conduction band edge, is dependent on those two materials' work function and electron affinity. If two materials' relevant energies (such as a metal's Fermi energy and a semiconductor's conduction band energy) are not aligned, this results in a barrier to the flow of electrons (or the flow of holes) between those materials.

144. Compounds in the "oxide of titanium" genus have different bandgap energies that affect the characteristics of the compound and the applications for which the compound may be employed. The bandgap energy determines the resistivity of a material, particularly of an undoped material, with lower bandgap materials being generally more conductive than higher-bandgap materials.

145. For example, TiO does not have a bandgap energy because it behaves like a metal, (Ex. 1063 [1966-Denker] at 149); the bandgap energy of TiO_2 is about 3.0 to 3.4 eV, (Ex. 1074 [1980-Szydlo] at 3310; Ex. 1058 [2005-Tian] at 1788); the bandgap energy of Ti_2O_3 is 0.1 eV, (Ex. 1059 [2017-Wang] at 1); the band gap energy of Ti_3O_5 is small, since Ti_3O_5 is a black (*i.e.*, absorbing) material, (Ex. 1076 [1982-Hong] at

211); and the band gap energy of $TiSiO_4$ ranges from 1.75 eV (708 nm) to 2.68 eV (462 nm). (Ex. 1081 [2017-Liu].) Some of the references, such as 2017-Wang and 2017-Liu, were not published until more than a decade after the alleged priority date of the '691 Patent: however, the articles are nonetheless relevant because they report the physical properties of those materials.

146. In light of the broad range of variation in the bandgap energy within the genus of oxide of titanium, the disclosure of "TiO_2" with "a barrier less than 1 eV" alone does not convey to a POSITA that the inventors had possession of the entire genus of oxide of titanium.

e) Dielectric Constants

147. The dielectric constant of a material is the ratio of the electrical permittivity of the material to the permittivity of vacuum. Permittivity of a material is its ability to store electrical energy in an electrical field. The dielectric constant of an insulator expresses the polarizability of the material and the ability of the insulator to store electric energy in an electrical field. The dielectric constants are used to describe characteristics of the insulators and thus determine the applications for which the insulators can be employed.

148. It was well-known to a POSITA that "oxides of titanium" have different dielectric constants which affect the characteristics of the compound and determine the applications for which the compound can be employed.

149. Titanium oxides have high dielectric constants. 2005-Brassard report that TiO_2 has "the highest dielectric constant of the metal oxide group, with *k* values in excess of 80 are routinely obtained."[7] (Ex. 1035 [2005-Brassard] at 154912-1; *see also* Ex. 1078 [1978-Takeuchi] at 88 (noting that the dielectric constant of TiO_2 is 100.).) Addition of another element, such as silicon, alters the dielectric constant of the compound. For example, the dielectric constant of $TiSiO_4$ is 16.5. (Ex. 1080 [2011-Bertaud] at 044110-2, Table 1.) $Ti_{0.5}Si_{0.5}O_2$ has a dielectric constant higher than 20. (Ex. 1036 [2007-Brassard] at 034106-1.) Even minor variations in the composition can affect the dielectric constant significantly. $Ti_{0.51}Si_{0.49}O_2$ has a dielectric constant that is as high as 26. (Ex. 1035 [2005-Brassard] at 054912-2.)

150. In light of the broad range of variation in dielectric constant within the genus of oxide of titanium, the disclosure of "TiO_2" with "a barrier less than 1 eV" alone does not convey to a POSITA that the inventors had possession of the entire genus of oxide of titanium.

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[7] It is known that the relative permittivity (*k* value) of high-k dielectric varies quite a bit depending on the micro-crystalline structure, material density, and its state (amorphous versus crystalline). For example, 2006-Brassard implies that the *k* value of TiO_2 is around 40. (Ex. 1102 [2006-Brassard] at 603, Fig. 5.)

f) Structural Characteristics

151. Structural characteristics, whether it is a crystal structure or a non-crystal structure, are fundamental properties that relate to the spatial arrangement of its atoms. I will use the term "crystal structure" here to denote the structure of the different forms of "oxides of titanium," and not necessarily limited to those of the equilibrium forms.

152. It was well-known that compounds in the "oxide of titanium" genus have different crystal structures that affect the characteristics (e.g., electrical properties) of the compound and the applications for which the compound may be employed. It is very natural that a material's properties depend on the crystal structure (even if the chemical formula, e.g. TiO_2, is the same) because it is associated with spatial arrangement of atoms.

153. For example, it was well-known that TiO_2 crystallizes in three different structures: the rutile structure, anatase structure, and brookite structure. (Ex. 1069 [1995-Mo].) I note that atoms in a crystal structure have specific positional relationships with each other. In each of the three crystal structures (rutile, anatase, and brookite), the constituent atoms have distinct positional relationships with each other. 1995-Mo found that TiO_2 of the rutile structure has a smaller bandgap energy than the two other crystal structures (relating to the valence band alignment). (Ex. 1069 [1995-Mo] at 51.) Additionally, 1995-Mo found that the TiO_2 brookite structure has a relatively smaller bulk modulus (relating to elastic properties and thus adhesion of the

interface-layer). (Ex. 1069 [1995-Mo] at Abstract.) A material's bulk modulus can indirectly influence its electrical behavior by affecting the arrangement and spacing of its atoms, which in turn can affect the movement of charge carriers within the material.

154. Other binary oxides of titanium were also known to have multiple different crystal structures, which can influence the electrical properties. For example, TiO (titanium monoxide) was known to have multiple different structures, such as cubic, tetragonal, orthorhombic, hexagonal, and monoclinic structures. (Ex. 1050 [2013-Kostenko]; Ex. 1051 [2017-Valeeva]; Ex. 1086 [1997-Bartkowski].) Ti_2O_3 has the corundum crystal structure, which is a hexagonal crystal structure. (Ex. 1076 [1982-Hong]; Ex. 1046 [1974-Mott].) Ti_4O_7 has a triclinic crystal structure. (Ex. 1076 [1982-Hong].) Ti_3O_5 (trititanium pentoxide) is reported to be of the "anosovite" structure and the "monoclinic" structure. (Ex. 1047 [1959-Åsbrink]; Ex. 1084 [2021-Yang].)

155. On the other hand, some ternary titanate compounds were also known to have different crystal structures or a non-crystal structure (e.g., a glass-like structure), and the structural characteristics can influence the electrical properties. For example, $TiSiO_4$ (titanium silicate) has a glass-like structure. (Ex. 1035 [2005-Brassard].) Similarly, $TiSi_xO_y$ is essentially glass. (Ex. 1052 [1976-Gerlich].) Because a glass is an amorphous material, it does not have a crystal structure. Thus, neither $TiSiO_4$ nor $TiSi_xO_y$ has a crystal structure.

156. In light of the broad range of variation in the structural properties within the genus of oxide of titanium, the disclosure of "TiO_2" with "a barrier less than 1 eV" alone does not convey to a POSITA that the inventors had possession of the entire genus of oxide of titanium.

g) Melting Point

157. The melting points of the following exemplary "oxide of titanium" are different: the melting point of TiO is 1,700 °C (Ex. 1117 [TiO Melting Point]); the melting point of TiO_2 is 1,855 °C (Ex. 1118 [TiO_2 Melting Point]); the melting point of Ti_2O_3 is 2,130 °C (Ex. 1119 [Ti_2O_3 Melting Point]); and the melting point of Ti_3O_5 is 1,700 °C (Ex. 1075 [Phelly Ti_3O_5].) I note that the melting point is indicative of high-temperature structural stability which is of interest for reliability considerations.

158. The melting point of an "oxide of titanium" used in a metal oxide layer of a metal-semiconductor junction is important when considering its usefulness in semiconductor manufacturing. For example, Physical Vapor Deposition (PVD) is a common process in semiconductor manufacturing that is used to deposit an "oxide of titanium" on a semiconductor substrate. The PVD process involves evaporating the "oxide of titanium" so that it can be deposited on the semiconductor substrate. The melting point of an "oxide of titanium" is indicative of the vapor pressure of the "oxide of titanium" and thus relevant to evaporation. That is, the melting point of an "oxide of titanium" is an indicator of the temperature required for the PVD process. In general,

the PVD process is more difficult when the "oxide of titanium" being deposited requires a higher source temperature.

159. In light of the broad range of variation in the melting point within the genus of oxide of titanium, the disclosure of "TiO_2" with "a barrier less than 1 eV" alone does not convey to a POSITA that the inventors had possession of the entire genus of oxide of titanium.

h) Optical Transparency

160. Compounds in the "oxide of titanium" genus have different optical properties that affect the properties of the compound and determine the manner in which the compound may be employed during manufacturing a layer that comprises an oxide of titanium. I note that the optical transparency gives an indication of the bandgap energy, with opaque materials having a lower bandgap energy, and transparent materials having a higher bandgap energy.

161. The optical reflectivity, absorbency, opacity, and transparency of a metal oxide may have a significant influence in semiconductor manufacturing. This is because photolithographic processes are influenced by the optical properties of the materials on the wafer surface so that the optical properties need to be taken into account when performing photolithographic exposure, baking, and development processes.

162. For example, TiO is optically reflective (similar to a metal), (Ex. 1066 [Coat TiO]); TiO_2 is optically transparent in the visible wavelength range (corresponding to high optical transparency), (Ex. 1079 [1972-Fitzgibbons]); Ti_2O_3 is optically absorbing and opaque ("dark violet"), (Ex. 1076 [1982-Hong] at 214)); Ti_3O_5 is optically absorbing and has the color black, *see id.*; and $TiSiO_4$ is at least partially transparent, (Ex. 1081 [2017-Liu]).

163. In light of the broad range of variation in the melting point within the genus of oxide of titanium, the disclosure of "TiO_2" with "a barrier less than 1 eV" alone does not convey to a POSITA that the inventors had possession of the entire genus of oxide of titanium.

i) Examples of The High Level of Variation In Properties Between Oxides of Titanium

164. As discussed above in Sections XI.A.4.a) through XI.A.4.h), the various oxides of titanium have different properties. Relying on the data presented in these abovementioned Sections, exemplary different properties of TiO, TiO_2, Ti_2O_3, Ti_3O_5

and $TiSi_xO_y$ (each being a different oxide of titanium) are summarized in the table below: [8]

Properties	TiO	TiO_2	Ti_2O_3	Ti_3O_5	$TiSiO_4$
Electrical conductivity	Conductor	SemiC	SemiC at RoomT exhibiting SemiC-to-M at higher temp.	SemiC at RoomT exhibiting SemiC-to-M at higher temp.	Insulator
Electron affinity	None	4 eV	Probably unknown	Probably unknown, but relatively small	Probably unknown
Bandgap energy	None (metallic)	3.0-3.4 eV	0.1 eV	Small bandgap with semiconductor -to-metal transition at 440 K	1.75-2.68 eV
Dielectric constant		80			16.5

[8] SemiC refers to semiconductor; RoomT refers to room temperature; SC-to-M refers to transition from semiconductor properties to metal properties. The blank entries in the table indicate that data is not available.

Properties	TiO	TiO_2	Ti_2O_3	Ti_3O_5	$TiSiO_4$
Structural properties	Monoclinic and cubic	Rutile, anatase and brookite	Corundum	Anosovite and monoclinic	Glass-like (no structure)
Melting point	1,700 °C	1,855 °C	2,130 °C	1,700 °C	
Optical transparency	Reflective (similar to a metal)	Transparent (high)	Optically absorbing and opaque ("dark violet")	Optically absorbing and opaque (black colored)	Partially transparent

5. A POSITA would not know whether some species in the genus of "oxide of titanium" would be suitable as a metal oxide layer or metal oxide separate layer because their properties were not well understood.

165. A person of ordinary skill would not find sufficient guidance to implement the full scope of the alleged invention claimed in the '691 Patent with respect to the genus of "an oxide of titanium" because properties of some of the species of "oxide of titanium" were not entirely well understood.

166. Though the compound TiO_2 (titanium dioxide) is widely used in the semiconductor industry, the properties of TiO_2 were not entirely well-understood even in 2018. Kashiwaya et al. reported that "[r]egardless of orientations and polymorph, a ***huge variation of the Fermi level and work function*** was achieved by varying the surface condition" after studying the position of the Fermi level relative to the valence

band edge and the vacuum level for TiO_2 having rutile or anatase crystal structures and various crystal orientations. (Ex. 1085 [2018-Kashiwaya] at 73.) While some of the data shown is consistent with an electron affinity of 4.0 eV (Ex. 1087 [2017-Marques] at 506), the “huge variation” found shows that the TiO_2 material suffered from quality variations that strongly influenced its properties. (Ex. 1085 [2018-Kashiwaya] at 73.) The results also show that even in 2018, the properties of TiO_2 were still being studied and identified. (Ex. 1085 [2018-Kashiwaya].)

167. In addition, the properties of non-stoichiometric species were neither known nor understood even in 2011 or 2014, as demonstrated by two noteworthy research articles from that time frame. These articles, Stella (published in 2011) and Lee (published in 2014), employ an oxide of titanium, specifically a non-stoichiometric oxide such as TiO_x. (Ex. 1054 [2011-Stella]; Ex. 1055 [2014-Lee].) TiO_x typically derives itself from TiO_2 yet is oxygen deficient so that the chemical formula becomes TiO_x with $x < 2$. Review of the 2011-Stella and 2014-Lee research articles reveals that the titanium oxide employed by the investigators is far from an established material. (Ex. 1054 [2011-Stella]; Ex. 1055 [2014-Lee].) Indeed, the carrier transport properties of TiO_x were neither known in the 2011-to-2014 time frame nor understood.

168. Specifically, 2011-Stella investigated charge transport properties of TiO_x with respect to changes in current when the material was subjected to various voltages

as well as photo excitation. (Ex. 1054 [2011-Stella].) 2011-Stella found that current transients have a long time constant (of several 100 seconds) which is highly surprising given that electronic devices typically react rapidly to any change in stimulus (e.g., voltage or light). (Ex. 1054 [2011-Stella] at Abstract.) 2011-Stella attributed the long time constants to internal chemical transport ("chemicurrent") of atoms such as hydrogen atoms. (Ex. 1054 [2011-Stella].) 2011-Stella concluded: "Thus, it seems to be surprising that such a low bias voltage drastically influences the transport in the [conduction] band." (Ex. 1054 [2011-Stella] at P70.) And: "The unusual behavior of the titanium oxide based samples can be found again in the experiments monitoring device currents after the application of voltage steps." (Ex. 1054 [2011-Stella] at P73.) And finally: "A theoretical model for the transport in the lower edge of the conduction band [...] cannot be given [at] the moment." (*Id.*) These results demonstrate that even in the 2011-to-2014 time frame, non-equilibrium oxides of titanium were poorly understood.

169. Similarly, Lee et al. reported the use of a TiO_x material as a tunneling barrier for resistive RAM applications. (Ex. 1055 [2014-Lee].) Lee et al. found that transport of oxygen atoms occurs through the vacancies of the oxygen-deficient material, thereby changing the structure of the material and its electronic properties. (*Id.*) Materials whose structure changes have a "memory" in that their electronic properties depend on the respective momentary structure. These results further

demonstrate that even in the 2011-to-2014 time frame, non-equilibrium oxides of titanium were highly complex and poorly understood.

B. Ancestor applications of the ’691 Patent fail to enable a specific contact resistivity less than 1 Ω-µm^2

170. Claims 18 and 25 recite “a specific contact resistivity . . . less than 1 Ω-µm^2.” Claims 26-29 include that limitation because they depend from Claim 25. I have been asked to consider whether the parent applications of the ’691 Patent enable the full scope of “a specific contact resistivity . . . less than 1 Ω-µm^2.” As the ’691 Patent does, I have treated “specific contact resistance” and “specific contact resistivity” as interchangeable.

171. I have reviewed each of the patent applications and patents to which the ’691 Patent claims priority. Those patent applications and patents are listed in the table below, with each row showing an application and its corresponding patent:

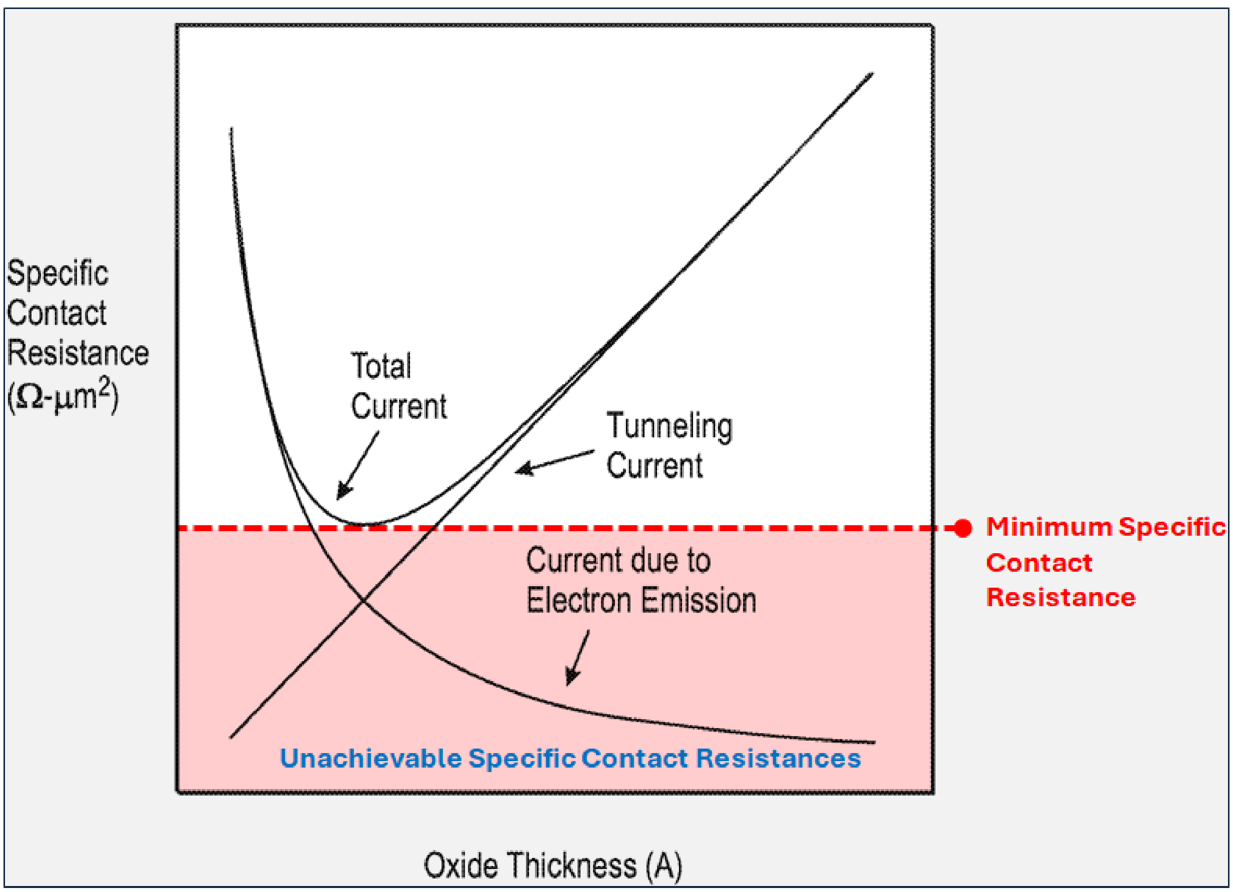
Application	Citation	Issued Patent	Citation
10/217,758	Ex. 1002, at 5-52	7,084,423	Ex. 1003
11/181,217	Ex. 1006, at 3-42	7,462,860	Ex. 1007
12/197,996	Ex. 1008, at 8-49	7,884,003	Ex. 1009
13/022,522	Ex. 1010, at 14-51	8,431,469	Ex. 1011
13/552,556	Ex. 1012, at 6-46	9,425,277	Ex. 1013

172. I observe that those parent applications and issued patents have the same specifications and figures as the ’691 Patent. Thus, I principally address the ’691 Patent’s specification and figures herein, with the understanding that the specifications and figures of the ’691 Patent’s parent applications are identical. But, the abstracts and claims differ somewhat. I have also considered those abstracts and claims and address them to the extent they affect my analysis.

173. I have also reviewed U.S. Patent No. 6,833,556 (Ex. 1005) and the application from which that patent issued. (Ex. 1004, at 4-44.) I understand that U.S. Patent No. 6,833,556 is incorporated by reference in each of the ’691 Patent’s ancestor applications.

174. Turning to “a specific contact resistivity . . . less than 1 Ω-μm^2,” that limitation specifies an upper bound, but not a lower bound. The specification shared by the ’691 Patent and its ancestor applications also does not specify any lower bound for the specific contact resistance limitations. While that specification describes various specific contact resistances that can purportedly be achieved, such as “less than or equal to approximately 2500 Ω-μm^2, 1000 Ω-μm^2, 100 Ω-μm^2, 50 Ω-μm^2, 10 Ω-μm^2 or even less than or equal to 1 Ω-μm^2” and while that specification describes a “minimum” specific contact resistance, it does not quantify that “minimum” specific contact resistance or put a lower bound on it. (Ex. 1001 [’691 Patent] at 4:9-22, 14:29-53.) Thus, plain and ordinary meaning of “a specific contact resistivity . . . less than 1

Ω-µm^2" in light of the specification has no lower bound, *i.e.*, it encompasses specific contact resistances down to and including approximately zero (such as 0.001 Ω-µm^2). According to the '691 Patent, an interface layer of an appropriate thickness can minimize the total specific contact resistance of a metal-semiconductor junction, which is given by the sum of (1) resistance to tunneling current with (2) resistance to current due to electron emission as depicted in Fig. 8. (Ex. 1001 ['691 Patent] at Fig. 8, 14:29-53.) But, the sum of those resistances leaves a range of specific contact resistances that cannot be achieved using the techniques in the '691 Patent, as shown below:



(Ex. 1001 [’691 Patent] at Fig. 8 (annotations added), 14:29-49.)

175. To summarize, the limitation “a specific contact resistivity . . . less than 1 Ω-µm^2” has no lower bound on specific contact resistivity, but the specification that the ’691 Patent shares with its parent applications teaches that at least some low specific contact resistances cannot be obtained by following the disclosed techniques. In other words, the claims encompass something that cannot be achieved according to the ’691 Patent: specific contact resistances (resistivities) all the way down to and including approximately zero.

176. Because the limitation “a specific contact resistivity . . . less than 1 Ω-µm$_2$” encompasses specific contact resistances (resistivities) that are impossible to achieve using the techniques disclosed in the ’691 Patent and its parent applications—namely, specific contact resistances (resistivities) down to and including approximately zero—the ’691 Patent and its parent applications do not enable the full scope of “a specific contact resistivity . . . less than 1 Ω-µm^2”. And because the ’691 Patent’s parent applications do not enable the full scope of that limitation, any claims reciting or including that limitation—which includes all of the challenged claims—cannot obtain a priority date earlier than the filing date of the ’691 Patent: February 19, 2016.

177. I understand that Patent Owner may argue that a POSITA would have understood the claims to include an “inherent lower limit.” But that’s not how the

claims are written and I have been informed and understand that the claims must be read in the manner they were written.

178. Claims 18 and 26-29 encompass specific contact resistances below 1 Ω-μm^2 and approaching 0 Ω-μm^2. *See above* at ¶¶ 170-175. I understand that Acorn's expert, Dr. Kuhn, has stated that these claimed values include 0.5 Ω-μm^2, 0.1 Ω-μm^2, 0.01 Ω-μm^2, 0.001 Ω-μm^2, and even values that are too low to measure. *See* Ex. 1048 [Dr. Kuhn's Deposition Transcript from 7-6-2021] at 124:10-24 ("Q. The last sentence of the first paragraph on page 14 states, "And a POSITA would understand that the resistivity values achievable with the invention are quite low, perhaps even negligible or too low to measure." Did I read that correctly? A. Yes, that appears to be correct. It's the last paragraph -- sorry, it's the last sentence in the first paragraph on the page which is kind of half a paragraph. It's like the fourth sentence on the page. That one? Q. Yep. A. Got it. Yes, you read that correctly. Q. Do you agree with that statement? A. Yes, I agree with that.").

179. However, the disclosure of the Priority Applications do not enable how to achieve the full scope of these claimed ranges when using an interface layer comprising a metal oxide. Specifically, the techniques described in the Priority Applications are plainly insufficient to enable a person of ordinary skill in the art to even know where to start in how to achieve the claimed ranges approaching 0 Ω-μm2, including values that are too low to measure. *See above* at ¶¶ 170-175.

180. For example, the Priority Applications do not specify or even hint at what materials, thicknesses, or other means a POSITA should use to achieve SCRs of 0.5 Ω-μm^2, 0.1 Ω-μm^2, 0.01 Ω-μm^2, or 0.001 Ω-μm^2. And I agree with Dr. Kuhn that nothing in the Priority Applications would even lead a POSITA to believe that one could achieve those claimed SCR values using the disclosure of the Priority Applications regardless of the amount of experimentation. *See* Ex. 1048 [Dr. Kuhn's Deposition Transcript from 7-6-2021] at 156:7-14 ("Q. But nothing in the patent guarantees that running this experiment hundreds of times for hundreds of materials and hundreds of thicknesses would in fact achieve [the claimed SCR] below 1 ohm microns squared; correct? A. The patent does not have any guarantees in it that I'm aware of."); 134:19-135:13 ("Q: … The '423 patent doesn't teach one of skill in the art what materials or thicknesses to choose in order to achieve a specific contact resistivity that is less than 1 ohm microns squared; correct? A. The '423 patent does not teach specific materials nor specific thicknesses to achieve a contact resistance of less than 1 ohm microns squared. It teaches a general methodology represented by Figure 8 to find the minimum contact resistance for a general materials processing thickness condition. Q. But the general methodology taught in the '423 patent does not provide any guarantee to a person of ordinary skill in the art that if he or she follows that methodology, he or she will achieve a specific contact resistivity of less than 1 ohm microns squared; correct? A. I'm not sure any patent guarantees anything. The word

"guarantee" is not used in the patent. I may be misunderstanding the point of the question, but I'm not sure guarantee comes into this.”). That, in my view, is the fundamental defect in the challenged claims and the Priority Applications: the challenged claims cover SCR ranges of 0.5 Ω-μm^2, 0.1 Ω-μm^2, 0.01 Ω-μm^2, or 0.001 Ω-μm^2 or even lower (too low to measure), but the Priority Applications do not teach how to achieve such low values, whether by teaching materials, thicknesses, or other means for achieving those values.

181. Approximately two years after the alleged 2002 priority date of the ’691 Patent, the named inventors of the ’691 Patent published a paper including experimental results of using an interface layer in a MIS junction. *See* Ex. 1120 [2004 Connelly Paper]. In the 2004 Connelly Paper, the researchers considered a SiN_x interface layer deposited between aluminum and silicon to form an MIS junction. *See* [2004 Connelly Paper] at 98 (Figure 1 shows the “[t]ransmission electron micrograph of an Al/SiN_x/Si junction, showing the ultrathin interfacial layer.”), 99 (“Fig. 3 shows the results of applying an insulator, in this case thermal SiNx, to the interface between Al and Si.”). The 2004 Connelly Paper does not consider using other materials, such as metal oxides, in the interface layer. The 2004 Connelly Paper also does not consider using multiple materials, such as what the ’691 Patent refers to as a passivation layer and separation layer, in the interface layer.

182. As shown in Figure 3 below, the 2004 Connelly Paper reports the Al/SiN_x/Si junction achieving specific contact resistivity values only as low as 0.3 kΩ-μm^2 (300 Ω-μm^2). *See* Ex. 1120 [2004 Connelly Paper] at 99. In that way, approximately two years after the priority date of the '691 Patent, the Acorn named inventors published experimental results that did not achieve the full scope of the claimed range of specific contact resistances based on any interface layer (let alone an interface layer comprising a metal oxide, which all of the challenged claims require).

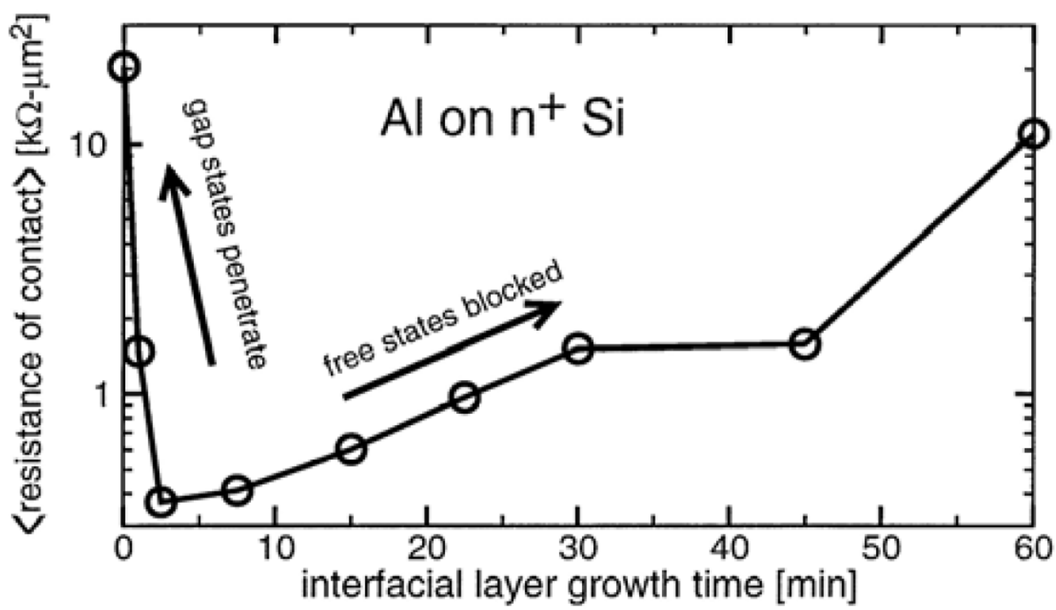


Fig. 3. Measured Al contacts on n^+ Si show a clear minimum. As interfacial treatment is increased, resistance drops sharply as gap states are blocked and the Fermi level is liberated. A further increase in the interfacial thickness, however, results in increased resistance due to the blocking of free carriers. Tunneling in Si due to high substrate doping reduces the contrast of thermionic barrier shifts. The wet-etched contacts are approximately 3 μm × 21 μm.

183. Additionally, Shine, an article published in 2013 (more than 10 years after the alleged priority dates of the ’691 Patent), describes the use of an Al/ZnO/n-Ge MIS junction, where ZnO comprises the interface layer being used. *See* Ex. 1121 [2013-Shine] at 70, 72. 2013-Shine describes using ZnO instead of TiO_2 as the interface layer because modeled data suggested that “ZnO is a superior alternative” to TiO_2. *See* Ex. 1121 [2013-Shine] at 70. And more than 10 years after the priority date of the ’691 Patent, 2013-Shine reports that the use of ZnO in an Al/ZnO/n-Ge MIS junction “show that the target [specific contact resistivity] of 10^{-9} Ω-cm^2 [(0.1 Ω-μm^2)] is within reach.” *See* Ex. 1121 [2013-Shine] at 70. Additionally, 2013-Shine’s work relies on other advances in the field that occurred between 2002 and 2013, such as advances in attainable doping levels. *See* Ex. 1121 [2013-Shine] at 71 (referring to “attainable doping levels”). And even after considering the use of interface layers in MIS junctions, 2013-Shine states that “it is worth noting that to reach the ultimate lower limits, there is no substitute for higher doping.” *See* Ex. 1121 [2013-Shine] at 72.

184. I understand that the Board rejected Acorn’s argument and held that “[e]nablement under section 112, which is required for priority under section 120, requires enablement of the ***full breadth of a claim***.” (Ex.1091 [Grupp ’483 IPR] at 33-34, 38.) The Board concluded that the ancestor applications of the ’691 Patent do not enable the breadth of the recited range of “less than 1 Ω-μm^2.” (Ex.1091 [Grupp ’483 IPR] at 38-39.)

C. Ancestor applications of the ’691 Patent fail to enable a “metal electrical contact” that is a “stack of metals”

185. Claims 5, 9, and 14 require a stack of metals deposited on the dielectric tunnel barrier layer. However, none of the ancestor applications describe “a stack of metals deposited on the interface layer.” Although the ’691 Patent and its ancestor applications describe depositing a metal on an interface layer and various examples of metals for depositing on the interface layer, none describes depositing a stack of metals on an interface layer. At most, they describe depositing a single body of metal or alloy on an interface layer. (Ex.1001, Fig. 6, Figs. 7a-7d, 11:15-19, 13:45-67.) The same is true of the incorporated-by-reference disclosure of U.S. Patent No. 6,833,556. (Ex. 1005, Figs. 1-3, Fig. 6B, 4:64-67, 7:8-12, 7:49-53, 8:67-9:6, 14:54-67.)

D. OVERVIEW OF PRIOR ART

1. GRUPP ’483

a) Grupp ’483 is prior art to the ’691 Patent

186. To disclose a genus, such as the genus of “oxides of titanium,” the inventors may give a representative number of species falling within the scope of the “oxide of titanium” genus, or structural features common to the members of the genus so that a person of ordinary skill in the art can visualize or recognize the members of the genus. The ’691 patent does not provide such disclosure, but instead provides a parenthetical remark giving a lone example of TiO_2. A person of ordinary skill would not consider the parenthetical disclosure of the lone example, TiO_2, as disclosure of a

genus by means of a representative number of examples, or a disclosure of structural features common to the members of the genus. Because the genus "oxide of titanium" was not disclosed and because the claimed genus is so large, diverse, and unpredictable, with the electrical conductivity spanning the greatest extent possible (ranging from conductor to semiconductor to non-conductor), the written description requirement for the genus "oxide of titanium" is not met by the Priority Applications predating the US Application No. 15/048,877 that was issued as the '691 Patent.

187. I further understand that describing a single species (such as TiO_2) is not sufficient to support claims to a genus when the evidence indicates that a person of ordinary skill could not predict the operability in the invention of any species other than the one disclosed. Given that the electrical conductivity of the oxides of titanium span the greatest extent possible (ranging from conductor to semiconductor to non-conductor) along with the great diversity of other properties and the fact that properties of some oxides of titanium are yet to be determined, a person of ordinary skill could not predict the operability in the invention of any species other than the one disclosed (that is, TiO_2). For this additional reason, the written description requirement is not met.

188. Accordingly, as summarized in **Section VIII** above, the Priority Date of all the Challenged Claims of the '691 Patent (except Claim 21) should be the filing date of the '877 Application. The filing date of the '877 Application is February 19,

2016. The priority date of Claim 21 of the ’691 Patent is February 7, 2011. Grupp’483 predates the 2016 date by more than a decade and for this reason is prior art to the ’691 Patent. Next, I will discuss how Grupp ’483 anticipates the Challenged Claims of the ’691 Patent.

b) Overview of Grupp ’483

189. Grupp ’483 is a patent that issued from a continuation-in-part application that claims priority to U.S. Patent No. 7,084,423. (Ex. 1003 [U.S. Patent No. 7,084,423]; Ex. 1021 [Grupp ’483] at Cover, 1:8-19.) U.S. Patent No. 7,084,423 is also the patent that issued from the first patent application in the priority chain of the ’691 Patent. (Ex. 1001 [’691 Patent] at 1:8-21.)

190. Exhibit 1034 is a redline of the specification of Grupp ’483 against the specification of U.S. Patent No. 7,084,423. (Ex. 1034 [Grupp ’483 Redline].) As that redline shows, Grupp ’483 includes substantially all of the disclosure of U.S. Patent No. 7,084,423. But, Grupp ’483 discloses at least two new features not disclosed in U.S. Patent No. 7,084,423.

191. *First,* Grupp ’483 describes carbon by itself as a semiconductor, as well as carbon in a germanium-carbon alloy. (Ex. 1021 [Grupp ’483] at 3:18-28; Ex. 1034 [Grupp ’483 Redline] at 3-5.) Further, Grupp ’483 describes various crystal structures for carbon: “If primarily C, the crystal structure may be either a diamond lattice, or another bonding scheme such as a fulleride (an example of which are carbon

nanotubes) or polymer." (Ex. 1021 [Grupp '483] at 3:25-28; Ex. 1034 [Grupp '483 Redline] at 4; *see also* Ex. 1021 [Grupp '483] at 5:49-56; Ex. 1034 [Grupp '483 Redline] at 9.)

192. *Second,* Grupp '483 discloses depositing a stack of metals on an interface layer. "A conductor may also consist of one conductor at the interface covered by a second conductor. If the first conductor is sufficiently thin, then the resultant workfunction may be a combination of the two conductors." (Ex. 1021 [Grupp '483] at 14:50-53; Ex. 1034 [Grupp '483 Redline] at 25.) "A submonolayer metal covered by a different metal may result in a workfunction different than either individual metal." (Ex. 1021 [Grupp '483] at 14:38-40; Ex. 1034 [Grupp '483 Redline] at 25.)

2. Wu

a) Wu is prior art to Claims 23 and 24

193. The application that matured as Wu was filed on December 17, 2007 and issued as a patent on June 1, 2010. (Ex.1126, Cover (22), Cover (45).) Because Claim 23 and 24 are not entitled to an earlier priority date than February 19, 2016, as discussed in **Section XI.C** above, Wu is prior art to Claims 23 and 24.

b) Overview of Wu

194. As stated in the Field of Invention section, the invention in Wu pertains to diffusion barrier films used in the field of integrated circuit fabrication. (Ex.1126 [Wu] at 1:7-8.). Wu discloses "methods and apparatus for depositing titanium-

containing diffusion barrier layers for use as copper diffusion barrier films in Damascene processing." (Ex.1126 [Wu] at 1:10-12.)

195. In the Background of the Invention Section, Wu discloses that "[i]n a typical Damascene process flow, metal (such as copper) is deposited onto a patterned dielectric to fill the vias and trenches formed in the dielectric layer." (Ex. 1126 [Wu] 1:24-26. "Before the metal is deposited into the vias and trenches, the patterned dielectric layer is lined with a thin layer of diffusion barrier material (e.g., Ta, TaN_x, or Ta/TaN_x bi-layer), and, subsequently, with a thin layer of seed layer material (e.g., Cu or copper alloy). The diffusion barrier layer protects inter-metal dielectric (IMD) and active devices from diffusion of copper and other readily diffusing metals into these regions." (*Id.* [Wu] at 1:32-36.) Wu mentions that "[t]he ongoing miniaturization of IC devices demands superior electrical properties from both the dielectric and conductive materials used in IC fabrication. As the features of IC devices continue to shrink, it becomes more common to use dielectrics with very low dielectric constants (k)." (*Id.* [Wu] at 1:47-51.)

196. In the Summary of the Invention Section, Wu discloses that the low-k dielectric materials are "however, are not always compatible with conventionally used diffusion barrier films, such as with tantalum-based diffusion barriers." [Ex. 1126 [Wu] at 1:64-66.) As a result, Wu recommends using titanium-based diffusion barriers. (*Id.* [Wu] at 2:7-15 ("Titanium-based diffusion barriers, on the contrary, can be used

in conjunction with dielectric materials containing residual moisture, such as with ULK dielectrics deposited by a spin-on method. When oxidized upon contact with moisture, titanium forms titanium oxide which does not substantially decrease the barrier properties of the diffusion barrier layer. In addition, titanium is less expensive than tantalum, and is, therefore, titanium-based diffusion barriers are more desirable from the economic standpoint.”).) Wu notes that use of a titanium-based barrier presents problems though. [*Id.* at 2:16-31.) Wu notes that the problems associated with titanium-based barriers can be “addressed herein by providing a diffusion barrier film containing a compositionally graded titanium nitride layer.” (*Id.* at 32-33.)

E. Grupp ’483 anticipates claims 6-8, 10-12, 15-17, and 19

197. I have reviewed **Section XIV.A** of the Petition that compares Claims 6-8, 10-12, 15-17, and 19 to the specification of Grupp ’483, and concur that Grupp ’483 anticipates Claims 6-8, 10-12, 15-17, and 19.

198. With respect to Claims 8 and 17, I want to add that a POSITA would be able to discern from Fig. 4 of Grupp ’483 that it depicts a junction of an n-type semiconductor and a metal based on the band diagram near the junction. Fig. 4 from the Sze Textbook depicts the energy band diagrams of metal *n*-type and *p*-type semiconductor junctions under different biasing conditions:

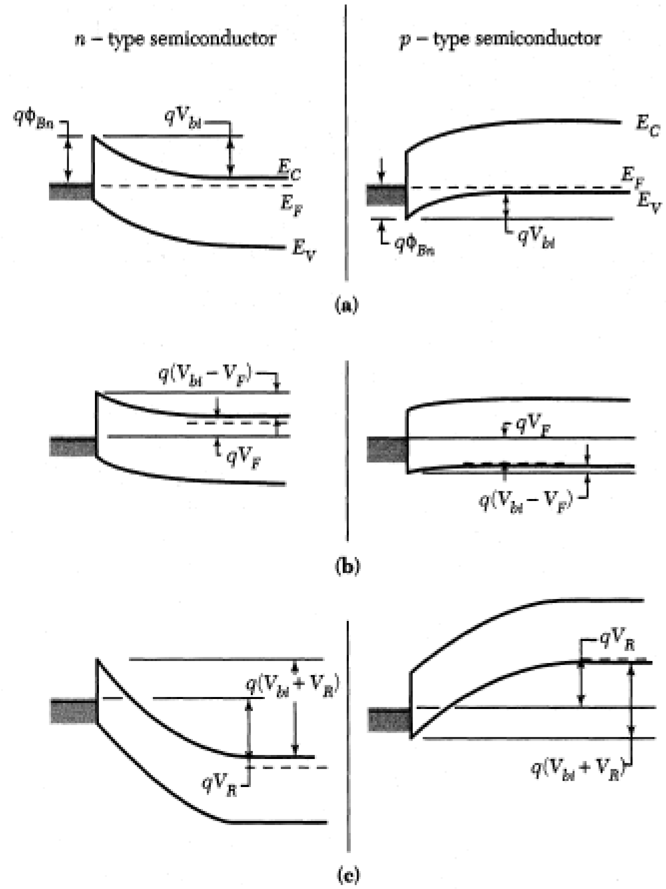


Fig. 4 Energy band diagrams of metal *n*-type and *p*-type semiconductors under different biasing conditions: (*a*) thermal equilibrium; (*b*) forward bias; and (*c*) reverse bias.

(Ex. 1107 (Sze Textbook) at 228.)

199. Fig. 4 of the Sze Textbook depicts a barrier height is $q\varphi_{Bn}$, conduction band energy E_C, Fermi level E_F and Valance band energy E_V. The figure depicts a junction between a metal and *n*-type semiconductor on the left and a junction between a metal and *p*-type semiconductor on the right. The band bending (also referred to as diffusion potential or built-in voltage) is due to the difference between the work function of metal φ_m and the work function of the semiconductor φ_s. (Ex. 1023 [Rhoderick] at 1.) The concept of work function is described in **Section XI.A.4.b)**

above. In nearly all cases $\varphi_m > \varphi_s$ for *n*-type semiconductors, the bands are bent upwards towards the junction. But $\varphi_m < \varphi_s$ for *p*-type semiconductors, the bands are bent downwards towards the junction. (Ex. 1023 [Rhoderick] at 1-2.)

F. Grupp ’483 anticipates claims 5, 9, and 14

200. I have reviewed **Section XIV.B** of the Petition that compares Claims 5, 9, and 14 to the specification of Grupp ’483, and concur that Grupp ’483 anticipates Claims 5, 9, and 14.

G. Grupp ’483 anticipates claims 18 and 26-29

201. I have reviewed **Section XIV.C** of the Petition that compares claims 18 and 26-29 to the specification of Grupp ’483, and concur that Grupp ’483 anticipates claims 18 and 26-29.

202. With respect to Claim 18, Grupp ’483 discloses that the semiconductor region comprises an n-type doped source or drain of a transistor, as discussed in **Section XI.E** above. Grupp ’483 therefore discloses some non-zero specific contact resistivity of less than 1 Ω-μm^2, such as a specific contact resistivity just under 1 Ω-μm^2, between the n-type doped source or drain and the metal electric contact.

H. Grupp ’483 anticipates claim 21

203. I have reviewed **Section XIV.D** of the Petition that compares Claim 21 to the specification of Grupp ’483, and concur that Grupp ’483 anticipates Claim 21.

204. Grupp '483 discloses that "[t]he thinner interface layers provided by the present invention permit higher current across the junction (i.e., *lower junction specific contact resistance*)." (Ex.1021, 18:56-59.) Grupp '483 further discloses that "the present junction can be fabricated with a much thinner interface layer as compared to the thickness of the silicide layer used previously. Indeed, thickness of an order of magnitude less than the silicide thickness can be expected." (Ex.1021, 18:47-50.) It is my opinion that because the dielectric tunnel barrier layer is part of the interface layer, as discussed in **Section XIV.A.2.b)** of the Petition, the dielectric tunnel barrier layer cannot be thicker than the interface layer. Accordingly, the dielectric tunnel barrier layer has a thickness less than that which would exist for a silicide layer at a contact junction between the metal electrical contact and the semiconductor region. Thus, Grupp '483 discloses that for a lower *specified contact resistivity* (i.e., "specific contact resistance" or "specific contact resistivity") across the junction, the dielectric tunnel barrier layer can have a thickness less than that which would exist for a silicide layer at a contact junction between the metal electrical contact and the semiconductor region.

I. Grupp '483 in view of Wu renders obvious Claims 23 and 24

205. I have reviewed **Section XIV.E** of the Petition that compares Claims 23 and 24 to the specification of Grupp '483 and Wu, and discusses why a POSITA would be motivated to combine the disclosures of Grupp '483 with disclosures of Wu, and

concur that the Grupp '483 in view of Wu renders obvious Claims 23 and 24. I offer additional opinions regarding a POSITA's motivation to combine.

1. Motivation to combine Grupp '483 and Wu

206. Before the priority date of Claims 23 and 24, a POSITA would appreciate the benefit of using copper (Cu) as a metal electrical contact in a semiconductor device. As Sze Textbook noted that "[i]t is well known that both high conductivity wiring and low-dielectric constant insulators are required to lower the *RC* time delay of the interconnect network. ***Copper is the obvious choice for a new metallization*** because it has higher conductivity and higher electromigration resistance than aluminum." [Ex. 1107 [Sze Textbook] at 396.) Wu also confirms that "[a]s the features of IC devices continue to shrink, it becomes more common to use dielectrics with very low dielectric constants (k)." (Ex. 1126 [Wu] at 1:47-51.) In my opinion, by the time of the priority of Claims 23 and 24 of the '691 Patent, the semiconductor industry was widely using copper-based interconnects and ultra low-k dielectrics in response to shrinking feature sizes in semiconductor devices.

207. However, a POSITA would know that use of copper as an interconnect is not without problems either. As the Sze Textbook noted a long time ago, "the use of Cu as an alternative to Al in ULSI circuits has drawbacks, such as its tendency to corrode under standard chip manufacture conditions, its lack of a feasible dry-etching method or a stable self-passivating oxide similar to Al_2O_3 on Al, and its poor adhesion

to dielectric materials." [Ex. 1107 [Sze Textbook] at 396.] As Wu also notes, a POSITA would also be aware of the fact that because copper atoms tend to diffuse or migrate, [Ex. 1126 [Wu] at 7:27-31.), use of copper as an interconnection metallization requires a suitable barrier layer to prevent such diffusion or migration of copper atoms. [Ex. 1107 [Sze Textbook] at 396 (recommending use of tantalum-based barriers in the 1980s.).) Wu also notes that when copper is used, the underlying silicon devices and dielectric layers should be protected from diffusion or migration of copper atoms. (Ex.1126 [Wu] at 7:27-33.)

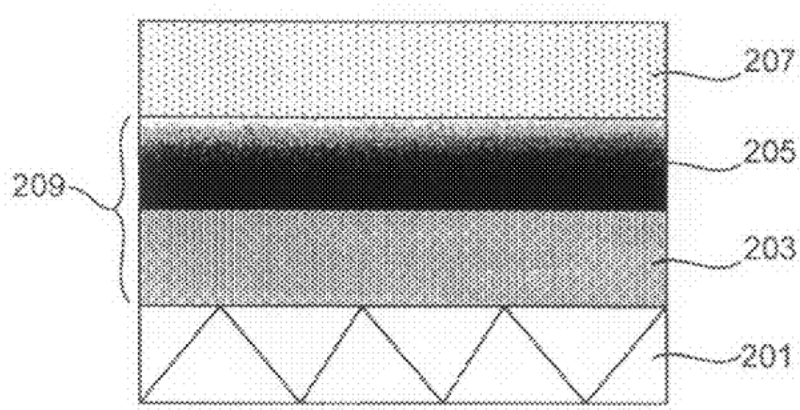
208. In the Summary of the Invention Section, Wu discloses that the low-k dielectric materials are "however, are not always compatible with conventionally used diffusion barrier films, such as with tantalum-based diffusion barriers." [Ex. 1126 [Wu] at 1:64-66.) Wu also discloses that traditional tantalum-based barrier layers exhibit poor performance when employed in conjunction with dielectrics having residual moisture. Wu mentions that "ULK [ultra low-k] dielectric materials are usually porous and often contain residual moisture." (*Id.* [Wu] at 9:65-67.)

209. As a result, Wu recommends using a titanium-based barrier layer when employing copper with such dielectric materials because "for any dielectric materials containing residual moisture, ***titanium-based diffusion barriers are particularly advantageous***." (Ex. 1126 [Wu] 9:67-10:2.) Wu explains that titanium oxide forms on the surface of the dielectric and "has good adhesion to the dielectric and exhibits good

diffusion barrier properties." (Ex.1126 [Wu] at 10:4-5; 2:7-15) Thus, Wu recommends forming a layer of TiO_x on the surface of the dielectric when using copper interconnects. (Ex.1126 [Wu] at 10:5-9.)

210. Wu notes that "[t]he use of titanium-based diffusion barriers, however, presents several challenging problems." (Ex. 1126 [Wu] at 2:16-17; *see also* 2:17-31 (enumerating problems associated with titanium-based diffusion barriers).) Wu discloses that the problems associated with titanium-based diffusion barriers can be resolved "by providing a diffusion barrier film containing a compositionally graded titanium nitride layer." (*Id.* [Wu] at 2:32-33.) Thus, the diffusion barrier proposed by Wu "includes a layer of compositionally graded titanium nitride (TiN_x), having a nitrogen-rich portion and a nitrogen-poor portion. It was recognized that nitrogen-rich TiN_x exhibits excellent diffusion barrier properties, while nitrogen-poor TiN_x has a good adhesion to copper." (*Id.* [Wu] at 2:36-41.) Thus, Wu also discloses depositing a graded TiN_x layer to serve both as a diffusion barrier and as an adhesion layer. (Ex. 1126 [Wu] at 10:10-11.).

211. The resulting titanium-based diffusion barrier layer recommended by Wu is depicted in Fig. 2 (below):



(Ex.1126, Fig. 2.) Wu discloses that the structure in Fig. 2 includes "a layer of dielectric 201; a Ti/TiO_x layer, 203; a layer of compositionally graded TiN_x, 205; and a layer of metal, 207. The layers are stacked in the recited order, with the dielectric layer 201 being the bottom layer of the stack." (Ex. 1126 [Wu] at 9:25-30.) "The Ti/TiO_x layer 203 and the graded TiN_x layer 205 together constitute the diffusion barrier film 209, which corresponds to barrier layers 123 and 105 as shown in FIG. 1H [and also Fig. 1A]." (Ex. 1126 [Wu] at 9:31-33.)

212. Wu also discloses how to form the diffusion barrier film 209. Regarding the Ti/TiO_x layer 203, Wu mentions that "a titanium-containing material capable of forming TiO_x is deposited on top of dielectric. For example, titanium or titanium alloy is deposited onto dielectric layer, and is partially or completely oxidized to an oxide. Therefore, layer 203 can contain Ti, TiO_x or both species." (Ex. 1126 [Wu] at 10:5-9.) Regarding the TiN_x layer 205, Wu mentions that "[t]he graded TiN_x layer 205 may include TiN_x layer with a gradually changing nitrogen composition throughout the

layer, as illustrated in FIG. 2. In this illustration, the concentration of nitrogen in layer 205 gradually decreases from the interface with layer 203 to the interface with layer 207." (*Id.* at 11:42-46.)

213. Fig. 1A of Wu shows cross sectional depictions of device structure created using a copper dual Damascene process. In Fig, 1A, substrate 100 includes a "pre-formed dielectric layer 103 (such as an organic-containing low-k or ULK material) with etched line paths (trenches and vias) in which a ***Ti-based diffusion barrier 105*** . . . has been deposited, followed by inlaying with copper conductive routes 107 ('copper plugs')." (Ex.1126 [Wu] at 7:18-23.)

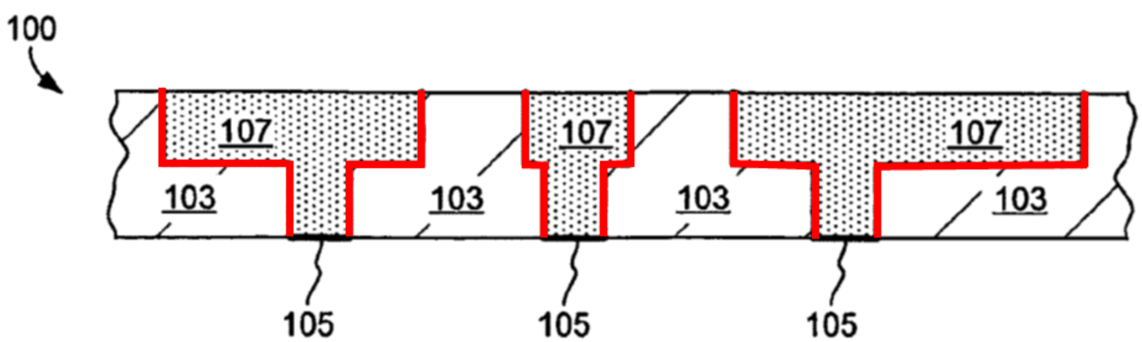


Figure 1A

(Ex. 1126 [Wu] at Fig. 1A (annotated).) Wu mentions that "[t]he diffusion barrier film 105 [**red**] includes a Ti/TiO_x layer adjacent to dielectric 103, and a graded TiN_x layer which contacts copper plug 107 with its nitrogen-poor portion." (Ex. 1126 [Wu]

7:40-42.) According to Wu, the Ti/TiO_x layer 203 is formed by depositing a titanium or titanium alloy onto the dielectric layer 103 and, as a result, the Ti/TiO_x layer will be formed on the sidewalls of the dielectric, as depicted in **red** in the annotated Fig. 1A above. A layer of TiO_x may not be formed at the bottom of the opening for the plug because the opening exposes the semiconductor substrate and not a dielectric layer. Thus, when the Ti-based diffusion barrier layer disclosed in Wu is incorporated in the copper-based metal contacts disclosed in Grupp '483, then such "metal electrical contacts" will comprise a Ti/TiO_x layer 203 and graded TiN_x 205 layer in addition to copper 207.

214. In my opinion, when implementing the semiconductor structures disclosed in the Grupp '483 that use copper, before the priority date of Claims 23 and 24, a POSITA would have been aware of the diffusion problems associated with copper and would have been motivated to improve Grupp '483 to address those problems. As I mentioned above, the semiconductor industry was aware of both the benefits of using copper and problems associated with such use in that time frame, including problems associated with ultra low-k dielectrics. However, though Grupp '483 recommends using copper (Cu) as a conductor, (Ex. 1021 [Grupp '483], Fig.6, 14:58-15:5), Grupp '483 does not disclose problems associated with use of copper and how to address them. Unlike Wu, Grupp '483 also does not disclose problems associated with the use of ultra low-k dielectric materials. Use of such dielectrics was

prevalent by the priority date of Claims 23 and 24 due to shrinking feature size in semiconductor devices. A POSITA would have understood that ultra low-k dielectric materials are essential to the fabrication of semiconductor devices with small feature sizes. As a result, a POSITA would have consulted analogous art, such as Wu, that discloses use of copper interconnects and proposes solutions to address problems associated with using copper in semiconductor fabrication. Both the Grupp ’483 and Wu pertain to structures and methods for improving quality and reliability of semiconductor devices. Grupp ’483 discloses an interface layer between a metal and semiconductor to reduce resistance of the junction. (Ex.1021 [Grupp ’483] at Abstract; Summary of Invention.) Wu recommends using a titanium-based diffusion barrier layer in a Dual Damascene process when copper is used to form plugs in order to address problems associated with migration of copper atoms, use of ultra low-k dielectrics and to improve adhesion. (Ex.1126 [Wu] at Abstract; Summary of Invention.) Because of the substantial overlap in the specification of the ’691 Patent and Grupp ’483, the three references (i.e., ’691 Patent, Grupp ’483, and Wu) are from analogous art. As discussed in **Section XI.D.2** above, a POSITA would have been aware of the problems associated with the use of copper. Wu discloses the benefits that titanium-based barrier layers confer when using copper as interconnect metallization, which includes use of copper plugs or metal electrical contacts. In view of the disclosure of Wu, a POSITA would have been motivated to improve the copper metallization and the metal electrical contacts disclosed in Grupp ’483 by incorporating a TiO_x-based diffusion barrier layer as disclosed by Wu. Use of such titanium-based diffusion barriers would have alleviated issues of copper migration and problems due to ultra low-k dielectrics. Wu’s diffusion barrier film would have provided better adhesion to copper plugs thereby improving the reliability and manufacturability of the semiconductor devices.

215. Inclusion of a titanium-based diffusion barrier that includes a Ti/TiO_x layer and a TiN layer, as suggested by Wu, into the metal electrical contact of the semiconductor structures disclosed in Grupp ’483 would have been a combination of prior art elements according to known methods to yield predictable results. For example, the Sze Textbook that was published several years before the priority date of Claims 23 and 24 discusses copper metallization, the Dual Damascene technology and use of tantalum-based barrier layer. (Ex. 1107 [Sze Textbook] at 396-397.) A POSITA would start with the Grupp ’483 that discloses use of metal oxide layer and dielectric tunnel barrier layer between a metal electrical contact and a semiconductor region. A POSITA would be motivated to use copper for the metal contact in view of benefits that use of copper confers. If the diffusion barrier layer disclosed by Wu is employed to form the contact taught by Grupp ’483, then a junction between the copper and semiconductor substrate may include a titanium nitride layer. However, a POSITA would not view that as an impediment because a titanium nitride layer is commonly

employed between a metal plug and a semiconductor region. Titanium nitride has the same electrical properties as a metal and also acts as a good diffusion barrier, as Wu notes. In fact, Grupp ’483 discloses using a nitride layer at the interface to provide passivation. (Ex. 1021 [Grupp ’483] at 10:53-54 (“the interface layer 520 may include a ***nitride***, an ***oxide***, a hydride, an arsenide and/or a fluoride.”); *see also* Summary of the Invention.) In view of the disclosure of Wu, a POSITA would include a titanium-based diffusion layer at least between the copper plug and the ultra low-k dielectric. Thus, in my opinion, a POSITA would have had a reasonable expectation of success when incorporating Wu’s TiO_x-based diffusion barrier layer into the copper metal electrical contact of the semiconductor structures disclosed in Grupp ’483 to arrive at the structure claimed by Claims 23 and 24 of the ’691 Patent.

J. Alleged Secondary Considerations

216. I reserve the right to address any other alleged evidence of secondary considerations of nonobviousness that Patent Owner may present in a reply declaration.

I declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code.

Date: June 2, 2025

E. Fred Schubert, Ph.D.

APPENDIX A: THE CHALLENGED CLAIMS OF ’691 PATENT

What is claimed is:

5. The structure of claim **3**, wherein the metal electrical contact is a metal or a stack of metals deposited on the dielectric tunnel barrier layer.

6. The structure of claim **3**, wherein the metal oxide comprises an oxide of titanium.

7. The structure of claim **6**, wherein the semiconductor oxide of the dielectric tunnel barrier layer has a thickness of approximately less than 1 nm.

8. The structure of claim **6**, wherein the semiconductor region comprises an n-type doped source or drain of a transistor.

9. The structure of claim **6**, wherein the metal electrical contact is a metal or a stack of metals deposited on the dielectric tunnel barrier layer.

10. The structure of claim **6**, wherein the semiconductor oxide comprises an oxide of silicon.

11. The structure of claim **6**, wherein the semiconductor oxide of the dielectric tunnel barrier layer is adjacent the semiconductor region.

12. The structure of claim **6**, wherein the metal electric contact comprises titanium.

14. The structure of claim **13**, wherein the metal electrical contact is a metal or a stack of metals deposited on the dielectric tunnel barrier layer.

15. The structure of claim **13**, wherein the metal oxide comprises an oxide of titanium.

16. The structure of claim **15**, wherein the metal electrical contact comprises titanium.

17. The structure of claim **15**, wherein the semiconductor comprises an n-type doped source or drain of a transistor.

18. The structure of claim **17**, wherein a specific contact resistivity between the n-type doped source or drain and the metal electric contact is less than 1 $\Omega \cdot \mu m^2$.

19. The structure of claim **1**, wherein the semiconductor region comprises silicon, the semiconductor oxide comprises an oxide of silicon, the metal oxide comprises an oxide of titanium, and the metal electrical contact comprises titanium.

21. The structure of claim **1**, wherein for a specified contact resistivity of the structure the dielectric tunnel barrier layer has a thickness less than that which would exist for a silicide layer at a contact junction between the metal electrical contact and the semiconductor region.

23. The structure of claim **1**, wherein the semiconductor oxide of the dielectric tunnel barrier layer comprises an oxide of silicon having a thickness of approximately 0.1 nm to 5 nm, the semiconductor region comprises an n-type doped source or drain of a transistor, and the metal electrical contact comprises an oxide of titanium.

24. The structure of claim **23**, wherein the semiconductor oxide of the dielectric tunnel barrier layer is adjacent the semiconductor region.

26. The electrical junction of claim **25**, wherein the metal oxide separation layer comprises an oxide of titanium.

27. The electrical junction of claim **26**, wherein the semiconductor oxide passivation layer comprises an oxide of the semiconductor.

28. The electrical junction of claim **27**, wherein the semiconductor oxide passivation layer has a thickness of approximately 0.1 nm to 5 nm.

29. The electrical junction of claim **27**, wherein the semiconductor oxide passivation layer is adjacent the semiconductor.

APPENDIX B: LIST OF MATERIALS CONSIDERED

Paper	Description
1	Petition for Inter Partes Review of U.S. Patent No. 10,090,691 (filed concurrently)

Exhibit	Description
1001	U.S. Patent No. 10,090,691
1002	File History of U.S. Patent No. 7,084,423
1003	U.S. Patent No. 7,084,423
1004	File History of U.S. Patent No. 6,833,556
1005	U.S. Patent No. 6,833,556
1006	File History of U.S. Patent No. 7,462,860
1007	U.S. Patent No. 7,462,860
1008	File History of U.S. Patent No. 7,884,003
1009	U.S. Patent No. 7,884,003
1010	File History of U.S. Patent No. 8,431,469
1011	U.S. Patent No. 8,431,469
1012	File History of U.S. Patent No. 9,425,277
1013	U.S. Patent No. 9,425,277
1014	U.S. Patent No. 10,090,395
1015	Blank
1016	Blank
1017	Blank
1018	Blank
1019	Blank
1020	File History of U.S. Patent No. 10,090,691
1021	U.S. Patent No. 7,176,483 (“Grupp ’483”)
1023	E.H. Rhoderick, *Metal-Semiconductor Contacts*, 129 IEE Rev. 1 (Feb. 1982) (“Rhoderick”)
1024	C.Y. Chang et al., *Specific Contact Resistance Of Metal-Semiconductor Barriers*, 15 Solid State Elecs. 541 (1971) (“Chang”)
1025	S.M. Goodnick et al., *Effects of a Thin SiO2 Layer On The Formation Of Metal-Silicon Contacts*, 18 J. Vac. Sci. & Tech. 949 (Apr. 1981) (“Goodnick”)

Exhibit	Description
1026	M.A. Sobolewski and C.R. Helms, *Studies Of Barrier Height Mechanisms In Metal-Silicon Nitride-Silicon Schottky Barrier Diodes*, J. Vac. Sci. & Tech. B 971 (Jul./Aug. 1989) ("Sobolewski")
1027	U.S. Patent No. 4,110,488 ("Risko")
1028	M.A. Taubenblatt et al., *Interface Effects In Titanium And Hafnium Schottky Barriers On Silicon*, 44 Applied Physics Letters 895 ("Taubenblatt 1984")
1029	U.S. Patent No. 3,983,264 ("Schroen")
1030	U.S. Patent No. 4,845,050 ("Kim")
1031	Japanese Laid-Open App. No. JPH11162874A (June 18, 1999)
1032	Certified Translation of Japanese Laid-Open App. No. JPH11162874A (June 18, 1999) ("Iwaguro")
1033	D. Brassard et al., *Tuning The Electrical Resistivity Of Pulsed Laser Deposited Tisio X Thin Films From Highly Insulating To Conductive Behaviors*, 84 Applied Physics Letters 2304 (2004) ("[2004-Brassard]")
1034	Redline of Specification of U.S. Patent No. 7,176,483 Against Specification of U.S. Patent No. 7,084,423
1035	D. Brassard and M.A. El Khakani, *Pulsed-Laser Deposition Of High-K Titanium Silicate Thin Films*, 98 J. Applied Physics 054912 (2005) ("[2005-Brassard]")
1036	D. Brassard et al., *Substrate Biasing Effect On The Electrical Properties Of Magnetron-Sputtered High-K Titanium Silicate Thin Films*, 102 J. Applied Physics 034106 (2007) ("[2007-Brassard]")
1037	Blank
1038	Complaint, *Acorn Semi, LLC v. Samsung Elecs. Co., Ltd.*, No. 2:19-cv-00347, ECF No. 1 (E.D. Tex. Oct. 23, 2019)
1039	Blank
1040	Blank
1041	Blank
1042	Exhibit E to Acorn's Preliminary Infringement Contentions, *Acorn Semi, LLC v. Samsung Elecs. Co., Ltd.*, No. 2:19-cv-00347 (Mar. 9, 2020)
1043	Redacted Acorn's Opposition to Samsung's Motion for Judgment, *Acorn Semi, LLC v. Samsung Elecs. Co., Ltd.*, No. 2:19-cv-00347, ECF No. 401 (E.D. Tex. Sept. 2, 2021)

Exhibit	Description
1044	E. Piner Trial Demonstratives, Redacted Acorn's Opposition to Samsung's Motion for Judgment, Ex.B-1, *Acorn Semi, LLC v. Samsung Elecs. Co., Ltd.*, No. 2:19-cv-00347, ECF No. 401-3 (E.D. Tex. Sept. 2, 2021)
1045	Verdict Form, *Acorn Semi, LLC v. Samsung Elecs. Co., Ltd.*, No. 2:19-cv-00347 (May 19, 2021)
1046	N.F. Mott and L. Friedman, *Metal-Insulator Transitions in VO2, Ti2O3 and Ti2-xVxO3*, 30 Philosophical Magazine 389 (1974) ("[1974-Mott]")
1047	S. Åsbrink and A. Magnéli, *Crystal Structure Studies on Trititanium Pentoxide, Ti3O5,* 12 Acta Crystallographica 575 (1959) ("[1959- Åsbrink]")
1048	Dr. Kuhn's Deposition Transcript, July 6, 2021
1049	Dr. Kuhn's Deposition Transcript, July 7, 2021
1050	M.G. Kostenko et al., *Simulation of the Short-Range Order in Disordered Cubic Titanium Monoxide TiO1.0*, 97 JETP Letters 616 (2013) ("[2013-Kostenko]")
1051	A.A. Valeeva and M.G. Kostenko, *Stable Ti9O10 Nanophase Grown From Nonstoichiometric Titanium Monoxide TiOy Nanopowder*, 8 Nanosystems: Physics, Chemistry, Mathematics 816 (2017) ("[2017-Valeeva]")
1052	D. Gerlich et al., *Thermoelastic Properties of ULE® Titanium Silicate Glass*, 21 J. Non-Crystalline Solids 243 (1976) ("[1976-Gerlich]")
1053	F.Y. Robb, *Plasma Etching of Oxygen Containing Titanium Silicide Films*, 131 J. Electrochem. Soc'y 2906 (1984) ("[1984-Robb]")
1054	K. Stella et al., *Charge Transport Through Thin Amorphous Titanium and Tantalum Oxide Layers*, 158 J. Electrochem. Soc'y 5 (Mar. 28, 2011) ("[2011-Stella]")
1055	S. Lee et al., *Tunnel Barrier Engineering of Titanium Oxide For High Non-Linearity of Selector-Less Resistive Random Access Memory*, 104 Applied Physical Letters (Feb. 7, 2014). ("[2014-Lee]")
1056	Murray et al., *The O-Ti (Oxygen-Titanium) System*, 8(2) J. Phase Equilibria 148-165 (1987) ("[1987-Murray]")

Exhibit	Description
1057	S.K.J. Al-Ani et al., *The Optical Absorption Edge of Amorphous Thin Films of Silicon Monoxide*, 19 J. Materials Sci. 1737 (1984) ("1984-Al-Ani)")
1058	G.L. Tian et al., *Effect of Microstructure of Tio2 Thing Films on Optical Band Gap Energy*, 22 Chinese Physical Soc'y 7 (February 25, 2006) ("[2005-Tian]")
1059	J. Wang et al., *High-Performance Photothermal Conversion of Narrow-Bandgap TiO2O3 Nanoparticles*, 29 Advance Materials 1603730 (Nov. 11, 2016) ("[2017-Wang]")
1060	D. Roy and S.B. Krupanidhi, *Pulsed Excimer Laser Ablated Barium Titanate Thin Films*, 61 Applied Physics Letters 2057 (1992) ("[1992-Roy]")
1061	J. Hao et al., *Dielectric Properties of Pulsed-Laser-Deposited Calcium Titanate Thin Films*, 76 Applied Physics Letters 3100 (2000) ("[2000-Hao]")
1062	G.P. Shveikin, *Magnetic Properties of Ti3O6 with Chromium Additions*, 544 Z. Anorg. Allg. Chem. (1987) ("[1987-Shveikin]")
1063	S.P. Denker, *Electronic Properties of Titanium Monoxide*, 37 J. Applied Physics Letters 1 (Jan. 1966) ("[1966-Denker]")
1064	R. van de Krol et al., *Electrical and Optical Properties of TiO2 in Accumulation and of Lithium Titanate Li0.5TiO2*, 90 J. Applied Physics 2235 (2001) ("[2001-van-de-Krol]")
1065	F. Imai et al., *Interfacial Reaction of Mgo/Tiox Superlattice Thin Films*, 228 Thin Solid Films 158 (1993) ("[1993-Ima]")
1066	CC Vacuum Coating Materials Co, Ltd., (July 21, 2021) http://coatmaterials.com/html_products/TiO-(Titanium-monoxide)-64.html ("[Coat TiO]")
1067	F.M. Pontes et al., *High dielectric constant of SrTiO3 thin films prepared by chemical process*, 35 J. Materials Sci. 4783 (2000) ("[2000-Pontes]")
1068	M.M. Doeff et al., *Titanate Anodes For Sodium Ion Batteries*, Lawrence Berkeley Nat'l Lab'y (Jan. 31, 2014), https://escholarship.org/uc/item/2wr1b5xt 24 ("[2014-Doeff]")
1069	S.D. Mo and W.Y. Ching, *Electronic and Optical Properties of Three Phases of Titanium Dioxide: Rutile, Anatase, and Brookite*, 51 Physical Rev. B 19 (May 15, 1995) ("[1995-Mo]")

Exhibit	Description
1070	N.V. Nguyen et al., *Optical Properties of Jet-Vapor-Deposited TiAlO and HfAlO Determined by Vacuum Ultraviolet Spectroscopic Ellipsometry, CP683 Characterization and Metrology for ULSI Technology: 2003 International Conference*, Am. Inst. Physics (2003) ("[2003-Nguyen]")
1071	V.-T. Rangel-Kuoppa and A. Conde-Gallardo, *Ohmic Contact Recipe on Tixcr2-Xo3 and Its Application to Temperature Dependent Hall Measurements, 1566 The Physics of Semiconductors*, Am. Inst. Physics Conf. Proc. 23 (2013) ("[2013-Rangel-Kuoppa]")
1072	L.B. Glebov et al., *Planar Optical Waveguides on Glasses and Glass-Ceramic Materials*, 1513 SPIE Glasses for Optoelectronics II 56 (1991) ("[1991-Glebov]")
1073	T. Shikama et al., *Erosion Behaviour of Physically Vapour-Deposited and Chemically Vapour-Deposited Sic Films Coated on Molybdenum During Oxygenated Argon Beam Thinning*, 117 Thin Solid Films 191 (1984) ("[1984-Shikama]")
1074	N. Szydlo and R. Poirier, *I-V and C-V Characteristics of Au/Ti02 Schottky Diodes*, 51 J. Applied Physics 6 (June 1980) ("[1980-Szydlo]")
1075	CPHMI Phelly Materials Inc, *Titanium Oxide (V), Ti3O5* (July 27, 2021), https://www.phelly.com/ti3o5/ ("[Phelly Ti3O5]")
1076	S.H. Hong, *Crystal Growth of Some Intermediate Titanium Oxide Phases y-Ti3O5, P-Ti3O5, Ti4O7 and Ti2O by Chemical Transport Reactions*, 36 Acta Chemica Scandinavica A (1982) ("[1982-Hong]")
1077	S. Gwo et al., *Local Electric-Field-Induced Oxidation of Titanium Nitride Films*, 74 Applied Physics Letters 1090 (1999) ("[1999-Gwo]")
1078	M. Takeuchi et al., *Dielectric Properties of Sputtered Tio2 Films*, 51 Thin Solid Films 83 (1978) ("[1978-Takeuchi]")
1079	E.T. Fitzgibbons et al., *Tio2 Film Properties as a Function of Processing Temperature*, 119 J. Electrochem. Soc. 6 (June 1972) ("[1972-Fitzgibbons]")
1080	T. Bertaud et al., *Ultra Wide Band Frequency Characterization of Integrated Titao-Based Metal–Insulator–Metal Devices*, 110 J. Applied Physics 044110 (2011) ("[2011-Bertaud]")

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1081	H. Liu et al., *Structural, Electronic, Mechanical, Dielectric and Optical Properties of Tisio4: First-Principles Study*, 251 Solid State Commc'ns 43 (2017) ("[2017-Liu]")
1082	D. Hallock et al., *Method to Fabricate Low Stress Refractory Metal Silicide Films*, 32 IBM Tech. Disclosure Bull. 190 (1989) ("[1989-Hallock]")
1083	U.S. Patent No. 4,912,286 ("Clarke")
1084	S. Yang et al., A *Novel Carbon Thermal Reduction Approach to Prepare Recorded Purity B-Ti3O5 Compacts From Titanium Dioxide And Phenolic Resin*, 853 J. Alloys & Compounds 157360 (2021) ("[2021-Yang]")
1085	S. Kashiwaya et al., *The Work Function of TiO2*, 2018 Chin. Surfaces. 1 (Sept. 7, 2018) ("[2018-Kashiwaya]")
1086	S. Bartkowski et al., *Electronic Structure of Titanium Monoxide*, 56 Physical Rev. B 10656 (1997) ("[1997-Bartkowski]")
1087	F. Marques and J.J. Jasieniak, *Ionization Potential and Electron Attenuation Length of Titanium Dioxide Deposited by Atomic Layer Deposition Determined by Photoelectron Spectroscopy in Air*, 2017 Applied Surface Sci. 422 (June 5, 2017) ("[2017-Marques]")
1088	Y. Chen, et al., *Ground State Structure and Physical Properties of Silicon Monoxide Sheet*, 527 Applied Surface Sci. 146759 (2020) ("[2020-Chen]")
1089	Petition, *Samsung Electronics Co., Ltd. v. Acorn Semi, LLC*, IPR2020-01207, Paper 2 (P.T.A.B. June 29, 2020)
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1091	Final Written Decision, *Samsung Electronics Co., Ltd. v. Acorn Semi, LLC*, IPR2020-01207, Paper 49 (P.T.A.B. Feb. 9, 2022)
1092	Trial Transcript, *Acorn Semi, LLC v. Samsung Elecs. Co., Ltd.*, No. 2:19-cv-00347 (E.D. Tex. May 14, 2021)
1093	Final Judgment, *Acorn Semi, LLC v. Samsung Elecs. Co., Ltd.*, No. 2:19-cv-00347, ECF No. 379 (E.D. Tex. July 13, 2021)
1094	Z. Luo, *High-K Gate Dielectrics For Si CMOS Applications*, A Dissertation Presented To The Faculty Of The Graduate School of Yale University, Dec. 2003 ("2003-Luo")

Exhibit	Description
1095	Complaint, *Oak IP, LLC v. GlobalFoundries, Inc., and GlobalFoundries US Inc.*, No. 25-cv-00142-MN, ECF No. 1 (D. Del. Feb. 4, 2025)
1096	Petition, *Samsung Electronics Co., Ltd. v. Acorn Semi, LLC*, IPR2020-01282, Paper 2 (P.T.A.B. July 13, 2020)
1097	Final Written Decision, *Samsung Electronics Co., Ltd. v. Acorn Semi, LLC*, IPR2020-01282, Paper 56 (P.T.A.B. Feb. 9, 2022)
1098	Decision Granting Institution, *Samsung Electronics Co., Ltd. v. Acorn Semi, LLC*, IPR2020-01282, Paper 20 (P.T.A.B. Feb. 10, 2021)
1099	Blank
1100	Markman Order, *Acorn Semi, LLC v. Samsung Elecs. Co., Ltd.*, No. 2:19-cv-00347, ECF No. 85 (E.D. Tex. Oct. 16, 2020)
1101	U.S. Patent No. 6,724,088 ("Jammy")
1102	D. Brassard et al., *Compositional Effect on the Dielectric Properties of High- Titanium Silicate Thin Films Deposited by Means of a Cosputtering Process*, J. Vac. Sci. Tech. A 24, 600 (2006) ("2006-Brassard")
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1105	Blank
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1107	S. M. Sze, *Semiconductor Devices: Physics and Technology*, 2nd Ed. 2002 Textbook ("Sze Textbook")
1108	Blank
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1110	Blank
1111	Blank
1112	Blank
1113	Blank
1114	Blank
1115	Toshiba, *e-learning: Basics of Schottky Barrier Diodes*, Ch. 1 (2002), https://toshiba.semicon-

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1116	Blank
1117	TiO Melting Point
1118	TiO_2 Melting Point
1119	Ti_2O_3 Melting Point
1120	D. Connelly, *A New Route to Zero-Barrier Metal Source/Drain MOSFETs*, 3 IEEE Transactions on Nanotechnology 98 (2004)
1121	G. Shine and K. C. Saraswat, *Limits of Specific Contact Resistivity to Si, Ge and III-V Semiconductors Using Interfacial Layers, in 2013 International Conference on Simulation of Semiconductor Processes and Devices (SISPAD)*, Glasgow, UK 69 (2013)
1122	Samsung's Opening Brief, *Samsung-Electronics Co. v. Acorn Semi, LLC*, No. 2022-1539, Doc. 19 (Fed. Cir. Jun. 24, 2022)
1123	Acorn's Corrected Response Brief, *Samsung-Electronics Co. v. Acorn Semi, LLC*, No. 2022-1539, Doc. 19 (Fed. Cir. Oct. 11, 2022)
1124	May 17, 2021 Trial Transcript, *Acorn Semi, LLC v. Samsung Electronics Co., et al*, No. 2:19-cv-000347-JRG (E.D. Tex.) (Redacted)
1125	Final Written Decision, *Samsung-Electronics Co. v. Acorn Semi, LLC*, IPR2020-01207, Paper 49 (P.T.A.B. Feb. 9, 2022)
1126	U.S. Patent No. 7,727,882 ("Wu")

APPENDIX C: CV

Curriculum Vitae: E. Fred Schubert

Contact information

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Citizenship

Born in Stuttgart, Germany (1956)
Naturalized United States Citizen (1995)

Education

University of Stuttgart	Electrical Engineering	Vordiplom	(U. S. equivalent BSEE)	1978
University of Stuttgart	Electrical Engineering	Diplom Ingenieur (Honors)	(U. S. equivalent MSEE)	1981
Oregon State University	Electrical Engineering	Exchange Student		1977–1978
University of Stuttgart	Electrical Engineering	Doktor Ingenieur (Honors)	(U. S. equivalent Ph.D.)	1986

Current appointment

2002 – present: Professor, Department of Electrical, Computer, and Systems Engineering; Rensselaer Polytechnic Institute, Troy NY

Previous appointments

2002 – 2015: Head and Founder of the Future Chips Constellation; Rensselaer Polytechnic Institute
2002 – 2015: Wellfleet Senior Constellation Professor, Future Chips (Chaired Professor); Rensselaer Polytechnic Institute
2002 – 2012: Professor Department of Physics, Applied Physics, and Astronomy; Rensselaer Polytechnic Institute
2008 – 2009: Director, Founding Director, and Principal Investigator, NSF Engineering Center for Smart Lighting, Rensselaer Polytechnic Institute
2002 – 2003: Adjunct Professor, Boston University
1995 – 2002: Professor, Boston University, Department of Electrical and Computer Engineering; Director of the Semiconductor Devices Research Laboratory; Affiliated Faculty of the Photonics Center.
1988 – 1995: Member of Technical Staff; Principal Investigator; and Member of Management at AT&T Bell Laboratories in Murray Hill, New Jersey
1985 – 1987: Post-Doctoral Member of Technical Staff at AT&T Bell Laboratories in Holmdel, New Jersey.
1981 – 1985: Scientific Member of Staff in the Department of Solid-State Chemistry at the Max Planck Institute for Solid-State Research in Stuttgart, Germany. Ph.D. Dissertation title: "Modern Schottky gate field-effect transistors based on III–V semiconductors"

Fields of Technical Expertise, Hands-on Experience, and Teaching

- Expertise, hands-on experience, and teaching in semiconductor opto-electronics including the following devices: LED, semiconductor laser, vertical cavity surface-emitting laser (VCSEL), solar cell, photo-detector, LED displays, micro-LED displays, LCD displays, and OLED displays. The activities include the design, fabrication, processing, and packaging of the devices, and the use of the devices in circuits and systems. (1981 to present)
- Expertise, hands-on experience, and teaching in semiconductor electronics including the following devices: MESFET, HFET, MOSFET, CMOS-FET, LDD MOSFET, LD MOS FET, FinFET, GAA FET, Vertical MOSFET (high-power MOSFET), thyristor, GTO thyristor, and IGBT. The activities include the design, fabrication, processing, and packaging of the devices, and the use of the devices in discrete and integrated circuits. (1979 to present)
- Expertise, hands-on experience, and teaching in thin-film deposition of metal, semiconductor, and insulator films by PVD (physical vapor deposition) and CVD (chemical vapor deposition) including PECVD (plasma enhanced CVD), MOCVD (metal-organic CVD), ALE (atomic layer epitaxy), ALD (atomic layer deposition), and bulk crystal growth (AlN, GaN, and sapphire). Epitaxial growth of silicon, III-V arsenide, phosphide and nitride epitaxial layers on GaAs, sapphire, Si, and GaN substrates by epitaxy including molecular beam epitaxy (MBE),

metal-organic chemical vapor deposition (MOCVD), and vapor-phase epitaxy (VPE). High-k materials, low-k-materials, phosphors, resins, polymers, encapsulants, alloy semiconductors and their deposition technologies such as epitaxy, CVD, and PVD. Doping of semiconductors by various means including delta doping and atomic monolayer doping. (1981 to present)

- Expertise, hands-on experience, and teaching in the design, operation, and usage of semiconductor devices in lighting systems, communication systems, and power-supply systems and in the analysis and development of LED power supplies using Boost and Buck Converters. (1993 to present)

Technical Research Activities

- Design, development and fabrication of a Si pressure sensor based on the piezo-resistivity of Si using a bridge configuration of four thin-film Si resistors (1979 – 1980)
- Design of a electro-optic Mach-Zehnder Interference Modulator based on Lithium niobate ($LiNbO_3$) operating at a wavelength of 1300 nm (1980 – 1981)
- First study of hot electron effects in selectively doped $Al_xGa_{1-x}As$/GaAs heterostructures (1983)
- Demonstration and elimination of parallel conduction in $Al_xGa_{1-x}As$/GaAs heterostructures (1984)
- First analysis of semiconductors doped with simultaneously shallow and deep donors (1984).
- Development and use of thyristor circuits (including GTO thyristor circuits) for the control of a lamp heating system (1984 – 1985)
- Proposal and demonstration of the δ-doped field-effect transistor. Short-channel effects in sub-micron field-effect transistors can be reduced to their theoretical minimum by using δ-doped structures (1985)
- Development of the theory of alloy broadening in luminescence spectra of alloy semiconductors such as $Al_xGa_{1-x}As$. The current understanding of the low-temperature spectral linewidths of ternary and quaternary alloy semiconductors is based on this theoretical model. The publication analyzing the phenomenon of alloy broadening has been referenced far in excess of 100 times (1984)
- First demonstration of a light-emitting diode with a doping superlattice active region (1985)
- Application of δ-doping to selectively doped heterostructures; Demonstration of high-electron-mobility transistors (HEMTs) with highest free electron concentrations; Analysis of structures by SEM, TEM, and SIMS (1986).
- Demonstration of delta-doped non-alloyed ohmic contacts with very low contact resistance and subsequent demonstration of self-aligned field-effect transistor with delta-doped non-alloyed ohmic contacts (1986)
- Demonstration of the spatial localization of dopants within 20 Å for a number of doping elements in delta-doped semiconductors including GaAs and Si for MESFET and lightly-doped drain (LDD) MOSFET applications and the analysis of delta-doped structures by SIMS (secondary ion mass spectrometry) (with colleague Henry S. Luftman, 1983-1995)
- Significant improvement of the optical properties of doping superlattices by employment of delta doping. Improvement is demonstrated by the first observation of quantized interband transitions in the absorption (1988) and in the emission spectra (1989)
- First demonstration of tunable doping superlattice laser (1989)
- First quantitative analysis of the capacitance-voltage (CV) profiling technique in semiconductors with quantum-confined carriers. Demonstration that resolution of CV profiles in quantum-confined semiconductors is not limited to the Debye screening length (1990)
- Invention and demonstration a new concept by which heterojunction band discontinuities occurring between two different semiconductors are eliminated. The *elimination of heterojunction barriers* is based on parabolic compositional grading of doped heterojunctions. This concept is widely used in the fabrication of vertical cavity surface emitting lasers and other heterojunction devices (1991)
- Invention and first demonstration of resonant cavity light-emitting diode (RCLED) which uses photon quantization in microcavities to enhance the spontaneous emission properties (1992)
- Demonstration of giant enhancement of luminescence intensity in Er-doped Si-SiO_2 microcavities (1992)
- First demonstration of a resonant-cavity detector which is useful for wavelength-selective detection (1993)
- Demonstration of resonant-cavity light-emitting diode (RCLED) with very high brightness. The experimental brightness of the RCLED is five times higher than that of conventional LEDs. Based on calculations, the brightness of RCLEDs is expected to exceed that of conventional LEDs by more than a factor of ten (1994)
- Demonstration of delta doping in silicon for the fabrication of shallow junctions in scaled-down Si lightly-doped drain (LDD) MOSFETs for integrated circuits (Si ICs) (with colleague Dr. H. J. Gossmann, 1990 – 1995)
- Invention of a new concept, *superlattice doping*, for enhanced p-type doping of GaN. All acceptors in GaN are deep, resulting in a low electrical acceptor activation of only 5 %. The new concept of superlattice doping is expected to increase the electrical activation of acceptors by more than a factor of ten (with post-doctoral associate Dr. W. Grieshaber, 1995)

- Investigation of yellow luminescence in GaN and the use of microcavity effects in Ag / GaN / sapphire structures to determine the refractive index of GaN (with post-doctoral associate Dr. W. Grieshaber, 1996)
- Demonstration of the first GaN / GaInN double heterostructure laser. The laser has cleaved facets and was optically pumped. Laser action was demonstrated by (*i*) a threshold in the light-versus-current characteristic, (*ii*) spectral narrowing below *kT* above threshold, (*iii*) a TE / TM polarization ratio greater than one hundred above threshold, and (*iv*) increased slope efficiency with increasing back-side facet reflectivity (with graduate student D. A. Stocker, 1997)
- Co-inventor of photonic-crystal light-emitting diode, PC-LED, jointly with group of Prof. John D. Joannopoulos at MIT (publication by Shanhui Fan *et al*. appeared in *Physical Review Letters* in 1997; US patent 5,955,749 was issued in 1999)
- First demonstration of crystallographic etching of GaN (with graduate student D. A. Stocker, 1998). The discovery, crystallographic etching, can be implemented by wet chemical etching, including photo-enhanced electrochemical (PEC) wet etching. The discovery is widely used in the LED industry to strongly enhance light extraction from LED chips and is found in LED light bulbs.
- Experimental demonstration of a ten-fold enhancement of p-type doping activation in $Al_xGa_{1-x}N$/GaN doped superlattices as compared to bulk GaN and $Al_xGa_{1-x}N$ (with graduate students D. A. Stocker and I. D. Goepfert, 1999)
- Invention and demonstration of the photon-recycling semiconductor light-emitting diode (PRS-LED) which emits *white* light and many other colors with very high luminous performance of > 300 lm/W (with graduate students X. Guo and J. W. Graff, 1999). Invention of the monolithically integrated GaInN/GaN PRS-LED (with graduate students X. Guo and J. W. Graff, 2000)
- Invention and demonstration of polarization-enhanced ohmic contacts in p-type and n-type GaN (with graduate students Y.-L. Li and J. W. Graff 2000)
- Invention and demonstration of AlGaInP light-emitting diode with omni-directional reflector (ODR) for high light extraction efficiency (with post-doctoral associate Th. Gessmann and graduate student J. W. Graff, 2001)
- Developed novel model for high diodes ideality factors (n >> 2.0) in UV LEDs based on multiple rectifying elements (with graduate student J. M. Shah and Prof. Th. Gessmann, 2003)
- Developed new class of materials, low-refractive index materials, or low-*n* materials, with an unprecedented low refractive index of n < 1.10; use of these materials as low-*k* materials for inter-metal-layer dielectrics in Si lightly-doped drain (LDD) MOSFETs in conjunction with ALD-deposited high-*k* gate dielectric MOSFETs for integrated circuits (Si ICs) (with Dr. Jong Kyu Kim, "JQ" Xi, Professors Joel Plawsky, Bill Gill, starting in 2003)
- Developed theory for temperature coefficient of forward voltage in light-emitting diodes, particularly UV light-emitting diodes (with graduate student Yangang "Andrew" Xi, Dr. Jong Kyu Kim, and collaborators at Sandia National Laboratories, 2004, 2005)
- Invented highly efficient "remote phosphor configurations" in white light-emitting diodes (with Jong Kyu Kim, Hong Luo, and collaborators at SAIT-Samsung) (2004, 2005)
- Discovered whispering gallery modes in white LEDs with remote phosphors (with graduate student Hong Luo, Jong Kyu Kim, Yangang "Andrew" Xi, and collaborators at SAIT-Samsung, 2005)
- Developed graded-index antireflection coatings that, unlike conventional anti-reflection coatings, have broadband omni-directional characteristics; the graded-index antireflection coatings use novel low-*n* materials (with Jingqun "JQ" Xi, Jong Kyu Kim, 2007)
- Developed efficiency-droop reducing GaInN / GaInN and GaInN / AlGaInN LED active regions grown by MOCVD and ALE that were demonstrated to reduce the efficiency droop by as much as 40% (with Jong Kyu Kim, Martin F. Schubert, Di Zhu, Jiuru Xu, Mary Crawford, and Dan Koleske, starting in 2007)
- Developed analytic model for efficiency droop based on drift-induced reduction of the carrier-injection efficiency (with Guan Bo Lin, Jaehee Cho, and others, 2012)

Honors and awards

- Google Scholar profile, including the Hirsch-index (h-index) can be found at < http://scholar.google.com > under profile "E. Fred Schubert"
- Elected to *Senior Member* of the *IEEE* "in recognition of professional standing" (1993)
- Recipient of the Literature Prize of the *Verein Deutscher Elektrotechniker* (*VDE*) for "Doping in III–V semiconductors" (Cambridge University Press, Cambridge, 1993). Citation: "The book concerns all aspects of doping in III–V semiconductors. Fundamental, practical, and technological issues of doping are addressed. The book covers the basic theory of shallow donors, shallow acceptors, deep levels, and their influence on the free carrier concentration. It also discusses doping during growth, epitaxy, diffusion, and ion implantation. In the field of semiconductor devices, the book emphasizes applications requiring highly controlled doping distributions. It is an excellent monograph equally suited for study, research, and industry" (1994)

- Elected as a member of the *Bohemian Physical Society* (Cornell University, Ithaca, NY). Citation: "For seminal contributions to the control of spontaneous emission by use of wavelength-size optical cavities, specifically the first demonstration in a glass host using rare earth implanted Si/SiO_2 resonant microcavities" (1994)
- Listed in "Who's Who In Science And Engineering" and "Who's Who in America" published by *Marquis Who's Who*, publishers of the original *Who's Who in America*. (*Marquis Who's Who*, New Providence, NJ) ISBN 0-8379-5755-9 (1996 – present)
- Elected Fellow *of the SPIE* "For pioneering research in semiconductor doping and sustained contributions to the development of high-efficiency light-emitting diodes and lasers". According to the Society's bylaws, a Fellow "shall be distinguished through his achievements and shall have made outstanding contributions in the field of optics, or optoelectronics, or in a related scientific, technical, or engineering field" (1999)
- Recipient of the *Alexander von Humboldt Senior Research Award* of the Alexander von Humboldt Foundation, a Bonn-based non-profit organization promoting the exchange of scientific knowledge between German and highly qualified foreign scholars. According to the Alexander von Humboldt Foundation, academic qualification is the only selection criterion for the award. The award resulted in two extended visits with the Microoptics Laboratory of Professor Jürgen Jahns at the University of Hagen, Germany (1999)
- Elected to *Fellow of the IEEE* "for contributions to semiconductor doping and resonant-cavity devices". According to the IEEE definition "the grade of Fellow is one of unusual professional distinction conferred by the Board of Directors only upon a person of extraordinary qualifications and experience" (1999)
- Listed in the "Dictionary of International Biography, 29th Edition" published by the *International Biography Center*, Cambridge, United Kingdom (2000)
- Recipient of the 2000 *Discover Magazine Award for Technological Innovation* presented by the *Christopher Columbus Foundation* in the category "Energy". The prize was awarded "for the invention and demonstration of the photon recycling semiconductor light-emitting diode", an all-semiconductor LED capable of emitting white light with very high efficiency, see < www.discover.com/awards > (2000)
- Recipient of the *RD100 Award* of the R&D Magazine that honors the "100 most technologically significant products of the year" (with Klaus Streubel of Osram-Sylvania Corp. and Rickard Marcks von Wurtemberg of Mitel Corp.). The prize was awarded for the "*Resonant-cavity light-emitting diode*" that uses enhanced spontaneous emission occurring in resonant cavities. The device is used in plastic optical fiber communication links, in telescopes for rifles, and many other applications (2000).
- Elected to *Fellow of the OSA* "for the invention and demonstration of the resonant-cavity LED and the photon-recycling semiconductor LED". OSA Fellows are elected by the OSA Board of Directors (2001)
- Recipient of the Boston University Provost Innovation Fund Award (Provost Dennis D. Berkey) valued at $ 25,000 for research and development of promising technologies (2001)
- Elected to *Fellow of the APS* "for pioneering contributions to the doping of semiconductors including delta doping, doping of compositionally graded structures resulting in the elimination of band discontinuities, and superlattice doping to enhance acceptor activation" (2001)
- Honored with RPI Medal as Senior Constellation Chair during Investiture Ceremony (2002)
- Received "2002 Rensselaer Polytechnic Institute Trustee Faculty Achievement Award" (2002)
- Inducted as Wellfleet Senior Constellation Professor, Future Chips, Rensselaer Polytechnic Institute, November 21 (November 2003)
- Distinguished Lecturer of the IEEE Electron Devices Society (2003–2006)
- Elected member in Eta Kappa Nu (2004)
- "Best Oral Presentation Award" was won by Ph. D. student Hong Luo (who was the presenter), J. K. Kim, Y. A. Xi, J. M. Shah, Th. Gessmann and E. F. Schubert "Improvement of extraction efficiency of GaInN light-emitting diodes by employment diffuse omni-directional reflectors" *Connecticut Microelectronics & Optoelectronics Consortium (CMOC)*, 14th annual symposium, New Haven CT, March 17 (March 2005).
- "Best Student Poster Award" of the *International Semiconductor Device Research Symposium (ISDRS)* was won by Ph. D. student J.Q. Xi (presenter), Jong Kyu Kim, Dexian Ye, Jasbir S. Juneja, T.-M. Lu, Shawn-Yu Lin, and E. Fred Schubert "Optical Thin Films with Very Low Refractive Index and Their Application in Photonic Devices", *International Semiconductor Device Research Symposium (ISDRS)*, Dec. 7 – 9, Bethesda, MD (December 2005)
- "MRS Silver Award" of the Materials Research Society was won by Ph. D. student Yangang Andrew Xi (who was the presenter), K. X. Chen, F. Mont, J. K. Kim, C. Wetzel, E. F. Schubert, W. Liu, X. Li, J. A. Smart "Extremely high quality AlN grown on (0001) sapphire by using metal-organic vapor-phase epitaxy" *Materials Research Society (MRS) Fall Meeting*, Boston MA, November 27 – December 1 (2006) Boston MA (December 2006)
- "25 Most Innovative Micro- and Nano-Products of 2007 Award" in July 2007 issue of *R&D Magazine* and *Micro/Nano Newsletter*. This recognition was given for the "Non-Reflective Coating" product that was published in *Nature Photonics* in 2007; full citation: Xi, J.-Q., Martin F. Schubert, J. K. Kim, E. F. Schubert,

Minfeng Chen, Shawn-Yu Lin, Wayne Liu, and Joe A. Smart "Optical thin-film materials with low refractive index for broadband elimination of Fresnel reflection" *Nature Photonics* **1**, 176, March 2007 (July 2007)

- "Scientific American 50 Award" of 2007, as published in the January 2008 issue of *Scientific American*. According to the *Scientific American Magazine*, this award "celebrates visionaries from the worlds of research, industry and politics whose recent accomplishments point toward a brighter technological future for everyone" (January 2008)
- "Editors' Choice" of *Science Magazine*, *Science*, Volume **319**, page 1163, February 29 (February 2008). This distinction was awarded for the publication: Jong Kyu Kim et al., "Light-extraction enhancement of GaInN light-emitting diodes by graded-refractive-index indium tin oxide anti-reflection contact" that appeared in *Advanced Materials* **20**, 801, 2008 (February / March 2008)
- Received "2008 Rensselaer Polytechnic Institute Trustee Faculty Achievement Award" (2008)
- "Best Oral Presentation Award" won by David J. Poxson (who was the presenter), Frank W. Mont, Jong Kyu Kim, and E. Fred Schubert "Multilayer nano-structured anti-reflection coating with broad-band omni-directional characteristics" *Connecticut Microelectronics and Optoelectronics Conference* (*CMOC*), University of Connecticut, Storrs, Connecticut, April 9 (April 2008)
- "Best Oral Presentation Award" for presentation: David Meyaard, Sameer Chhajed, Jaehee Cho, E. Fred Schubert, Jong Kyu Kim, Daniel D. Koleske, and Mary H. Crawford "Temperature-dependent light-output characteristics of GaInN light-emitting diodes with different dislocation densities" *Connecticut Microelectronics and Optoelectronics Consortium* (CMOC) Symposium, New Haven CT, March 2 (March 2011)
- Identified as top 1% of patentees in the field of optoelectronics by study conducted by Professor Erica Fuchs of Carnegie Mellon University under a study supported by the US National Science Foundation (July 2011)
- Received "2012 Rensselaer Polytechnic Institute Trustee Faculty Achievement Award" (November 2012)
- My "LinkedIn" profile was one of the top 10% most viewed "LinkedIn" profiles during 2012 (January 2013)
- My graduate student, Mr. Ming Ma, received the $ 30,000.00 Lemelson-Rensselaer Student Prize for the invention entitled "Graded-refractive-index (GRIN) structures for brighter and smarter light-emitting diodes"; The Prize is awarded annually by the Lemelson Foundation (March 2013)
- Received the IEEE Life Fellow Award (2022)

Service to the technical community

- Current or former member of the *American Physical Society* (Member of the *Division of Materials Physics*, Member of the *Division of Condensed Matter Physics*), *Institute of Electrical and Electronics Engineers*, *Materials Research Society*, *Optical Society of America*, *Society for Optical Engineering* (*SPIE*), and the *Verein Deutscher Elektrotechniker*
- Co-author of hundreds of research articles, co-inventor of more than 30 United States patents, and numerous foreign patents (1981 – present)
- Gave many invited talks at scientific conferences organized by the *American Physical Society*, *Institute of Electrical and Electronic Engineers*, *Materials Research Society*, *SPIE* (*The International Society for Optical Engineering*), *Electrochemical Society*, *American Vacuum Society*, *Engineering Foundation*, and other professional societies (1985 – present).
- Co-editor (with A. M. Glass) of a Special Issue of the *Journal of Optical and Quantum Electronics* (Vol. **22**, 1990) on "Charge-transport assisted optical non-linearities in semiconductors" (1990)
- Symposium chair of the *American Vacuum Society Greater New York and New Jersey Chapter* on "Epitaxially grown semiconductors with atomic level control" (1991).
- Moderator of MRS Internet discussion on "Doping and Dopants in GaN" (MRS Internet Journal, 1995 – 1997)
- Member of review panels of the National Science Foundation (1995 – present)
- Conference Chair of SPIE Photonics West conference on "Light-emitting diodes: Research, Manufacturing, and Applications" San Jose, CA (1997)
- Technical work has been featured in popular journals, magazines and newspapers including the New Scientist, Discover Magazine, Wall Street Journal, Boston Globe, Focus, and on National Public Radio (1996 – present)
- Conference Chair of SPIE Photonics West conference on "Light-emitting diodes: Research, Manufacturing, and Applications" San Jose, CA (1998)
- Program Committee Member: IEEE IEDM, International Electron Devices Meeting (1999 and 2000)
- Conference Chair of SPIE Photonics West conference on "Light-emitting diodes: Research, Manufacturing, and Applications" San Jose, CA (1999)
- Program Committee Member: ISBLLED, International Symposium on Blue Laser and Light-Emitting Diodes, Berlin, Germany, March 5 – 10 (2000)
- Conference Chair of SPIE Photonics West conference on "Light-emitting diodes: Research, Manufacturing, and Applications" San Jose, CA (2000)

- Conference Chair and Co-Organizer of the TMS- and ONR-sponsored conference on "Doping, Dopants, and Low Field Carrier Dynamics in Wide Gap Semiconductors", Copper Mountain, Colorado, April 2 - 6 (2000)
- Chair, IEEE LEOS, Central New England Chapter. During my tenure as Chair, the Central New England Chapter won the IEEE LEOS Chapter award for the highest membership growth (1999 – 2000)
- Expert Witness involving semiconductor materials, devices, and packaging including elemental and compound semiconductors such as Si, SiGe, SiC, as well as III–V arsenides, phosphides and nitrides (1998 – present)
- Member of the Board of Governors, IEEE Laser and Electro-Optics Society (LEOS) (1999 – 2000)
- Member of the Optoelectronics Industry Development Association (OIDA) Roadmap Panel on Solid-State Lighting, Albuquerque NM Oct. 26 – 28 (2000)
- Conference Chair of SPIE Photonics West conference on "Light-emitting diodes: Research, Manufacturing, and Applications" San Jose, CA (2001)
- Panel Member of National Research Council meeting on "Solid-State Lighting:" held at NAS and NAE, Washington DC, March 26 (2001)
- Program Committee Member of SPIE Photonics West conference on "Laser and LED Applications" chaired by Dr. Kurt Linden, San Jose CA Jan (2002)
- Conference Chair of SPIE Photonics West conference on "Light-emitting diodes: Research, Manufacturing, and Applications" San Jose, CA (2002)
- Program Committee Member: ISBLLED, International Symposium on Blue Laser and Light-Emitting Diodes, Cordoba, Spain, March 11–15 (2002)
- Program Committee Member for subcommittee on "Semiconductor lasers and LEDs" for OSA Conference on Lasers and Electro-Optics and Quantum Electronics and Laser Science Conference (CLEO / QELS) (2002 – 2003) Baltimore MD June 1–6 (2003)
- Reviewer for the National Research Council of report entitled "Partnerships for Solid-State Lighting: Report of a Workshop" authored by the Board on Science, Technology, and Economic Policy. This report is forwarded to the US Congress for the initiation of a national Solid-State Lighting Initiative. (2002)
- Program Committee Member "Lester Eastman conference on high performance devices" University of Delaware, Newark, Delaware, August 6 – 8 (2002)
- Conference Chair of SPIE Photonics West conference on "Light-emitting diodes: Research, Manufacturing, and Applications" San Jose CA (2003)
- OIDA Next Generation Lighting (NGL) Consortium. Member of "Light-Emitting Diode" Committee (2003)
- Program Committee Member, International Semiconductor Device Research Symposium (ISDRS) Washington DC, Dec. 8 – 12 (2003)
- Program Committee Member of "Display and Solid-State Lighting Devices" conference for OSA/IEEE Conference on Lasers and Electro-Optics (CLEO) (2003 – 2004)
- Elected Member of the IEEE Electron Device Society Administration Committee (IEEE AdCom) (2003 – 2008)
- Conference Chair of SPIE Photonics West conference on "Light-emitting diodes: Research, Manufacturing, and Applications" San Jose CA (2004)
- Program Committee Member "Fourth International Conference on Solid-State Lighting" August 2 – 6 Denver, CO (2004)
- Program Committee Member for the "Blue 2004: Advanced LEDs and Lasers Conference" Hsinchu, Taiwan, May 10 – 12 (2004)
- Conference Chair of SPIE Photonics West conference on "Light-emitting diodes: Research, Manufacturing, and Applications" San Jose CA (2005)
- Program Committee Member "International Semiconductor Device Research Symposium" December 7 – 9 Washington, DC (2005)
- Chair of "Display and Solid-State Lighting Devices" conference of OSA/IEEE Conference on Lasers and Electro-Optics (CLEO) (2005)
- Best Oral Presentation Award (Presenter: Hong Luo) at *Connecticut Microelectronics & Optoelectronics Consortium* (CMOC), 14th annual symposium, New Haven CT, March 17 (March 2005)
- Conference Chair of MRS Spring meeting "Symposium DD: Solid-State Lighting Materials and Devices" San Francisco, April 17 – 21 (April 2006)
- Member on the International Advisory Committee of *First International Conference on Display LEDs* (ICDL 2007), Seoul, Korea, January 31 to February 2 (2007)
- Member, Program Committee of *SPIE Photonics West* conference "Light-Emitting Diodes: Research, Manufacturing, and Applications XI" San Jose, CA, January 20 – 25 (2007)
- Program Chair of *SPIE Photonics West* conference "Semiconductor Lasers and LEDs" San Jose, CA, January 20 – 25 (2007)
- Member, Executive Organizing Committee *SPIE Photonics West* conference "LASE 2007" San Jose, CA, January

20 – 25 (2007)

- Opto Track Chair of *SPIE Photonics West* conference “Semiconductor Lasers and LEDs” San Jose, CA, January 21 – 24 (January 2008)
- Member, Program Committee, Light-emitting diodes: Research, Manufacturing, and Applications, SPIE Photonics West 2008, San Jose, California, January 19 – 24 (January 2008)
- Program Committee Member of the 7th International Symposium on Semiconductor Light Emitting Devices (ISSLED-2008) held in Phoenix, Arizona (USA), April 27 – May 2 (April 2008)
- Member, Program Committee, China SSL 2008, Shenzhen Convention & Exhibition Center, China, July 24 – 26 (July 2008)
- Member, Program Committee, International Workshop on Nitride Semiconductors, IWN 2008, Montreux, Switzerland, October 6 – 10 (October 2008)
- Opto Track Chair of *SPIE Photonics West* conference “Semiconductor Lasers and LEDs” San Jose, CA, January 25 – 29 (January 2009)
- Guest Editor of Special Issue on *Solid-State Lighting* published in the *IEEE Journal of Selected Topic in Quantum Electronics*, July / August edition (August 2009)
- Honorable Conference Chair, 6th China International Forum on Solid-State Lighting (China SSL), Shenzhen Convention & Exhibition Center, China, October 14 – 16 (October 2009)
- Program Committee Member, International Conference on Nitride Semiconductors (ICNS), Jeju, South Korea, October 18 – 23 (October 2009)
- Program Committee Member, The Second International Conference on White LEDs and Solid-State Lighting, Taipei, Taiwan, December 13 – 16 (December 2009)
- Editor, *Compound Semiconductors and Energy Applications and Environmental Sustainability*, Materials Research Society (MRS) Symposium Proceedings Volume 1167 (MRS, Warrendale PA, 2009)
- Conference Chair, OPTO, *SPIE Photonics West 2010*, San Francisco, California, January 23 – 27 (January 2010)
- Guest Editor of Special Issue on *Light-Emitting Diodes* published in the *IEEE Transactions on Electron Devices* (January 2010)
- Program Committee Member, *8th International Symposium on Semiconductor Light Emitting Devices* (ISSLED), Beijing, China, May 16 – 21 (May 2010)
- International Advisory Committee Member of the 16th *Microoptics Conference* (MOC’10) held in Hsinchu, Taiwan, sponsored and endorsed by OSA and IEEE/Photonics Society and organized by National Chiao Tung University, Oct. 31 to Nov. 3 (October 2010)
- Member of Academic Committee of *China Solid-State Lighting Conference* (CHINA SSL 2010) Shenzhen, China, October 14 – 16 (October 2010)
- Conference Co-Chair, OPTO, *SPIE Photonics West 2011*, San Francisco, California, January 22 – 27 (January 2011)
- Executive Organizing Committee OPTO, *SPIE Photonics West 2011*, San Francisco, California, January 22 – 27 (January 2011)
- Program Committee Member of conference entitled: “Light-Emitting Diodes: Materials, Devices, and Applications for Solid-State Lighting XV *SPIE Photonics West 2011*, San Francisco, California, January 22 – 27 (January 2011)
- Member of CLEO Subcommittee 15, entitled “LEDs, Photovoltaics and Energy-Efficient (“Green”) Photonics” for the 2011 Conference on Lasers and Electro-Optics (CLEO), Baltimore, Maryland May 1 – 6 (May 2011)
- Member of the Academic Committee of the 8th China International Forum on Solid-State Lighting (CHINA-SSL-2011) Guangzhou November 8 – 10 (November 2011)
- Program Committee Member of conference entitled: “Light-Emitting Diodes: Materials, Devices, and Applications for Solid-State Lighting XV *SPIE Photonics West 2012*, San Francisco, California, January 21 – 26 (January 2012)
- Member of CLEO Subcommittee 15, entitled “LEDs, Photovoltaics and Energy-Efficient (“Green”) Photonics” for the 2012 Conference on Lasers and Electro-Optics (CLEO), San Jose, California, May 6 – 11 (May 2012)
- Member of Academic Committee of the 9th China International Forum on Solid-State Lighting (CHINA SSL 2012), Guangzhou, China, November 5 – 7, 2012 (November 2012)
- Program Committee Member of conference entitled: “Light-Emitting Diodes: Materials, Devices, and Applications for Solid-State Lighting XVI *SPIE Photonics West 2013*, San Francisco, California, 2 – 7 February 2013 (February 2013)
- Member of CLEO Subcommittee in the topic area: “Science & Innovation 15: LEDS, Photovoltaics and Energy-Efficient ("Green") Photonics” for the CLEO 2013 conference, April 28 – May 3, 2013 in Baltimore, Maryland (May 2013)
- Member, International Advisory Committee of the International Conference on Advanced Electromaterials (ICAE 2013) held on Jeju Island, Korea, from November 12 – 15, 2013 (November 2013)

- Program Committee Member, *Solid-State and Organic Lighting* (*SOLED*), OSA Topical Meeting, 3 – 7 November 2013, Marriott Tucson Star Pass, Tucson, Arizona, USA (November 2013)
- Co-Chair, OPTIC International Conference, Chung Li, Taiwan, National Central University, December 5 – 7, 2013 (December 2013)
- Program Committee Member of conference entitled: "Light-Emitting Diodes: Materials, Devices, and Applications for Solid-State Lighting XVII" *SPIE Photonics West* 2013, San Francisco, California, 1 – 8 February (2014)
- Publication Committee Member, *5th International Conference on White LEDs and Solid-State Lighting* (White LEDs), Jeju Island, Korea, May 25 – 28, 2014 (May 2014)
- Sub-Committee Chair of Track 6: Displays, Solid-State Lighting, Photovoltaics, and Energy-Efficient Photonics of *Asia Communications and Photonics Conference 2014* (ACP 2014). ACP is the largest and the most influential conference in Asia and Pacific Rim for communications and photonics technologies. ACP 2014, Shanghai International Convention Center, Shanghai, China, November 11 – 14 (2014)
- International Consultant of technical seminar of the 11th China International Forum on Solid-State Lighting (SSL-China 2014) Guangzhou, China, November 6 – 8 (2014)
- Member of the International Advisory Committee of the 11th International Symposium on Semiconductor Light Emitting Devices (ISSLED 2017) held in Banff, Canada on October 8 – 13 (2017)
- Assisting the US Judicial Government Branch (various US District Courts), the USPTO (US Patent and Trademark Office) and the ITC (International Trade Commission) by serving as an independent Technical Expert Witness (1997 to present)

Books

- ***Doping in III-V semiconductors*** (author) Hardback and paperback, 628 pages (Cambridge University Press, Cambridge, UK, 1993). The following excerpt is from a book review by D. L. Miller, *University of Pennsylvania*, University Park PA, which appeared in *Physics Today*, Oct. 1994, p. 71: "[...] Fred Schubert has written a book that very nicely fills two roles: It serves as a reference volume for those of us who use III-V materials, and it provides enlightening explanations of interesting and important problems in semiconductor physics. [...] Schubert, who is employed by AT&T Bell Laboratories, brings his extensive research involvement with III-V materials physics straight to this book. His lucid explanations of some of the important physics of doped semiconductors is a major strength. For example, the chapter on deep centers provides the clearest treatment of the DX center I can remember reading, and it uses the large lattice distortion model and configurational coordinates introduced for the DX center to describe the EL2 deep level. This book can also serve as an excellent reference volume, because it briefly describes epitaxial growth techniques and the doping methods used with them, catalogs dopant-related phenomena, describes characterization techniques and provides 45 pages of citations to published articles and books. [...] I will use it to help my graduate students in the physics of semiconductors. [...] It will certainly be available on my bookshelf, in part to remind me what the Burstein-Moss shift is and in part for the literally hundreds of references that it provides on nearly every topic related to III-V semiconductor doping. Because of its clarity in treating some interesting phenomena of modern semiconductor physics, you too might want to get a copy of this book, even if you believe that Ga and As are just poor alternatives for doping silicon"
- ***Delta doping in semiconductors*** (editor) Hardback and paperback, 616 pages (Cambridge University Press, Cambridge, U. K., 1996)
- ***Light-emitting diodes*** (author) Hardback and paperback, 328 pages (Cambridge University Press, Cambridge, UK, 2003). The following excerpt is from a book review by David Bour, *Agilent Laboratories*, Palo Alto CA, which appeared in *Physics Today*, Nov. 2004, p. 66: "[...] In "*Light-emitting diodes*", E. Fred Schubert provides an excellent review of the physics and technology of semiconductor LEDs. [...] Interesting anecdotes like [the first demonstration of electroluminescence], clearly written by someone with a broad perspective and expertise, appear throughout the book, making it enjoyable to read. [...] Schubert provides an excellent description of the undesirable [non-radiative] recombination pathway. [...] Schubert has made pioneering contributions to those devices, and this variety of LEDs may become more widely used in the future. [...] Overall, "*Light-emitting diodes*" is an excellent examination of the physics and technology of semiconductor LEDs. The narration is simple and direct, and the book is well referenced for those seeking a deeper understanding of the topic. Written for the graduate level, the text will appeal to a broad audience; and for specialists who make semiconductor LEDs and laser diodes, it will serve as a useful connection to the scientific literature."
- ***Light-emitting diodes, second edition*** (author) Hardback, 422 pages (Cambridge University Press, Cambridge, UK, 2006)
- ***Physical Foundations of Solid-State Devices*** (author) eBook, 275 pages, ISBN-13: 978-0-9863826-2-8 (Google Books, Mountain View CA, 2015)

- ***Light-emitting diodes, 3rd edition*** (author) eBook, 672 pages with hundreds of colored illustrations, ISBN: 978-0-9 863826-6-6 (Google Books, Mountain View CA, 2018) "The 1st edition of the book "Light-Emitting Diodes" was published in 2003. The 2nd edition was published in 2006. The current 3rd edition of the book is a substantial expansion of the second edition and has 37 chapters. The book includes a thorough discussion of white light-emitting diodes (LEDs), phosphor materials used in white LEDs, packaging technology, and the various efficiencies and efficacies encountered in the context of LEDs. The background of light, color science, and human vision is provided as well. The fully colored illustrations of the 3rd edition are undoubtedly beneficial given the prominent role of light and color in the field of LEDs. The book is a comprehensive discussion of the LED, particularly its semiconductor physics, electrical, optical, material science, thermal, mechanical, and chemical foundations. The 3rd edition is published in electronic format in order to make the book affordable and easily accessible to a wide readership."

Courses and laboratories developed at Boston University

- Developed first laboratory for "Physics of semiconductor devices" (SC-471) Fall (1998)
- Developed course "Quantum mechanics applied to semiconductor devices" (SC-574) Fall (1999)
- Developed course "Semiconductor light emitters" (SC-760) Fall (2000)
- Developed distance-learning course and NTU course on "Light-emitting diodes – Device physics and applications" Fall (2000)

Courses taught at Boston University

- Undergraduate Course "Physics of semiconductor devices" (SC-471)
- Graduate course "Fiber optic communication systems" (SC-563)
- Graduate course "Quantum mechanics applied to semiconductor devices" (SC-574)
- Graduate course "Introduction to solid-state physics of devices" (SC-577)
- Graduate course "Quantum electronics" (SC-700)
- Graduate course "Integrated optoelectronics" (SC-770)
- Graduate course "Compound semiconductor devices" (SC-771)
- Graduate course "Light-emitting diodes" (SC-760)
- Graduate course "Research seminar" (SC-860, SC-892)
- Other courses "Research", "Guided Study", "Master Thesis", and "Dissertation" (SC-900)

Courses taught at Rensselaer Polytechnic Institute

- Graduate Course "Semiconductor devices and models II" (ECSE-6290)
- Undergraduate course "Microelectronics technology" (ECSE-2210)
- Undergraduate course "Fields and Waves 1" (ECSE-2100)
- Graduate course "Quantum mechanics applied to semiconductor devices" (ECSE-6968)
- Graduate course "Physical foundations of solid-state devices" (SC-6960)
- Graduate course "Light-emitting diodes and solid-state lighting" (SC-6961)
- Undergraduate course "Introduction to Electronics" (ECSE-2050)
- Other courses "Research", "Guided Study", "Master Thesis", and "Dissertation"

Teaching evaluations and students' comments

1997 – Students made the following comments: "Clear … organized … excellent explanations … I've never had a professor like him – I wish all were like him … very clear and concise presentations … strong response to students' questions and concerns … Professor provided excellent notes … laid out lectures in a clear and precise manner which worked out wonderfully … well organized and confident … responsive to students' concerns … excellent for students going into the semiconductor industry … excellent hand-outs and course materials … well prepared … clear lectures … I was strongly encouraged … materials are very interesting … hand-outs were excellent … material is very important … the presentation of materials was very clear … hand-outs were excellent support to the class … efforts made by Prof. Schubert in keeping everyone at the same pace was remarkable …"

1998 – Students made the following comments: "Professor was always well prepared … excellent content … very relevant for the field of solid-state devices … excellent preparation for the class … handouts were very good … very well-organized teacher … excellent knowledge of material … provided a complete background of all material … easy to talk to … excellent overall teaching skills … really enjoyed coming to class … his choice of topics and homework helped me a lot … enthusiastic in teaching and helpful during the office hours … one of the best professors I have had at BU … course gave a very good overview of the different solid-state physics principles … the course was very well organized … relevant examples and homework were given … good explanations were given … presented clearly … presentation was clear … communicated effectively … very knowledgeable … good demonstrations in class … gives clear descriptions … asks questions of class … grades homework fairly … good at answering questions … no weak points … excellent instructor and scientist … inspiring professor … thorough … the instructor is very precise and well prepared … his knowledge of the material is exact … very responsive to feedback … encourages student questions, class participation and discussion … the instructor cared about whether students understood material … the instructor used applications immediately after showing theory … handouts were excellent … guest lecture and lab tour excellent idea … excellent class notes … presented topics neatly … well prepared … review of ongoing research topics was great … Professor Schubert is undoubtedly an expert in his area …"

1999 – Students made the following comments: "He enjoyed teaching the material and was very clear … the presentation of the material in class was excellent … he helped me to understand a lot about semiconductors … Prof. Schubert always tried to make sure that we would all have a clear understanding of the material … manuscripts were very helpful … encouraged lots of class participation and was always readily available for help … presentation was excellent … the instructor was always willing to help me … very helpful … Clearly, Prof. Schubert is *more* than just extremely knowledgeable about this material … very thorough and exact communication of points … excellent course packet written by the instructor … he was very well prepared for class … He is extremely fair and encourages participation … he is also very accessible … excellent instructor … very approachable and easy to ask questions of … handouts were very effective and helpful … Prof. Schubert is very prepared and concepts are well explained … materials will be very useful for my future … very open to questions"

2000 – Students made the following comments: "He did a lot of experiments which really helped … the material is very interesting and cutting edge … clear presentations … good in-class demonstrations … very clear lectures … the material really does challenge you … takes the time to answer your questions … very interesting material … relevant to today's world of communication … the field trip was fun … in-class demonstrations really added to class … good understanding of course material … excellent details, willing to help, good explanations … in-depth details on quantum mechanics … the instructor was extremely accessible to students … he encouraged participation in class … he gave intuitive arguments and explained concepts in a very physical way … I very much enjoyed Professor Schubert and would like to take more classes with him … material was very beautiful … I *very much* enjoyed the papers that were discussed … everything is well organized … hand-out material is very complete and clear … lectures are clear … the professor prepared an excellent manuscript … explained things very clearly … he has strong enthusiasm to solve students' questions … it's a very important course … Professor follows the course notes exactly, so one can concentrate on material without having to focus on details … clearly presented material … the course is great preparation for future courses in solid-state physics … I greatly admire Professor Schubert …"

2001 – Students made the following comments: "He has a thorough understanding of the subject … I like the fact that he shows us examples in class demonstrations … the manuscript was good … instructor provides good notes … materials are presented clearly … in this course you learn a lot … very illustrative and in depth … very interesting course … Professor presented the material well … Professor seemed to have a strong grasp on what he was teaching … the basics were presented correctly … smooth transition into more complex materials … presented basics well … Professor's strong points are knowledge, organization and class materials … clear conception … very important and useful class … Professor knew what was going on … manuscript and his notes were very helpful … responded to suggestions … notes were comprehensive … just fine … manuscript was good … knows the material very well … notes handed out are good … expert knowledge of material … developed lectures logically and straightforward … lecture notes were prepared for us - very nice touch … Professor has deep knowledge of the materials … Professor is always prepared for lectures … he emphasizes principles and the concepts … good preparation … good stuff and clear presentation … good research and industry experience … excellent handout notes and materials … excellent teaching skills … inspires the interest of students … great knowledge of material … well organized course notes … Professor Schubert gave very clear instructions … listening to his presentation is a true enjoyment of an excellent art of lecture style … the manuscript has the quality of an excellent book … the manuscript was an excellent reference source book … the instructor was very clear and well organized and encouraged participation … text [written by Schubert] was extremely good … expert knowledge of materials … class demonstrations were very beneficial … can clearly relate complex ideas – very good … has a high amount of patience … excellent understanding of material … very enthusiastic in teaching … always available for discussion … very knowledgeable … I don't see any weak points … he explains the theory very clearly …"

2002 – Students made the following comments: "Always prepared … presented difficult material in a manner that was easy to understand … presented everything neatly … very helpful and organized … presents subjects in a very easy and friendly format … very well qualified … great experience … very detailed notes … well organized … very useful … very good diagrams and explanations … he knows the material extremely well … notes given to us are extremely helpful … professor was very knowledgeable … was able to answer any of our questions … very informative course … very knowledgeable and a great teacher … the instructor is enthusiastic to teach students … the instructor can explain the theory very clearly …"

2003 – Students made the following comments: "Great overall knowledge … good organization skills … demonstrations were very interesting and useful … effective instructor … handouts were extremely useful and organized … good course for completely understanding many points of fiber optics …"

2004 – SPIE short course: "Encouraged questions and handled them well … excellent short course … I really appreciated and enjoyed this course … good course – covered very broad matters … the instructor was very knowledgeable on the topic … excellent! …"; RPI Semiconductor devices and models II (ECSE 6290): Overall excellence of teacher: 4.8 out of 5.0. Student comments: "course was very well prepared … [course] was very organized … this is an excellent course … I learned a lot from this course … the course was very good … thanks Prof. Schubert for a wonderful course … it's been a great course … thank you …" RPI Microelectronics Technology (ECSE 2210): Overall excellence of teacher: 4.7 (average 4.2). Overall excellence of course: 4.3 (average 3.9). Student comments: "Understandable presentation … great job [of] Prof. Schubert … very nicely done class … very helpful throughout the entire course … provided timely explanations to complicated material … very informative … course was fun and interesting … very interesting lecturer … very down to earth and easy to ask for help … [instructor] did a good job in presenting [material] … good course … fun course … excellent instructor … he is a great guy and very knowledgeable … I would definitely take a class from him again" **Book review** by Neal Oldham (San Jose, CA, USA) on "Doping in III–V semiconductors" (E. F. Schubert, Cambridge University Press, Cambridge UK, 1993) on amazon.com (May 17, 2002): "[This is the] best book I've encountered in the semiconductor field. This is, no question, the best book that I've encountered in the entire field of semiconductor physics. It is expertly organized and indexed, easy to follow, complete in its treatment of electrical and materials-science aspects of III-V semiconductor production and measurement, well-written ... worth every penny if you even have the most remote interest in the subject." **Book review** by Debdeep Jena (Santa Barbara, CA, United States) on "Doping in III–V semiconductors" (E. F. Schubert, Cambridge University Press, Cambridge UK, 1993) on amazon.com (July 6, 2001): "Very useful text for semiconductor crystal growers. Doping is a big, big issue in semiconductors; this text does appreciable justice in its treatment of the issue. In addition, Schubert treats heterostructure physics appreciably well (in fact better than many textbooks on semiconductor physics!). Perusal of this book has proved very rewarding for me, and I expect it will do the same wonder for you too."

2005 – SPIE Photonics West short course student comments: "Very good instructor! … very knowledgeable … clear on complex subjects … good job fielding questions … (numerical score 4.3 out of 5.0). Educational materials on the web: … I have greatly enjoyed your LED slideshow. CLEO short course: … very good and well-organized course!" ECSE 6968: "Class presentations were very helpful in learning … very useful in learning *the details* of fundamental concepts … the course is very good … the course is excellent for engineers … your […] treatment brought about a much better understanding … examples were great and helpful … [discussion of] history and photons […] helped increase interest … After your course now, I can actually approach a quantum mechanics text book without fear … overall, I just wanted to say – *thank you* … excellent course … the instructor made it interesting and taught very effectively … the manuscript provided was also very well written … class was excellently structured … will benefit my studies in the future … especially liked the term paper requirement … Prof. Schubert is an excellent instructor, who is well prepared …" (excellence of instructor: 4.8 out of 5.0). SPIE Photonics North short course: "Very good and clear in presentation …" (numerical score 4.4 out of 5.0). ECSE 6960 mid-course and final feedback by students: "Professor has provided all course materials … I really appreciate it … well presented … technical support was great … my learning experience has been good … responses to my homework questions have been very timely … I have enjoyed the course and found it interesting and useful … homework assignments have been extremely beneficial … the set of notes is very comprehensive … good class structure …" (numerical scores of students' course and instructor evaluation: 5.0 out of 5.0). Comment on web educational materials: "Notes look very thorough and clear …"

2006 – SPIE Photonics West short course student feedback: "Excellent, knowledgeable … excellent presentation …" (numerical score 3.91 out of 5.0). ECSE 6961 (Light-emitting diodes and solid-state lighting): "excellent … Informative, comprehensive and interesting … the best part of this course, in terms of my learning experience, has been the course materials … just an outstanding class … so much is newly discovered and so much is current on-going research and commercially relevant … Dr. Schubert is obviously a leading researcher and did a great job of conveying his experience and understanding to the class … a highly technical topic that still makes a good general conversational topic … I liked the course material … I liked the fact that Prof. Schubert lectured directly from the textbook … I liked the structure of the course … I learned a lot about lasers and LEDs and other optical devices … it is a basic and fundamental class … the instructor gives ideas, concepts, and samples very clearly … very good course … students interested in LEDs and solid-state lighting are strongly recommended to take it … liked the overall coverage … the teaching pace was good … he covered a lot of material that is important for the subject, but it was clearly always related to the topic … the manuscript that he let us use was excellent in my opinion … the most important thing I liked about the course was the course material and the structure of the course … right amount of homework and the two exams and the term paper presentation … it was great to learn this course from someone who is a world leader in this field … well-organized material … liked the course format … organization was good … allowed me to know exactly what we were covering so I could look through the material prior to the lecture … course content was good, starting with LED basics and covering materials through modern technologies, and then a look at solid-state lighting and sort of an intro to communication devices … good fundamentals in LEDs … GREAT Professor … awesome course … informative course … ability to view course materials online was helpful … very fruitful course … covering a lot of materials … very good and very important for graduate students to take this one … for people in industry it's also useful … for the instructor, this course is thought through very clearly … the text book is also very good … great course … excellent instructor … cute instructor … course is very good … I benefited a lot from it …" (numerical scores: 4.7 out of 5.0). ECSE 2210 (Microelectronics Technology) student comments "Excellent teaching method … I like that the Professor asks random questions at the end of class – it helped me understand the subject better … I thought Prof. Schubert was fabulous … his organization of the class encouraged learning … I highly recommend this class to everyone … a devoted and involved teacher … displayed more enthusiasm in teaching than other Professors I had … he also seemed to have a philosophy about teaching that was beyond helping students get good grades … he emphasized real-world applications of material and had general advice about working in the real world after leaving academia … helpful … although he was harder in grading and exams, Prof. Schubert challenged us more and made the course more interesting … the many class activities provide lots of practice of materials just learned … provided good back-up information … made sure students understand concepts …thank you for asking students questions during class to reinforce concepts … thank you for allowing open book exams …" (numerical scores: excellence of teacher 4.4 out of 5.0; excellence of course 4.3 out of 5.0; overall average of ratings 4.4 out of 5.0)

2007 – Book review by Steven J. Wojtczuk (Lexington, MA, USA) on "Light-Emitting Diodes" (E.F. Schubert, Cambridge University Press, Cambridge UK, 2003) on amazon.com (March 14, 2006): "Schubert (RPI) has written an excellent book on LEDs that manages to explain and derive simple quantitative models for many phenomena of current interest … many monographs are a compendium of results in the field with hundreds of references … in contrast, Schubert, while giving copious references, is the sole author, leading to a coherent presentation well suited to learning … there are plentiful and good figures and drawings, as well as many exercises and solutions integrated into the text …" SPIE photonics West Short Course: "Excellent talk …" ECSE 2210 (Microelectronics Technology) "Thank you … great course … excellent instructor … interesting course … appreciated that you did not lecture completely from the slides and that you probed the class to ensure that we were understanding the key points … course is fine … good professor … Professor Schubert is one of the best lecturers I had … the pace at which he moves the topic, the way he explains things, and the manner in which he asks students questions all came together to help me learn much more form his lectures than I could on my own … instructors are absolutely very intelligent … Professor Schubert was a good professor … I actually learned things when Professor Schubert taught …" ECSE 6968 (Physical Foundations of Solid-State Devices) "The instructor explained every concept in a very simple and effective manner … I really enjoyed taking this course …" (numerical scores: 4.5 out of 5.0)

2008 – SPIE Photonics West short course feedback: "Very good … clear … very nice … answered questions readily …" (numerical score 4.3 out of 5.0) … ECSE 6961 (Light-emitting diodes and solid-state lighting) feedback: "It was great for me to have the opportunities to take two consecutive classes, *Physical Foundation* and *LEDs*, from you … both these classes have taught me a lot … they were very well organized … thank you for all the help … I have really enjoyed your classes … relevant material … very good professor …" (numerical scores: 4.3 out of 5.0) … Internet educational materials feedback: "I recently came across your course notes while trying to get a basic understanding about semiconductors and I wanted to thank you. Your notes for course "ECSE-2210 Microelectronics Technology" are the most useful and informative thing I have found on semiconductors on the Internet. I'm a chemist by trade and this is a great introduction for me …" 2007 Chautauqua Short Course and High School Teacher Summer Course, held at RPI June 26 and July 12, 2007 (numerical average of scores: 9 out of 10) … ECSE 6968 (Physical Foundations of Solid-State Devices) feedback: "Prof. Schubert is one of the best professors I've ever had … his ability to explain difficult and complex materials in a clear and concise manner is unmatched … the presentations, although time consuming, I felt were a great idea … thanks for your efforts professor! … I have really enjoyed taking this course …" By email: "Thank you professor … it has been a pleasure taking this course with you …" (numerical scores: 4.4 out of 5.0)

2009 – SPIE Photonics West short course feedback by students: "One of the best short courses I have taken … it was very nice to hear about the history of LEDs … very interesting but also very theoretical …" (numerical score 4.1 out of 5.0). ECSE 2210 (Microelectronics Technology) "Great course … instructors were excellent … encourages students to stay up to date with the subject matter … Thanks for this well-organized class … [the instructor] tries to get students to come out with the best grade possible … this was a good class …" ECSE 6968 (Physical Foundations of Solid-State Devices) feedback by students: "It is really an excellent course … clear hand script … great professor! …" (numerical scores: 4.7 out of 5.0)

2010 – SPIE Photonics West short course feedback by students: "Good to get the latest data and charts … very good … very broad course and well organized … it was great …" (numerical score 4.04 out of 5.0) … ECSE 6961 (Light-emitting diodes and solid-state lighting) feedback by students: "A good course … this was a wonderful course … it has given me a lot of understanding … the course has inspired me to take up LED research … useful … straight forward … very good advisor … good course …" (numerical scores: 4.3 out of 5.0) … ECSE 6220 (Physical Foundations of Solid-State Devices) feedback by students: "Overall excellent course … Professor Schubert is a good teacher … he can explain every discipline very clearly and relate them to practical applications … I like his teaching style very much … overall, it was a nice course … material explained in a clear organized manner …" (numerical scores: 4.7 out of 5.0)

2011 – SPIE Photonics West short course feedback: "Very nice overview … the instructor was excellent! … very good instructor … I would recommend lengthening to 6 hours … excellent presentation, materials and text … thanks … very clear and easy to follow … to be recommended … excellent presentation … good compromise for a person with a busy schedule …" (numerical score 4.45 out of 5.0); … ECSE 2210 (Microelectronics Technology) "This was a great course … I enjoyed Professor Schubert's views … I was successful … this course was taught very well … this subject I now find quite interesting and am no longer intimidated by it … I liked the material of this course … thank you …" (numerical scores: 3.3 out of 5.0); Feedback on book *Light-Emitting Diodes*: "I am a graduate student from National Chiao Tung University, Taiwan … your wonderful book *Light-Emitting Diodes*, both first- and second-edition, gave me a lot of information and help … I would like to ask when can the third of the masterpiece be published? I wish I can get it as soon as possible and study more about the lighting devices; Feedback on Internet pages: I found your website and information […] quite enlightening and provides a great start … I simply wish to quickly express my thanks and gratitude." Feedback on book *Physical Foundations of Solid-State Devices*: "Dear Prof. Schubert, I have read your book Physical Foundations of Solid-State Devices and I must say it is amazing the explanations are really good and I am most thankful that you have decided to put the book online thank you." Itamar Jade Balla, The Israel Institute Of Technology. Feedback on book *Light-Emitting Diodes* by Trung Nguyen (San Jose, California): "It is a good book about Light Emitting Diodes (LEDs). It provides very good info and it is a good reference for engineers who work in the LED field"; … ECSE 6220 (Physical Foundations of Solid-State Devices) feedback: "Amazing course … great instructor … very good course … The text and lectures were very useful and informative … I definitely learned a lot from taking this course … I liked the course materials! …" (numerical scores: 4.6 out of 5.0)

2012 – Feedback on Internet-based materials: "I'm Cheng Liu [Wuhan National Laboratory for Optoelectronics, China], currently a graduate student majoring in Physical Electronics … I deeply admire your profound knowledge on this field and your unselfish sharing of it …"; … SPIE Photonics West short course feedback: "Dr. Schubert was very clear and very patient with people who had questions … the materials were comprehensive …"; Feedback on Internet-based materials: "Supremely-rich course contents posted on your website. Thank you very much for showing such awesome materials for the world to see …" (Prof. Natee Tangtrakarn, Thailand) … ECSE 6962 (Light-Emitting Diodes and Solid-State Lighting) feedback: "… very interesting course … Professor Schubert did a great job explaining the material … his textbook is very clear and understandable … nice course … I learned a lot of new things by taking it …" (numerical scores: 4.7 out of 5.0)

2013 – ***SPIE Photonics West short course*** feedback (SC-052, Light-Emitting Diodes): "Great instructor with admirable combination of knowledge in academic and commercial knowledge … I appreciated the depth of his knowledge and experience … the length of the course was good … Overall this was an excellent course … Thank you … course is very easy and I understand it easily … Excellent course! … Instructor was fantastic -- clear, explicit, took questions as we went and answered well … One of the best SPIE courses I've taken (and I've taken lots)! … Great course -- thanks! … I was happy that the slides were updated with 2012 data". ***RPI course numerical scores (ECSE-6962, Light-Emitting Diodes and Solid-State Lighting)***: Numerical score of students' evaluations: 4.67 out of 5.0; Verbatim comments: "The course is pretty good … needs no improvement … I can appreciate the more wide-angle approach from the course … These areas are very important and previously I had no knowledge of them … It was a pleasure attending your class …" ***RPI course numerical scores (ECSE-6968, Physical Foundations of Solid-State Devices)***; Verbatim comments: "It has been an awesome experience of learning for me in this course ... Thank you for everything ... Thank you for the great semester ... Have a good break ... Thank you for the great semester ... Have a good break ... Professor, thank you for an engaging and interesting class this semester ... I enjoyed the subject of my paper and learned quite a bit particularly about GaN, which I had not had a chance to really do any research into before ... Very good and interactive class ... I liked the style of the class ... I thought the topics covered were very interesting ... I think I got much more out of the class this way than if we would have followed the manuscript chapter by chapter …" Numerical score of students' evaluations: 4.83 out of 5.0

2014 – *SPIE Photonics West short course* verbatim feedback (SC-052, Light-Emitting Diodes): "Very knowledgeable instructor ... the course was packed with information ... handouts are excellent ... Excellent presentation and contents ... the color rendering section which was interesting and fun ..." Numerical score of students' evaluations: 4.36 out of 5.0; ***RPI Course ECSE-2210 Microelectronics Technology***; Verbatim comments: "Instructor is clearly very knowledgeable about the topics ... Very clear and comprehensive ... This is the best class ever ... I'm quite enjoying this course ... I don't really have any recommendations on things to change ... The homework and lectures being sent out at the beginning was very helpful ... Both the TA and the professor were able to explain things very well ... I think he is a good lecturer ... I think the homework each was very, very good at teaching me the material, and the exam was fairly graded and easy to understand ... I definitely like the professor and I would have him again ... A good class ... I enjoyed Prof. Schubert's style of teaching ... I would still recommend Prof. Schubert as a professor ... Microelectronics is a good class ... Prof. Schubert keeps it interesting though ... he's a great professor ... The two TAs are also great ..." Numerical score of students' evaluations of instructor: 4.25 out of 5.0. ***RPI Course ECSE-6220 Physical Foundations of Solid-State Devices***; Verbatim comments: "The book and lectures seem to be entirely in sync with one another ... it really enforces the material covered in the book ... the material is covered thoroughly and improves students' understanding of quantum physics ... The class was interesting with excellent learning materials ... I loved how the course was so well organized ... The lectures were very well put together ..." Numerical score of students' evaluations of instructor: 4.75 out of 5.0.

2015 – ***SPIE Photonics West Short Course SC-052 titled Light Emitting Diodes***, Verbatim comments: "I was very satisfied with this short course" Numerical score of students' evaluations: 4.53 out of 5.0; ***RPI Course ECSE-6960 Light-Emitting Diodes***; Verbatim comments: "the class has been excellent! ... I've learned a good amount about LEDs ... Also I'd like to thank you for a great semester and say that you've peaked my interest in the LED field! ... I would like to add that the course was an excellent experience for me and that I really enjoyed learning about LED technology! ... Thank you very much for teaching such a wonderful class ... It was a great learning course" Numerical score of students' evaluations: 5.0 out of 5.0. ***RPI Course ECSE-2100 Fields and Waves 1***; Verbatim comments: "This class is going perfectly and I love the way it's run ... The material is great and understandable ... the pace is perfect ... I like the pacing of the course and the fact that we spend time really developing an understanding of the theory and concepts that we will be using ... I like the Professor ... The lectures are great ... I really enjoy this professor and he is very understanding of the students' levels of learning and focused on that ... Professor Schubert is clear and easy to understand ... Overall a very good professor ... very knowledgeable and helpful ... I thought the professor was very knowledgeable and was an excellent instructor ..." Numerical score of students' evaluations of instructor: 4.17 out of 5.0.

2016 – ***SPIE Photonics West Short Course SC-052 titled Light Emitting Diodes***, Verbatim comments: "This has been my favorite course (over 3 years) ... Well-structured presentation, and well given ... I was surprised by how much I didn't know. I learned a lot ... Explained difficult concepts in a clear and simple manner ... Able to go "off script" to clarify during questions." Numerical score of students' evaluations: 4.56 out of 5.0; ***RPI Course ECSE-2100 Fields and Waves 1***; Verbatim comments: "This is cool material ... This class was one of the most well put together I have ever taken in terms of lecture pace, lecture clarity, TA support, and quality of teaching and communication ... The lectures never felt too long or too short, the pace was good, I never felt lost or without an option to turn for help ... The homework was neither too long nor too short, and was well balanced with conceptual and quantitative questions ... Prof. Schubert's lecture style was very clear, concise, and to the point, with many useful examples in real life scenarios which made the material more interesting ... Very well done ... Great class ... I liked the pace of the class ... it helps with understanding the material a lot ... The labs [...] were fun and very educational ... Overall, I learned a lot from this course ... The speed of the class is perfect ... I really got a chance to learn ... This professor is very good ... Also, [in] the lab section I was able to really break down what I learned in class ... Schubert has the neatest handwriting of any professor I've ever had in my 3 years here ... His diagrams are extremely neat and he is easy to understand verbally too ... Lots of conceptual knowledge covered ... Overall [...] it was an enjoyable class ..." Numerical score of students' evaluations: 5.0 out of 5.0. ***RPI Course ECSE-2210 Microelectronics Technology***; Verbatim comments: "So far, this has been one of my favorite courses at RPI … I'm a huge fan of Prof. Schubert's ability to clearly describe concepts both conceptually and mathematically … Class activities […] were really helpful! … Otherwise the class is great! … Prof Schubert knows his stuff … Best professor I have had … This course was well taught … Professor Schubert's explanations were very clear and understandable … he took time to address student questions with in-depth answers … I feel as though I gained a lot from this course, especially with regards to explanations of why certain things in ECSE-2050 (Intro to Electronics) occur the way they do like where the diode property comes from and how material properties of electronic components give rise to the very real circuit characteristics we see in ECSE-2050 labs … In this sense, Microelectronics Tech is a very good companion class to Intro to Electronics, and I highly recommend future students take them at the same time … this was a quite good class … Best MET instructor … I was so actively engaged during the lectures that it was kind of scary ... The lecture notes and lectures were mostly great … The material covered in it was succinct and interesting, yet still covered the knowledge needed to tackle engineering problems in semiconductors …" Numerical score of students' evaluations: 4.64 out of 5.0.

2017 – ***RPI Course ECSE-2100 Fields and Waves 1***; Verbatim comments: "I thoroughly enjoy this class … Schubert is awesome! … Enjoyed the class … He is a good teacher … Most teachers talk really fast making it hard to follow … Schubert talks slow and explains things really well … Professor Schubert is an excellent professor, and has been one of my favorites at RPI so far … He made a difficult topic approachable, interesting and understandable … I hope I have him as a professor in the future … Thank you … I enjoyed this class, especially the labs … Lectures were good too … great class! … The professor does a great job of engaging the students by asking questions and making students ask questions to make them think about the labs … This course is overall excellent in that the professor does know the pace of class and gives feedback appropriately …"; Numerical score of students' evaluations: 4.63 out of 5.0. ***SPIE Photonics West Short Course SC-052 titled Light Emitting Diodes***, Verbatim comments: "the course covered a wide variety of concepts …" Numerical score of students' evaluations: 4.03 out of 5.0.

2018 – ***RPI Course ECSE-2100 Fields and Waves 1***; Verbatim comments: "Professor Schubert is great and very entertaining to listen to in the lab and in lecture ... Really appreciate how Prof. Schubert structures lectures ... Schubert is great! … The professor is excellent at relaying concepts ... This course is very interesting and it goes at a good pace ... One of the better professors here at RPI … He cares about his students and helps them to learn the most through lectures and labs … Fantastic course that goes into great detail into not only knowing the material but also understanding the material … [the course] has been clarified and allowed for a greater learning process." Numerical score of students' evaluations of instructor: 4.17 out of 5.0. ***RPI Course ECSE-6220 Physical Foundations of Solid-State Devices***; Verbatim comments: "Perfect professor, no complaints." Numerical score of students' evaluations (median): 5.0 out of 5.0.

2019 – ***RPI Course ECSE-2100 Fields and Waves 1***; Verbatim comments by students: "Schubert is excellent in relating information in a practical manner especially in the lab … Overall, both the professor and TAs prioritize if students understand material over semantics in reports and homework, which is really helping me in the course, and feedback given is incredibly helpful in both … Schubert is a mystery. He speaks very slowly and clearly, but you somehow learn everything at a very fast rate … Class […] being just the right amount focused and adequately paced … Overall great class … Labs were educational and we were allowed to have fun with it … Otherwise great lectures, notes were available and understandable … this was one of my favorite classes … Very well run by Schubert … lectures were informative and easy … labs were fun … The TA's were allowed to have personalities and interact with the students … 10/10 would take again … Schubert was okay … The best parts about the course for me were everything was online and I could copy the notes at my leisure with my busy schedule … I also liked that exams were open book and we had a lot of opportunities for practice … I have nothing but good things to say about both TAs and Professor Schubert – this has been my favorite class this semester … Though challenging, I have found the course material very interesting and all teachers have been excellent … Course was good … I like Professor Schubert's class notes online. They're super well written and helpful." Numerical score of students' evaluations of instructor: 4.63 out of 5.0 (average) and 5.0 out of 5.0 (median).

2019 – ***RPI Course ECSE-6280 Light Emitting Diodes***; Verbatim comments by students: "This was a great course … I learned a lot during the semester … Great class … I really enjoyed Professor Schubert's expertise on the subject … Gives both in-depth technical knowledge as well as high level background to better understand the driving factors of the LED industry … I would highly recommend it to anyone in ECSE." Numerical score of students' evaluations: 4.83 out of 5.0 (average) 5.0 out of 5.0 (median).

2020 – ***RPI Course ECSE-2100 Fields and Waves 1***; Verbatim comments by students: "I really enjoyed this class … the cool labs with good help and good lectures made me really enjoy this class and help the information stick in my head better … The labs provided a great use to show theory in practice and how certain concepts are applied to real-life applications ... The laboratory session was also a great time to ask questions and have in-depth talks about the material … I would have already commended this professor for class organization and material availability prior to online courses (course material easily available, organized well, and easy to understand; interactive lectures; interactive labs better than most other ECSE courses), Prof. Schubert handled the change to online coursework best of all of my professors and maintained the quality of lecture almost perfectly … The 'live' online classes were interactive and courteous by students and the professor, organized, and just as in-depth as before, even including miniature homemade demonstrations and experiments … The course was taught very fundamentally which allowed me to think and learn more … Thank you, Professor Schubert … I really missed your live lectures and labs! … Professor Schubert made the best of the situation of online learning … Great class … I learn a lot from this class … I enjoy lab sessions and try never to miss any class … Prof. Schubert is really good!" Numerical score of students' evaluations: 4.75 out of 5.0 (average) 5.0 out of 5.0 (median).

2020 – ***RPI Course ECSE-2050 Introduction to Electronics***; Verbatim comments by students: "I really enjoyed how easy it was to follow along with the lecture … I really enjoyed the content of this course, and I feel that the applications of this content in the lab were extremely effective to help students understand the content ... the concepts in general were extremely interesting … I liked how the lecture sessions for this class provided much more room for discussion and examples than nearly any other ECSE course I have taken at RPI so far … Schubert was very aware of the students ability to fully comprehend the topic ... He was very patient with the students that needed extra explaining … I learned a lot about the course material … I liked the one-on-one attention we received in the in-person lab … I enjoyed the in person laboratory sessions, they were a good place to get all my questions answered … I really like the lecture notes and the detailed diagrams / graphs that help explain the concepts … Professor Schubert does a great job of breaking down the material, he always tries to engage the students in every lecture … Very clear notes, responded quickly, answered any confusing questions really well, and very nice and accommodating towards the current COVID situation everyone is going through … He had very organized notes that helped especially with the difficulties of online learning … I loved the explanation of diodes, it's never been so clear to me before! … Examples were excellent … The course was great! … I learned a lot and this course stimulated my interest … Very engaging … stimulates participation … Professor Schubert was a refreshing exception … the professor was very knowledgeable in the subject area … explanations were clear and easy to understand … I really like the format of this class compared to my other classes … I really enjoyed the format … Very detailed lecture, very helpful with students, made very complex material easy to understand … Prof is really understanding and cares about his students ... He is really willing to work with us which I found is really rare at RPI ... He is easily one of the best professors I have had … He cares most about whether we are learning and understanding, rather than following his desired schedule perfectly ... Cannot say anything bad about Prof Schubert … Class is great" Overall instructor rating: 4 out of 5. Overall course rating: 4 out of 5.

2021 – ***RPI Course ECSE-2050 Introduction to Electronics***; Verbatim comments by students: "Class has been going smoothly … Professor Schubert includes real world-examples of devices in his lectures, showing the importance of our course materials … He is always very considerate of students, trying to adapt to what would help people most … He engages students in lectures." Overall instructor rating: 4.8 out of 5.0. Overall course rating: 4.6 out of 5.0.

2021 – ***RPI Course ECSE-2050 Introduction to Electronics***; Verbatim comments by students: "Professor is always able to conceptually answer our questions, and run through circuit analysis with us if the results we're measuring don't match up … I tried taking this class once before, and I failed it. This time around, I feel like I know everything about everything. I had never imagined just what a difference teaching style could make in my ability to learn information, but this class is so much more welcoming to me this time around. It was with a different professor the first time. I much prefer Professor Schubert and the way he conveys information so effortlessly. He also seems like he's passionate about teaching the information and his handwritten notes are astonishingly detailed … Great professor! I appreciate Professor Schubert taking the time to clarify different topics and always checking in with the students. He seems to genuinely care about our education. He is strict about deadlines, more so than other professors at least, but I think he has earned that … Professor Schubert is very friendly to his students … He was very helpful and one of the few professors who actually stays and talks to students all throughout the lab period. It was very helpful because often I would think that I fully understood a concept and then he would ask a question that would either stump me or reinforce information. Additionally he kept lectures short and to-the-point, which I appreciate." Overall instructor rating: 4.3 out of 5.0. Overall course rating: 4.3 out of 5.0.

2022 – ***RPI Course ECSE-2050 Introduction to Electronics***; Verbatim comments by students: "Great professor! … Handwriting is amazing … His notes are flawless and easy to understand … This course covers much more than most other EE courses I've taken, and yet I feel as though this has been the easiest EE course due to his teaching abilities … Professor Schubert is a very knowledgeable professor … It's clear that he wants his students to learn …" Overall instructor rating: 4.3 out of 5.0. Overall course rating: 4.4 out of 5.0.

2022 – ***RPI Course ECSE-2210 Microelectronics Technology***; Verbatim comments by students: "I think Schubert does a great job of teaching … He makes the pn junctions as interesting as he can … I also love the chalk-board! So great, every professor should be forced to use it, because you can follow the work so smoothly (not like powerpoints) … I would not change the class … I also like how Prof. Schubert asks for feedback from everyone after class … Course was at a great pace and the level of difficulty … Professor Fred Schubert is one of my most favorite professors at RPI … I am sad to see in the course schedule for Spring 2023 that he is not teaching any 4000 level ECSE courses … I think that the department and students are missing out by not having someone as knowledgeable as him teaching more conceptually hard topics because Professor Schubert does that exceptionally … Best ever lecture experience, clear structure of lecture notes, comprehensive homework that helps to improve students' understandings, and always eager to solve students' questions … Thanks for another great course Professor!"

2024 – ***RPI Course ECSE-2050 Introduction to Electronics***; Verbatim comments by students: "... It's great to learn how a component works and learn "Iconic Circuits" that use those components … I really appreciated the

Homeworks, they were well thought out and helped me understand the content … I liked the open notes exams, they allowed me to use the notes I took in class and demonstrate how I can apply the concepts we learned in class to a different problem … I appreciated [Professor Schubert] talking to everyone in [the] lab one-on-one … I also liked that he showed interest in all the students and answered our questions promptly and thoroughly … Very nice and understanding professor, one of the best in the ECSE department … Professor Schubert seems to know what he is talking about … Professor Schubert is very nice and during labs walks around and asks students questions making sure we understand the concepts … He also introduced some applications not taught in the previous versions of the course and even added a lecture on class-D amplifiers to attempt to keep the course up with modern technology … The last few lectures left a good impression though and were extremely engaging …"

2024 – ***RPI Course ECSE-2210 Microelectronics Technology***; Verbatim comments by students: "... Professor Schubert is very passionate about his subject and that passion rubs off on his students … The professor was truly excellent and I enjoyed attending his lectures twice a week … He was very good at teaching. …"

Post-doctoral & visiting personnel for which I served as Major Research Advisor

Dr. Li-Wei Tu	Post-Doctoral Fellow	1988–1990
Dr. Neil Hunt	Post-Doctoral Fellow	1991–1993
Dr. Matthias Passlack	Post-Doctoral Fellow	1993–1995
Dr. Wolf Grieshaber	Post-Doctoral Fellow	1995–1997
Dr. Thomas Gessmann	Post-Doctoral Fellow	2000–2002
Dr. Jong Kyu Kim	Post-Doctoral Fellow	2003–2005
Dr. Min Ho Kim, SEMCo	Visiting Engineer	2007–2008
Prof. Ji-Myon Lee, Sunchon Univ.	Visiting Professor	2007–2008
Dr. Jaehee Cho	Post-Doctoral Fellow	2008–2009
Dr. Yongjo Park, Samsung LED	Visiting Vice President	2010–2012
Dr. Yangang Andrew Xi	Visiting Scientist	2013–2014
Dr. Guan-Bo Lin	Post-Doctoral Fellow	2014–2015

Graduate students for which I served as Major Research Advisor

Dr. Dean A. Stocker	Ph.D. Dissertation	Ph. D. completed in 1999
Xiaoyun (Jane) Guo	Master Thesis	M.S.E.E. completed in 1999
John W. Graff	Master Thesis	M.S.E.E. completed in 1999
Dr. Ian D. Goepfert	Ph.D. Dissertation	Ph. D. completed in 2000
Yun-Li Li	Master Thesis	M.S.E.E. completed in 2000
Dr. Xiaoyun (Jane) Guo	Ph.D. Dissertation	Ph. D. completed in 2001
Dr. John W. Graff	Ph.D. Dissertation	Ph. D. completed in 2002
Dr. Erik L. Waldron	Ph.D. Dissertation	Ph. D. completed in 2002
Jay M. Shah	Master Thesis	M.S.E.E. completed in 2002
Dr. Yun-Li Li	Ph.D. Dissertation	Ph. D. completed in 2003
Jingqun ("JQ") Xi	Master Thesis	M.S. completed in 2003
Yangang Andrew Xi	Master Thesis	M.S. completed in 2003
Ronald Jackson	Master Thesis	M.S. completed in 2004
Sameer Chhajed	Master Thesis	M.S. completed in 2004
Hong Luo	Master Thesis	M.S. completed in 2005
Xiaolu Li	Master Thesis	M.S. completed in 2005
Kaixuan Chen	Master Thesis	M.S. completed in 2005
Dr. Jay M. Shah	Ph.D. Dissertation	Ph. D. completed in 2006
Frank Mont	Master Thesis	M.S.E.E. completed in 2006
Dr. Hong Luo	Ph.D. Dissertation	Ph. D. completed in 2006
Dr. Jingqun ("JQ") Xi	Ph.D. Dissertation	Ph. D. completed in 2006
Dr. Yangang Andrew Xi	Ph.D. Dissertation	Ph. D. completed in 2006
Won Seok Lee	Master Thesis	M.S. completed in 2007
Qi Dai	Master Thesis	M.S. completed in 2007
Di Zhu	Master Thesis	M.S. completed in 2007

Jiuru Xu	Master Thesis	M.S. completed in 2007
Ahmed Noemaun	Master Thesis	M.S. completed in 2007
Roya Mirhosseini	Master Thesis	M.S. completed in 2008
David Poxson	Master Thesis	M.S. completed in 2008
Qifeng Shan	Master Thesis	M.S. completed in 2009
Ming Ma	Master Thesis	M.S. completed in 2010
Xing Yan	Master Thesis	M.S. completed in 2010
Dr. Roya Mirhosseini	Ph.D. Dissertation	Ph. D. completed in 2010
Dr. Sameer Chhajed	Ph.D. Dissertation	Ph. D. completed in 2010
Dr. Jiuru Xu	Ph.D. Dissertation	Ph. D. completed in 2011
Dr. Frank Mont	Ph.D. Dissertation	Ph. D. completed in 2011
Dr. Wonseok Lee	Ph.D. Dissertation	Ph. D. completed in 2011
Dr. Di Zhu	Ph.D. Dissertation	Ph. D. completed in 2011
Dr. Qi Dai	Ph.D. Dissertation	Ph. D. completed in 2011
Dr. Ahmed Noemaun	Ph.D. Dissertation	Ph. D. completed in 2011
Dr. David Poxson	Ph.D. Dissertation	Ph. D. completed in 2011
Dr. Qifeng Shan	Ph.D. Dissertation	Ph. D. completed in 2012
Dr. Ann Mao	Ph.D. Dissertation	Ph. D. completed in 2013
Dr. Xing Yan	Ph.D. Dissertation	Ph. D. completed in 2013
Dr. Ming Ma	Ph.D. Dissertation	Ph. D. completed in 2013
Dr. David Meyaard	Ph.D. Dissertation	Ph. D. completed in 2013
Dr. Guan-Bo Lin	Ph.D. Dissertation	Ph. D. completed in 2013

Expert Witness Consulting Service

1997 ***Case***: Hewlett-Packard Company versus CEO of United Epitaxy Company (Taiwan)
Nature: Trade secret misappropriation
Venue: U.S. District Court.
Law firm: Morrison & Foerster LLP, Washington DC.
Role: I served as technical expert witness on behalf of United Epitaxy (Defendant). I wrote one or more expert reports.

1998 ***Case***: Hewlett-Packard Company versus United Epitaxy Company (Taiwan)
Nature: Patent infringement.
Venue: U.S. District Court for the Northern District of California.
Law firm: Quinn Emanuel Urquhart Oliver and Hedges LLP
Role: I served as technical expert witness on behalf of United Epitaxy (Defendant). I wrote one or more expert reports.

2006 ***Case***: Kerr Company versus 3M and Dentsply International Company.
Nature: Patent infringement.
Venue: U.S. District Court for the Western District of Wisconsin.
Law Firm: Woodcock Washburn LLP, Philadelphia, Pennsylvania.
Role: I served as technical expert witness on behalf of Dentsply (Defendant). I wrote one or more expert reports.

2006 ***Case***: Nichia Corporation (Japan) versus Seoul Semiconductor Company (Korea).
Nature: Design patent infringement.
Venue: U.S. District Court for Northern District of California, San Francisco Division.
Law firm: Foley & Lardner LLP Washington DC.
Role: I served as technical expert witness on behalf of Nichia (Plaintiff). I wrote one or more expert reports; I was deposed.

2008 ***Case***: Seoul Semiconductor (SSC) Company LTD (Korea) versus Nichia Corporation (Japan).
Nature: Patent infringement.
Venue: U.S. District Court for the Eastern District of Texas, Beaumont Division.
Law firm: Morrison & Foerster LLP, Palo Alto, California.
Role: I served as technical expert witness on behalf of Nichia (Defendant). I wrote one or more expert reports; I testified in District Court during the claim construction / Markman hearing.

2008 ***Case***: Professor Gertrude Rothschild versus Toshiba Company (Japan).
Nature: Patent infringement.
Venue: U.S. International Trade Commission (ITC), Washington DC.
Law firm: DLA Piper LLP, San Francisco California.
Role: I served as technical expert witness on behalf of Toshiba (Defendant). I wrote one or more expert reports; I was deposed.

2008 ***Case***: Honeywell Company versus Cree Company and Lumileds Company.
Nature: Patent infringement and Reexamination of patent.
Venue: U.S. District Court for the Eastern District of Texas, Marshall Division. Reexamination before the USPTO's Patent Trial and Appeal Board.
Law firms: Paul Hastings LLP, Washington DC and Ingrassia, Fisher & Lorenz PC, Washington DC.
Role: I served as technical expert witness on behalf of Honeywell (Plaintiff). I wrote one or more expert reports. I testified at the USPTO during a re-examination hearing.

2010 ***Case***: Landmark Screens Company versus MLB Company and Kohler.
Nature: Mishandling of a patent application.
Venue: U.S. District Court for the Northern District of California, San Jose Division.
Law firm: Keker & Van Nest LLP, San Francisco, California.
Role: I served as technical expert witness on behalf of MLB and Kohler (Defendant). Negligence in conjunction with a patent application; I wrote one or more expert reports.

2011 ***Case***: Koninklijke Philips Electronics N.V. versus Seoul Semiconductor (SSC) Company LTD.
Nature: Patent infringement.
Venue: U.S. District Court for the Central District of California Southern Division
Law firm: Latham & Watkins LLP, Washington DC.
Role: I served as technical expert witness on behalf of SSC (Defendant). I wrote one or more expert reports.

2011 ***Case***: Jeou-Nan Tseng versus Home Depot USA Inc. and Guangde LEDup Enterprise Inc.
Nature: Patent infringement.
Venue: U.S. District Court for the Western District of Washington at Seattle.
Law firm: DLA Piper, Philadelphia, Pennsylvania.
Role: I served as technical expert witness on behalf of Home Depot (Defendant). I wrote one or more expert reports.

2011 ***Case***: Lightpanels Ltd. Company versus Fuzhou F&V Photographic Company.
Nature: Patent infringement.
Venue: U.S. International Trade Commission (ITC), Washington DC.
Law firm: Locke Lord LLP, New York, New York.
Role: I served as technical expert witness on behalf of Fuzhou F&V and Nanguang Photographic (Defendant). I wrote one or more expert reports; I was deposed.

2012 ***Case***: Osram Company versus LG Company.
Nature: Patent infringement.
Venue: U.S. International Trade Commission (ITC), Washington DC.
Law firm: Finnegan, Henderson, Farabow, Garrett & Dunner, LLP, Washington DC.
Role: I served as technical expert witness on behalf of LG (Defendant). I wrote one or more expert reports; I was deposed; I testified at the ITC Hearing.

2012 ***Case***: Osram Company versus LG Company and Samsung Company.
Nature: Patent infringement.
Venue: U.S. International Trade Commission (ITC), Washington DC.
Law firm: Covington & Burling LLP, Washington DC.
Role: I served as technical expert witness on behalf of LG and Samsung (Defendant). I wrote one or more expert reports; I was deposed; I testified at the ITC Hearing.

2013 ***Case***: Chao Tai Electron Co. LTD. versus LEDup Enterprise Inc. and others.
Nature: Patent infringement.
Venue: U.S. District Court for the Central District of California.
Law firm: Hunton & Williams LLP, Washington DC.
Role: I served as technical expert witness on behalf of LEDup Enterprise Inc. and others (Defendants). I wrote one or more expert reports.

2013 ***Case***: Nichia Corporation versus Everlight Company and Emcore Company.
Nature: Inter Partes Review (IPR).
Venue: USPTO Patent Trial and Appeal Board.

Law firm: Foley & Lardner LLP, Washington DC.
Role: I served as technical expert witness on behalf of Nichia Corporation (Petitioner). I wrote one or more expert reports; I was deposed.

2014 ***Case***: Everlight Electronics Co. LTD. versus Nichia Corporation.
Nature: Patent infringement.
Venue: U.S. District Court for the Eastern District of Michigan, Southern Division.
Law firm: Foley & Lardner LLP, Washington DC.
Role: I served as technical expert witness on behalf of Nichia Corporation (Defendant). I wrote one or more expert reports; I was deposed; I testified at Phase 1 of trial (jury trial) and I testified at Phase 2 of trial (bench trial).

2014 ***Case***: LEDup Company versus Nicolas Holiday Company.
Nature: Patent infringement.
Venue: U.S. District Court for the Central District of California.
Law firm: Pendleton, Wilson, Hennessey, and Crow PC, Denver, Colorado.
Role: I served as technical expert witness on behalf of LEDup (Plaintiff). I wrote one or more expert reports.

2014 ***Case***: Nichia Corporation versus Everlight Electronics Co. LTD.
Nature: Patent infringement.
Venue: U.S. District Court for the Eastern District of Texas, Marshall Division.
Case number: 02:13-cv-702-JRG (E.D. Texas).
Law firm: Rothwell, Figg, Ernst & Manbeck PC, Washington DC.
Role: I served as technical expert witness on behalf of Nichia (Plaintiff). I wrote one or more expert reports; I was deposed; I testified at trial (bench trial).

2015 ***Case***: Cree Company versus Unity Opto, Unity Microelectronics, and Feit Electric Company
Nature: Patent infringement.
Venue: U.S. International Trade Commission (ITC), Washington DC.
Law firm: Alston & Bird LLP, Silicon Valley, East Palo Alto, California.
Role: I served as expert witness on behalf of Unity Opto Technology *et al*. (Defendants). I wrote one or more expert reports; I was deposed; I testified at trial (ITC Hearing).

2015 ***Case***: Honeywell International Inc. versus Cree Inc.
Nature: Inter Partes Review (IPR).
Venue: USPTO Patent Trial and Appeal Board.
Law firm: Arnold & Porter LLP, San Francisco, California.
Role: I served as expert witness on behalf of Honeywell International Inc. (Plaintiff). I wrote one or more expert reports.

2015 ***Case***: Honeywell International Inc. versus Cree Inc.
Nature: Patent infringement.
Venue: U.S. District Court for the District of New Jersey.
Law firm: Arnold & Porter LLP, San Francisco, California.
Role: I served as expert witness on behalf of Honeywell International Inc. (Plaintiff).

2015 ***Case***: Cree Inc. versus Kingbright Electronic Co. LTD and SunLED Corporation.
Nature: Patent infringement.
Venue: U.S. District Court for the Western District of Wisconsin.
Law firm: Hansen Reynolds Dickinson Crueger LLC, Milwaukee, Wisconsin.
Role: I served as technical expert witness on behalf of Kingbright and SunLED (Defendants). I wrote one or more expert reports; I was deposed.

2016 ***Case***: Acuity Brands Lighting Inc. versus Lynk Labs Inc.
Nature: Inter Partes Review (IPR).
Venue: USPTO Patent Trial and Appeal Board.
Law firm: Haynes Boone LLP, Chicago, Illinois.
Role: I served as technical expert witness on behalf of Lynk Labs (Plaintiff). I wrote one or more expert reports.

2016 ***Case***: Godo Kaisha IP Bridge 1 Company versus Broadcom Company and others.
Nature: Patent infringement.
Venue: U.S. District Court for the Eastern District of Texas, Marshall Division.
Law firm: Ropes and Gray LLP, New York City, New York.
Role: I served as technical expert witness on behalf of IP Bridge 1 (Plaintiff). I wrote one or more expert reports; I was deposed.

2016 ***Case***: TSMC Company versus Godo Kaisha IP Bridge 1 Company.
Nature: Inter Partes Review (IPR).
Venue: USPTO Patent Trial and Appeal Board.
Law firm: Greenblum & Bernstein, P.L.C., Reston, Virginia.
Role: I served as technical expert witness on behalf of IP Bridge (Patent Owner). I wrote one or more expert reports; I was deposed.

2017 ***Case***: Harvard University versus Micron Technology Company.
Nature: Patent infringement.
Venue: U.S. District Court for MA, Boston; U.S. District Court for Delaware, Wilmington.
Law firm: Weil Gotshal & Manges LLP, Redwood Shores, California.
Role: I served as technical expert witness on behalf of Micron Technology Company (Defendant). I wrote one or more expert reports; I was deposed.

2017 ***Case***: Seoul Viosys Company versus P3 Company.
Nature: Patent infringement.
Venue: U.S. District Court, Southern District of New York, New York City.
Law firm: Holland & Knight LLP, New York City, New York.
Role: I served as technical expert witness on behalf of Seoul Viosys (Plaintiff). I wrote one or more expert reports.

2017 ***Case***: Nitride Semiconductor Company versus Rayvio Company.
Nature: Patent infringement.
Venue: US District Court for the Northern District of California.
Law firm: Dentons LLP, Palo Alto, California.
Role: I served as technical expert witness on behalf of Rayvio (Defendant).

2018 ***Case***: CRX Tech LLC versus Samsung Electronics Co. LTD.
Nature: Patent infringement.
Venue: U.S. District Court for the Eastern District of Texas, Marshall Division.
Law firm: Arnold & Porter LLP, Los Angeles, California.
Role: I served as technical expert witness on behalf of Samsung (Defendant).

2018 ***Case***: Macom Technology Solutions Holdings Inc. versus Infineon Technologies AG.
Nature: Patent infringement.
Venue: U.S. District Court Central District of California Western Division, Los Angeles.
Law firm: Perkins Coie LLP, Denver, Colorado.

Role: I served as technical expert witness on behalf of Macom (Plaintiff). I wrote one or more expert reports; I was deposed.

2018 ***Case***: Vizio Inc. versus Nichia Corporation.
Nature: Inter Partes Review (IPR).
Venue: USPTO Patent Trial and Appeal Board.
Case number: Case No. IPR-2017-01608 and IPR-2017-01623 (PTAB).
Law firm: Rothwell, Figg, Ernst & Manbeck, P.C., Washington DC.
Role: I served as technical expert witness on behalf of Nichia Corporation (Patent Owner). I wrote one or more expert declarations.

2018 ***Case***: Lowe's Companies Inc. versus Nichia Corporation.
Nature: Inter Partes Review (IPR).
Venue: USPTO Patent Trial and Appeal Board.
Case number: Case No. IPR2017-02014 (PTAB).
Law firm: Rothwell, Figg, Ernst & Manbeck, P.C., Washington DC.
Role: I served as technical expert witness on behalf of Nichia Corporation (Patent Owner). I wrote one or more expert declarations.

2018 ***Case***: Ultravision Technologies LLC versus Prismaflex USA Inc.
Nature: Patent infringement.
Venue: US International Trade Commission (ITC), Washington DC.
Case number: Investigation No. 337-TA-1114 (ITC)
Law firm: Womble Bond Dickinson LLP, Winston-Salem, NC
Role: I served as technical expert witness on behalf of Prismaflex USA (Defendant). I wrote one or more expert reports. I was deposed.

2019 ***Case***: Carl Zeiss AG versus Nikon USA Inc.
Nature: Patent infringement.
Venue: US International Trade Commission (ITC), Washington DC.
Case number: Investigation No. 337-TA-1129 (US ITC)
Law firm: Morrison & Foerster LLP, Los Angeles CA.
Role: I served as technical expert witness on behalf of Nikon USA (Defendant). I wrote one or more expert reports. I was deposed.

2019 ***Case***: ASM IP Holding B.V. versus Hitachi Kokusai Electric Inc.
Nature: Arbitration related to IP licensing dispute.
Venue: ICDR (International Center for Dispute Resolution), Palo Alto CA.
Case number: Case No. ICDR 01-17-0005-1963 (Palo Alto CA)
Law firm: Quinn Emanuel Urquhart & Sullivan LLP, San Francisco CA.
Role: I served as technical expert witness on behalf of ASM IP Holding B.V. (Complainant). I authored multiple witness statements. I testified at the Arbitration Hearing.

2019 ***Case***: Power Integrations Inc. versus C. W. Park.
Nature: Breach of employment contract.
Venue: US District Court, Northern District of California, San Jose Division.
Case number: 5:16-cv-02366-BLF (Northern District of California)
Law firm: Miclean Gleason LLP, San Mateo CA.
Role: I served as technical expert witness on behalf of Power Integrations Inc. (Complainant). I performed analyses relating to switched-mode power supplies (SMPS) including flyback transformers. The matter ended in settlement.

2019 ***Case***: Omni MedSci Inc. versus Apple Inc.
Nature: Patent infringement.
Venue: US District Court, Eastern District of Texas, Marshall Division.
Case number: Civil Action No. 2:18-cv-134-RWS (E.D. Texas)
Law firm: Sidley Austin LLP, Washington DC.
Role: I served as technical expert witness on behalf of Apple Inc. (Defendant). I performed a non-infringement analysis relating to the heart rate monitor of the Apple Watch, authored an expert report, and testified at a deposition.

2019 ***Case***: Fluxwerx Illumination Inc., versus OKT Lighting USA LLC
Nature: Design patent infringement.
Venue: US District Court, Southern District of Texas, Houston Division.
Case number: Civil Action No. 4:19-CV-01113 (S.D. Texas)
Law firm: Burns & Levinson LLP, Boston MA.
Role: I served as technical expert witness on behalf of Fluxwerx Illumination, Inc. (Plaintiff). I performed an infringement analysis.

2020 ***Case***: Lighting Science Group Corporation versus Nichia Corporation and others
Nature: Patent infringement.
Venue: US ITC, Office for Unfair Import Investigations, Washington DC
Case number: Investigation No. 337-TA-1168
Law firm: Shearman & Sterling LLP, New York, NY.
Role: I served as technical expert witness on behalf of Nichia Corporation. I performed a non-infringement analysis, authored an expert report, was deposed, and testified at the ITC hearing as key technical witness on behalf of Nichia and Respondents (6 hours live testimony).

2020 ***Case***: Regents of the University of California versus Amazon, Walmart, Ikea, Target, and others
Nature: Patent infringement.
Venue: US ITC, Office for Unfair Import Investigations, Washington DC
Case number: Investigation No. 337-TA-1172
Law firm: Nixon Peabody LLP, Los Angeles CA.
Role: I served as technical expert witness on behalf of the Regents of the University of California. I performed an infringement analysis, authored an expert report, and was deposed.

2020 ***Case***: Samsung Electronics Company versus Acorn Technologies Company.
Nature: USPTO Inter Partes Review.
Venue: USPTO, Patent Trial and Appeal Board, Alexandria VA.
Case numbers: IPR-2020-01183 ('261), IPR-2020-01182 ('423), IPR-2020-01204 ('336), IPR-2020-01264 ('336), IPR-2020-01205 (‘167), IPR-2020-01241 (‘167), IPR-2020-01206 (‘691), IPR-2020-01279 (‘691), IPR-2020-01207 ('395), and IPR-2020-01282 ('395)
Law firm: Desmarais LLP, New York NY.
Role: I served as technical expert witness on behalf of Samsung Electronics Company. I authored several expert declarations and was deposed multiple times.

2020 ***Case***: Satco Company versus The Regents of the University of California.
Nature: USPTO Inter Partes Review.
Venue: USPTO, Patent Trial and Appeal Board, Alexandria VA.
Case number: IPR-2020-00579, IPR-2020-00695, IPR-2020-00780, and IPR-2020-00813.
Law firm: Nixon Peabody LLP, Los Angeles CA.
Role: I served as technical expert witness on behalf of The Regents of the University of California. I authored several expert declarations and was deposed.

2020 ***Case***: Godo Kaisha IP Bridge 1 Company versus Micron Technology Company.
Nature: Patent infringement.
Venue: US District Court for the Western District of Texas, Waco Division.
Case number: C.A. No. 6:20-cv-178-ADA.
Law firm: Orrick Herrington & Sutcliffe LLP, Menlo Park CA.
Role: I served as technical expert witness on behalf of Micron Technology Company. I authored multiple expert reports and was deposed.

2020 ***Case***: Nichia Company versus Healthe Company and Lighting Science Group Company.
Nature: Patent infringement.
Venue: US District Court for the Middle District of Florida, Orlando Division.
Case number: 6:19-cv-1332-RBD-EJK and 6:19-cv-1333-RBD-EJK.
Law firm: Rothwell, Figg, Ernst & Manbeck, PC, Washington DC.
Role: I served as technical expert witness on behalf of Nichia Company. I authored one or more expert reports.

2020 ***Case***: Semiconductor Energy Laboratory (SEL) Co., Ltd. versus BOE Technology Group Co., Ltd.
Nature: Patent infringement.
Venue: US District Court for the Northern District of California.
Case number: 3:20-cv-04297-EMC, N.D. Cal.
Law firm: Fish and Richardson, P.C., Redwood City CA.
Role: I served as technical expert witness on behalf of SEL.

2021 ***Case***: The University of California versus General Electric, Ikea, Home Depot and others
Nature: Patent infringement.
Venue: US ITC, Office for Unfair Import Investigations, Washington DC
Case number: Investigation No. 337-TA-1220
Law firm: Nixon Peabody LLP, Los Angeles CA.
Role: I served as technical expert witness on behalf of the University of California. I performed multiple analyses, authored several expert reports, was deposed multiple times, and testified at trial.

2021 ***Case***: Tianma Microelectronics Co., Ltd. versus Japan Display Inc. (JDI)
Nature: USPTO Inter Partes Review.
Venue: USPTO, Patent Trial and Appeal Board, Alexandria VA
Case numbers: IPR-2021-01029, IPR-2021-01057 and IPR-2021-01058
Law firm: Finnegan, Henderson, Farabow, Garrett & Dunner, LLP, Washington DC.
Role: I served as technical expert witness on behalf of Tianma. I performed multiple analyses and authored several declarations.

2021 ***Case***: Japan Display Inc. (JDI) versus Tianma Microelectronics Co., Ltd.
Nature: Patent infringement.
Venue: US District Court for the Eastern District of Texas, Marshall Division.
Case numbers: Civil Action No. 2:20-cv-00283-JRG; 2:20-cv-00284-JRG; and 2:20-cv-00285-JRG
Law firm: Finnegan, Henderson, Farabow, Garrett & Dunner, LLP, Washington DC.
Role: I served as technical expert witness on behalf of Tianma. I performed multiple analyses, authored several expert reports, and was deposed multiple times.

2022 ***Case***: Satco Products Inc. versus The Regents of the University of California.
Nature: USPTO Inter Partes Review.
Venue: USPTO, Patent Trial and Appeal Board, Alexandria VA.
Case number: IPR-2021-00662.
Law firm: Nixon Peabody LLP, Los Angeles CA.

Role: I served as technical expert witness on behalf of The Regents of the University of California, authored one expert declaration, and was deposed.

2022 ***Case***: Samsung Electronics Co. Ltd. versus Bishop Display Tech LLC.
Nature: USPTO Inter Partes Review.
Venue: USPTO, Patent Trial and Appeal Board, Alexandria VA.
Case numbers: IPR-2022-00500 and IPR-2022-00502.
Law firm: Baker Botts LLP, New York City NY.
Role: I served as technical expert witness on behalf of Samsung Electronics and have authored two expert declarations.

2022 ***Case***: Semiconductor Energy Laboratory (SEL) Co. Ltd. versus TCL China Star Optoelectronics Technology Co., Ltd.
Nature: Patent infringement.
Venue: US District Court for the Central District of California, Southern Division.
Case number: 8:21−cv−00554−JAK−ADS.
Law firm: Fish and Richardson, P.C., Redwood City CA.
Role: I served as technical expert witness on behalf of SEL, authored two expert reports, and was deposed.

2022 ***Case***: Nvidia Corporation versus Ocean Semiconductors LLC.
Nature: USPTO Inter Partes Review.
Venue: USPTO, Patent Trial and Appeal Board, Alexandria VA.
Case number: IPR2022-01288.
Law firm: Sheppard Mullin LLP, Menlo Park CA.
Role: I served as technical expert witness on behalf of Nvidia and authored one expert declaration.

2022 ***Case***: Nicor, Inc. versus SourceBlue LLC and InfiniLux Corporation.
Nature: Patent infringement.
Venue: US District Court for the Central District of California.
Case number: 2:21-cv-05876-AB(PDx) (C.D. Cal.).
Law firm: Loza & Loza IP LLP, Upland CA.
Role: I served as technical expert witness on behalf of Nicor, Inc., authored three expert reports, and was deposed.

2023 ***Case***: Dr. Shimon Maimon versus Lockheed Martin Corporation.
Nature: Dispute relating to a License Agreement.
Venue: JAMS ADR (Alternative Dispute Resolution).
Case number: JAMS Ref. No. 1460005932.
Law firm: Finnegan, Henderson, Farabow, Garrett & Dunner, LLP, Washington DC.
Role: I served as technical expert witness on behalf of Lockheed Martin Corporation, authored three expert reports, was deposed, and testified at the Hearing.

2023 ***Case***: Samsung Electronics Co. Ltd. versus Daedalus Prime LLC.
Nature: USPTO Inter Partes Review.
Venue: USPTO, Patent Trial and Appeal Board, Alexandria VA.
Case number: IPR2023-00536 and IPR2023-00653.
Law firm: Fish & Richardson PC, Minneapolis MN.
Role: I served as technical expert witness on behalf of Samsung Electronics and authored two expert declarations.

2023 ***Case***: Seoul Semiconductor Co. Ltd., et al. versus GE Healthcare Inc.
Nature: Patent infringement.
Venue: United States District Court for the District of Delaware.
Case number: Civil Action No. 1:22-cv-01455.
Law firm: Shearman & Sterling LLP, New York, NY.
Role: I served as technical expert witness on behalf of GE Healthcare.

2023 ***Case***: Efficient Power Conversion Corp. versus Innoscience (Zhuhai) Technology Company.
Nature: Patent infringement.
Venue: US International Trade Commission (ITC), Washington DC.
Case number: Investigation No. 337-TA-1366.
Law firm: Blank Rome LLP, Washington DC
Role: I served as technical expert witness on behalf of EPC, authored multiple expert reports, was deposed, and testified at the ITC Hearing.

2023 ***Case***: Innoscience (Zhuhai) Technology Company versus Efficient Power Conversion Corp.
Nature: USPTO Inter Partes Review.
Venue: USPTO, Patent Trial and Appeal Board, Alexandria VA.
Case number: IPR2023-01381, IPR2023-01382, IPR2023-01383, and IPR2023-01384.
Law firm: Blank Rome LLP, Washington DC.
Role: I served as technical expert witness on behalf of Efficient Power Conversion Corp. and authored multiple expert declarations.

2023 ***Case***: Xu Peicheng (Hong Kong) Optoelectronic Technol. Co. versus SemiSilicon Technol. Corp.
Nature: USPTO Inter Partes Review.
Venue: USPTO, Patent Trial and Appeal Board, Alexandria VA.
Case number: IPR2024-00156 and IPR2024-00157 (US Patent 8,124,988 and US 8,884,546)
Law firm: Rimon Law PC, McLean VA.
Role: I served as technical expert witness on behalf of Xu Peicheng and authored two expert declarations.

2024 ***Case***: Seasonal Specialties, LLC versus LEDUP Manufacturing Group LTD.
Nature: Patent infringement.
Venue: US District Court, Central District of California, Western Division.
Case number: 2:23-cv-06318-SB-AS.
Law firm: Fairfield & Woods PC, Denver CO.
Role: I served as technical expert witness on behalf of LEDUP Manufacturing Group and composed multiple Invalidity Claim Charts.

2024 ***Case***: Wuxi Autowell Technology Co. Ltd. versus Teamtechnik Maschinen und Anlagen GmbH.
Nature: USPTO Inter Partes Review.
Venue: USPTO, Patent Trial and Appeal Board, Alexandria VA.
Case number: US patent numbers 8,247,681 and 8,253,009.
Law firm: Novick, Kim & Lee, PLLC, (NKL Law), Fairfax VA.
Role: I served as technical expert witness on behalf of Wuxi Autowell Technology and composed one expert declaration.

2024 ***Case***: Greenthread LLC versus Omnivision Technologies, Inc., and Texas Instruments, Inc.
Nature: Patent infringement.
Venue: US District Court, Eastern District of Texas, Marshall Division.
Case numbers: 2:23-cv-00212-JRG and 2:23-cv-00157-JRG.
Law firms: Benesch Friedlander Coplan & Aronoff LLP and Caldwell Cassady & Curry PC.
Role: I served as technical expert witness on behalf of Omnivision Technologies and Texas

Instruments, composed one expert declaration, and was deposed.

2024 ***Case***: Lian Li Industrial Co. Ltd. and CHEN, Chien-Hao versus Thermaltake Technology Co. Ltd.
Nature: Patent infringement.
Venue: US District Court, Central District of California.
Case numbers: 2:23-cv-07470.
Law firm: The Gikkas Law Firm, PC, Palo Alto CA
Role: I served as technical expert witness on behalf of Thermaltake Technology, composed one expert declaration, and was deposed.

2024 ***Case***: Pictive Displays International Ltd. versus Samsung Electronics Co. Ltd.
Nature: Patent infringement.
Venue: US District Court, Eastern District of Texas, Marshall Division.
Case numbers: 2:23-cv-00495-JRG.
Law firm: Quinn Eammanual Urquhart & Sullivan LLP, Seattle WA.
Role: I served as technical expert witness on behalf of Samsung Electronics Co., composed one expert declaration, and was deposed.

2024 ***Case***: Feit Electric Company versus Savant Technologies and additional parties
Nature: Patent infringement.
Venue: US District Court, Northern District of Ohio and additional venues.
Case numbers: 1:24-cv-473.
Law firm: Benesch, Friedlander, Coplan & Aronoff LLP, Chicago ILL.
Role: I served as technical expert witness on behalf of Feit Electric Company, composed one or more expert declarations, and was deposed.

2024 ***Case***: Savant Technologies LLC and LEDvance LLC versus Feit Electric Company.
Nature: USPTO Inter Partes Review.
Venue: USPTO, Patent Trial and Appeal Board, Alexandria VA.
Case number: US patent number 8,604,678. IPR2024-01357.
Law firm: Novick, Kim & Lee, PLLC, (NKL Law), Fairfax VA.
Role: I served as technical expert witness on behalf of Feit Electric Company and composed one expert declaration.

2024 ***Case***: 138 East LCD Advancements Ltd. versus BOE Technology Group Co., Ltd.
Nature: Patent infringement.
Venue: US District Court, Eastern District of Texas, Marshall Division.
Case numbers: 2:23-cv-515-JRG-RSP.
Law firm: Robins Kaplan LLP Law Firm, Minneapolis MN.
Role: I served as technical expert witness on behalf of 138 East LCD Advancements Ltd. and composed one or more expert declarations.

2024 ***Case***: BOE Technology Group Co., Ltd. versus 138 East LCD Advancements Ltd.
Nature: USPTO Inter Partes Review.
Venue: USPTO, Patent Trial and Appeal Board, Alexandria VA.
Case number: IPR2024-00973, IPR2024-00977, and IPR2024-00977.
Law firm: Robins Kaplan LLP Law Firm, Minneapolis MN.
Role: I served as technical expert witness on behalf of 138 East LCD Advancements Ltd. and composed multiple expert declarations.

2025 ***Case***: YMTC (Yangtze Memory Technologies Company, Ltd.) versus Micron Technology Inc.
Nature: Patent infringement.
Venue: US District Court, Northern District of California
Case number: 3:23-cv-05792-RFL.

Law firm: Orrick, Herrington & Sutcliffe LLP.
Role: I served as technical expert witness on behalf of Micron Technology Inc. and composed one expert declaration.

United States Patents

1. A. Fischer, Y. Horikoshi, K. Ploog, and E. F. Schubert "Semiconductor devices with at least one monoatomic layer of doping atoms" European Patent No. 0183 146 A2; US Patent No. 4,882,609; issued on November 15 (1985)

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Patent Licensing: Several patents listed above have been licensed to companies, including the Luminus Devices Company, Samsung Company, Epistar Company, Cree Company, Osram Company, and Lumileds Company.

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