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Hendrix et al.

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(54) **OPTICAL FILTER AND SENSOR SYSTEM**

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(73) Assignee: **VIAVI Solutions Inc.**, San Jose, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 166 days.

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(51) **Int. Cl.**

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(52) **U.S. Cl.**

CPC ***G02B 5/281*** (2013.01); ***C23C 14/08*** (2013.01); ***C23C 14/185*** (2013.01);

(Continued)

(58) **Field of Classification Search**

CPC G02B 5/281; G02B 1/115; G02B 1/11; G02B 5/207; G02B 5/285; C23C 14/5806;

(Continued)

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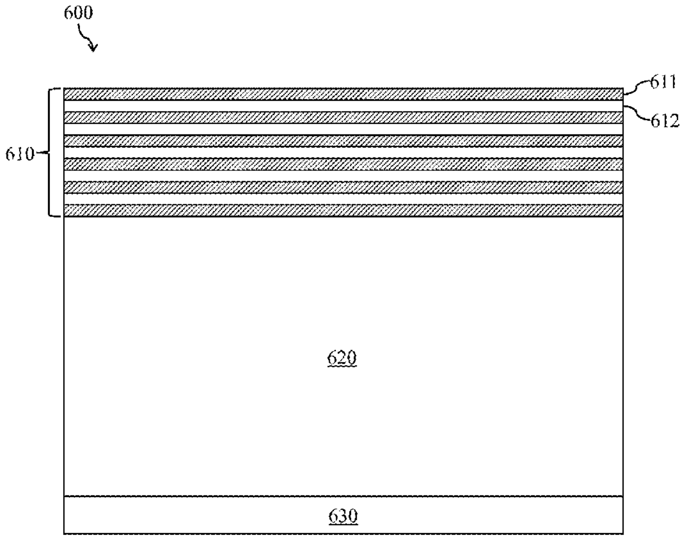
(57) **ABSTRACT**

An optical filter having a passband at least partially overlapping with a wavelength range of 800 nm to 1100 nm is provided. The optical filter includes a filter stack formed of hydrogenated silicon layers and lower-refractive index layers stacked in alternation. The hydrogenated silicon layers each have a refractive index of greater than 3 over the wavelength range of 800 nm to 1100 nm and an extinction coefficient of less than 0.0005 over the wavelength range of 800 nm to 1100 nm.

19 Claims, 14 Drawing Sheets



Related U.S. Application Data

continuation of application No. 15/099,180, filed on Apr. 14, 2016, now Pat. No. 9,945,995, which is a continuation of application No. 13/943,596, filed on Jul. 16, 2013, now Pat. No. 9,354,369.

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(58) **Field of Classification Search**
CPC C23C 14/08; C23C 14/548; C23C 14/185; H04N 13/254; H04N 5/33; G06K 9/00335; G01J 5/0862
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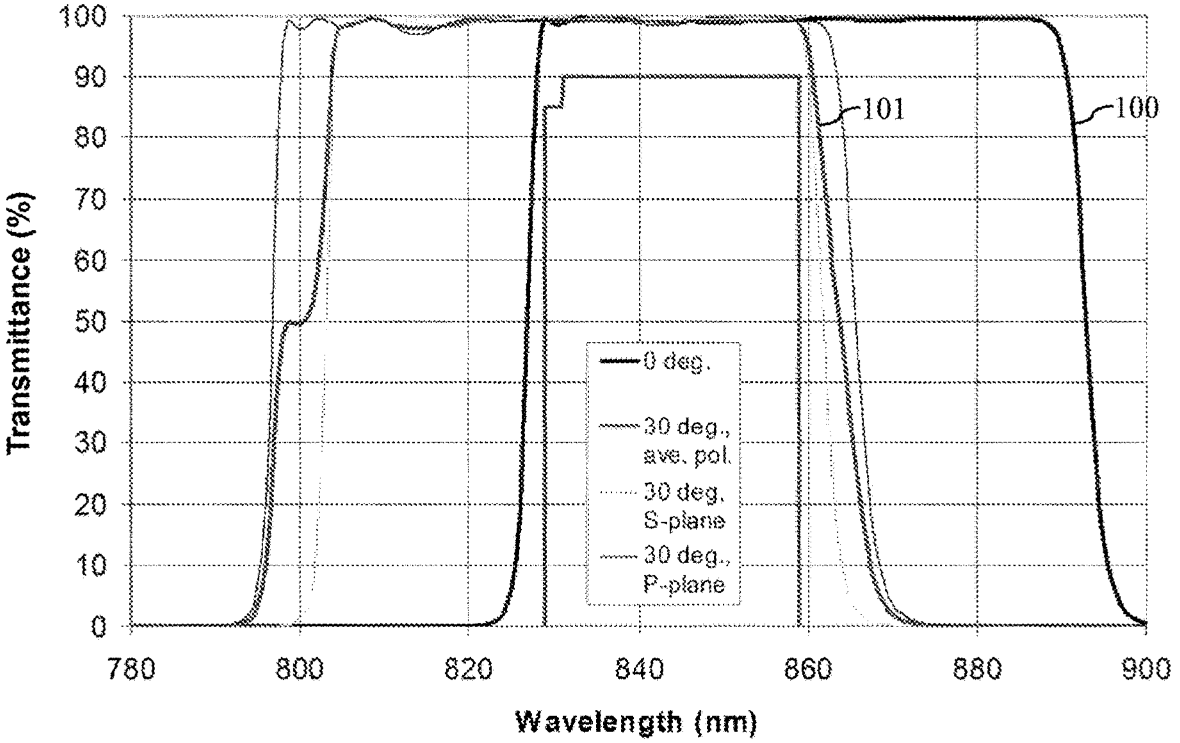


FIG. 1
PRIOR ART

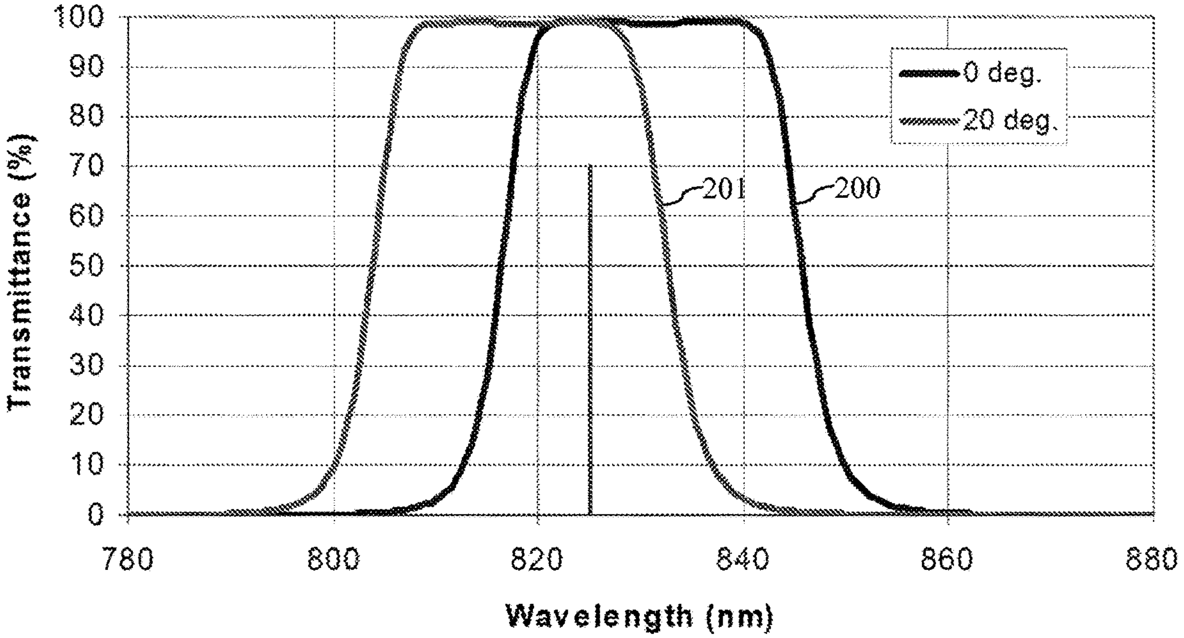


FIG. 2
PRIOR ART

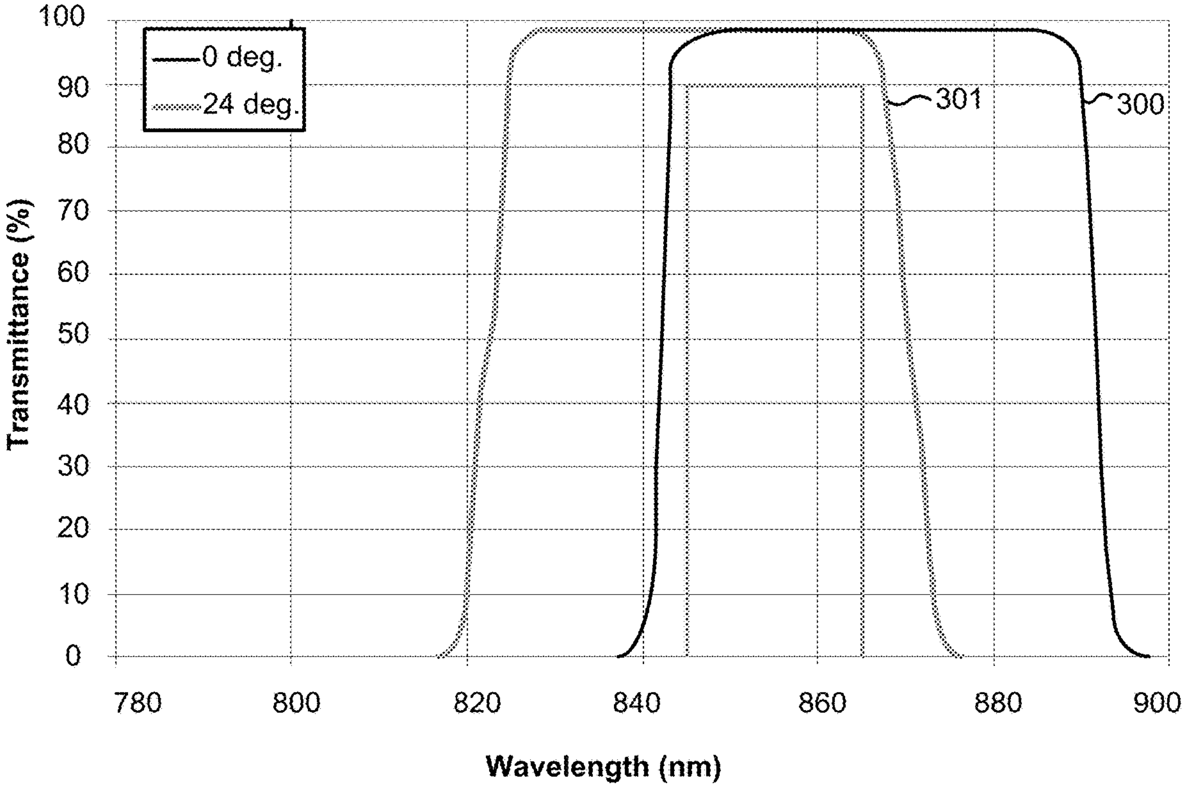


FIG. 3
Prior Art

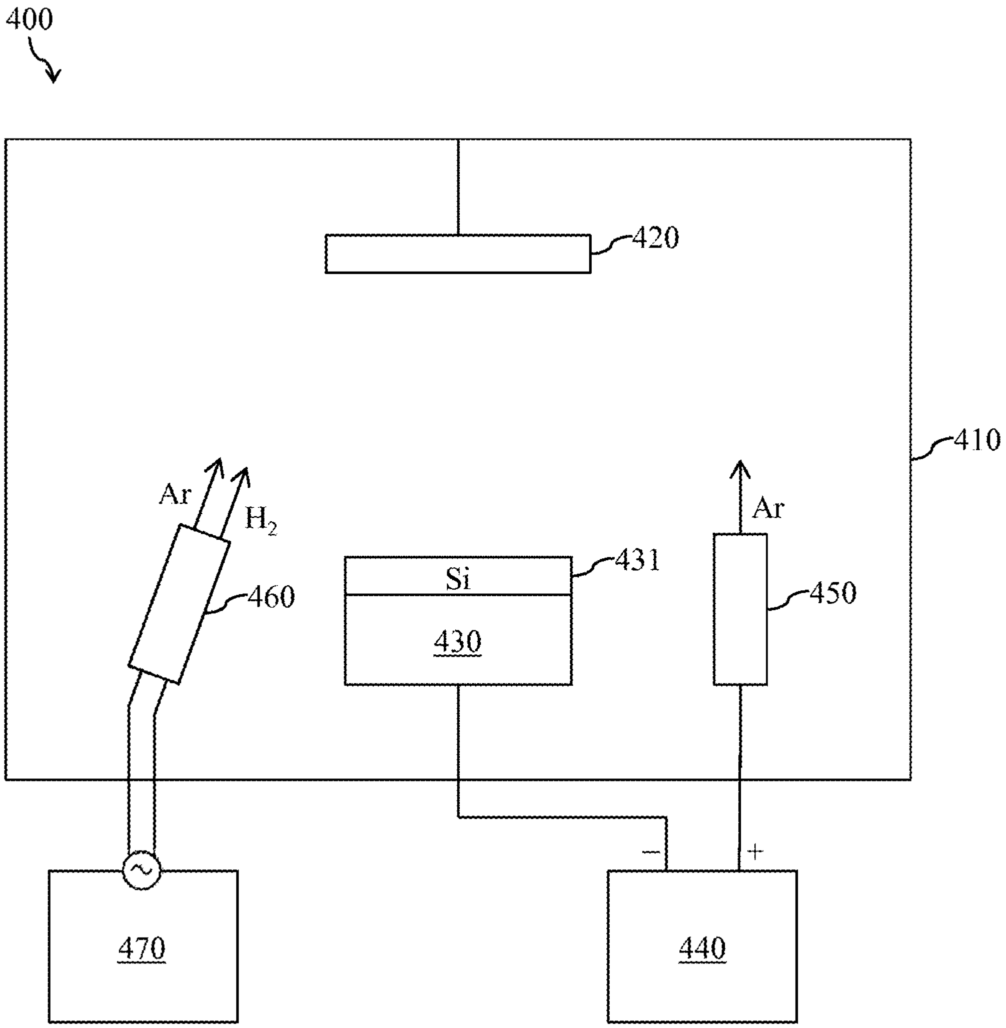


FIG. 4

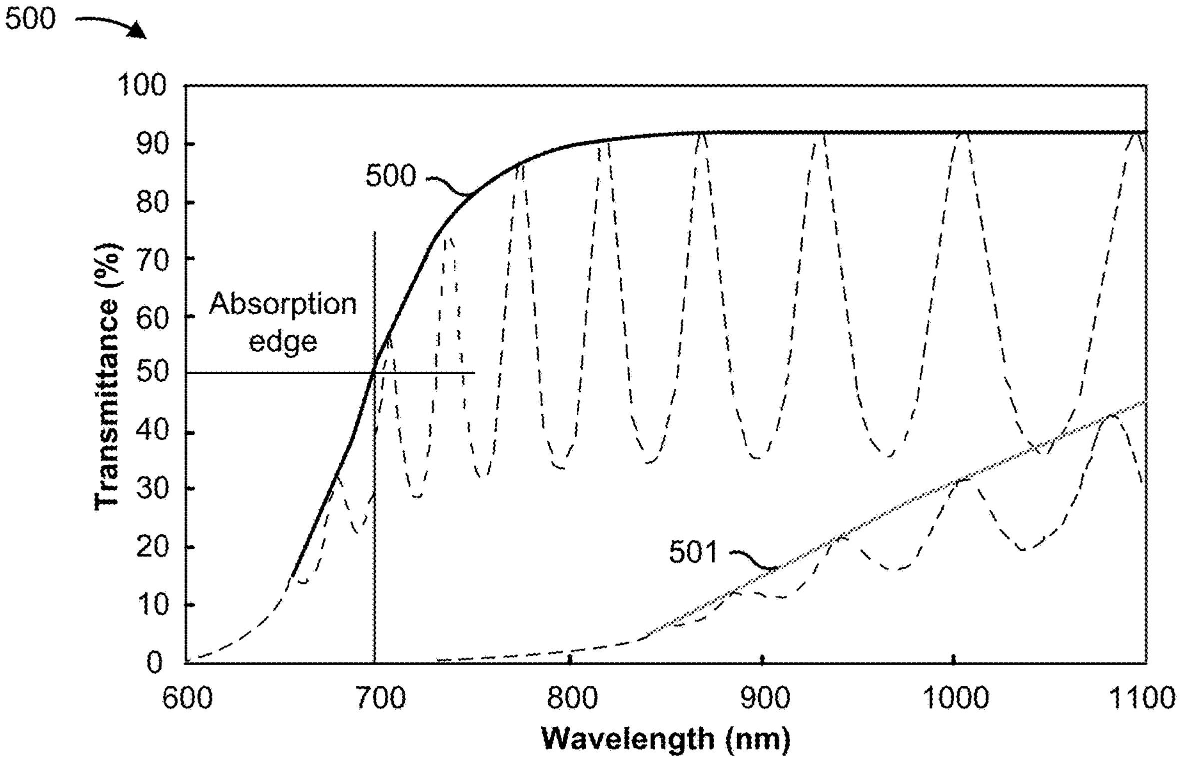

500
100
90
80
70
60
50
40
30
20
10
0
Transmittance (%)
500
Absorption edge
501
600
700
800
900
1000
1100
Wavelength (nm)

FIG. 5A

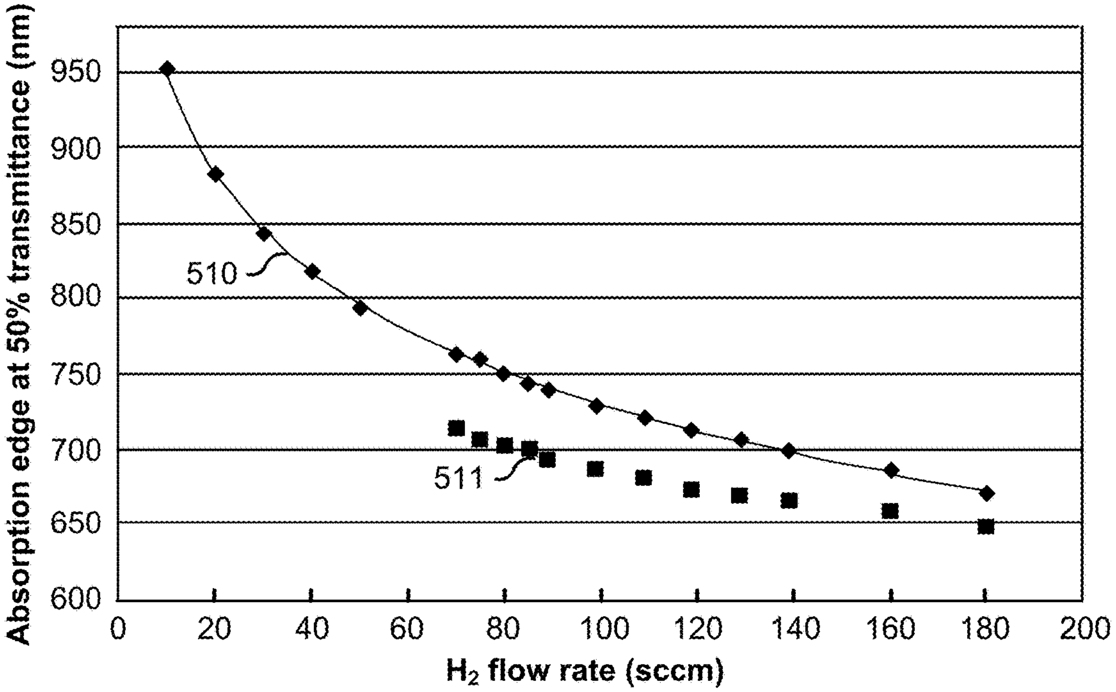

950
900
850
800
750
700
650
600
Absorption edge at 50% transmittance (nm)
510
511
0
20
40
60
80
100
120
140
160
180
200
H_2 flow rate (sccm)

FIG. 5B

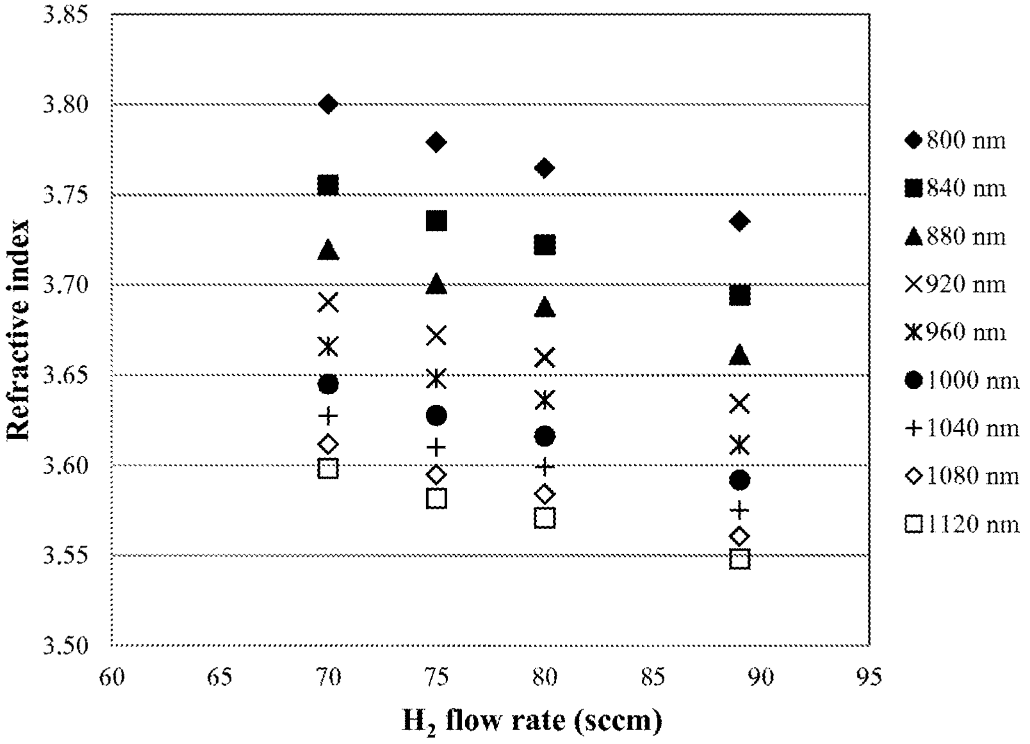

3.85
3.80
3.75
3.70
3.65
3.60
3.55
3.50
Refractive index
60
65
70
75
80
85
90
95
H_2 flow rate (sccm)
◆800 nm
■840 nm
▲880 nm
×920 nm
✱960 nm
●1000 nm
+1040 nm
◇1080 nm
□1120 nm

FIG. 5C

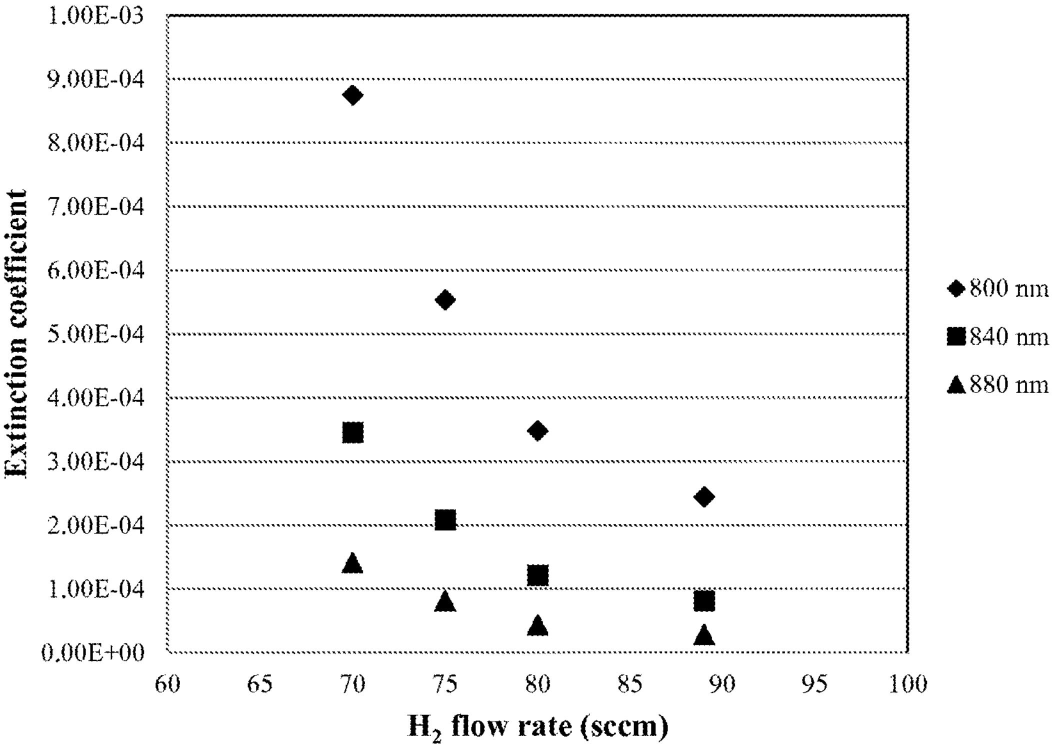

1.00E-03
9.00E-04
8.00E-04
7.00E-04
6.00E-04
5.00E-04
4.00E-04
3.00E-04
2.00E-04
1.00E-04
0.00E+00
Extinction coefficient
60
65
70
75
80
85
90
95
100
H_2 flow rate (sccm)
◆800 nm
■840 nm
▲880 nm

FIG. 5D

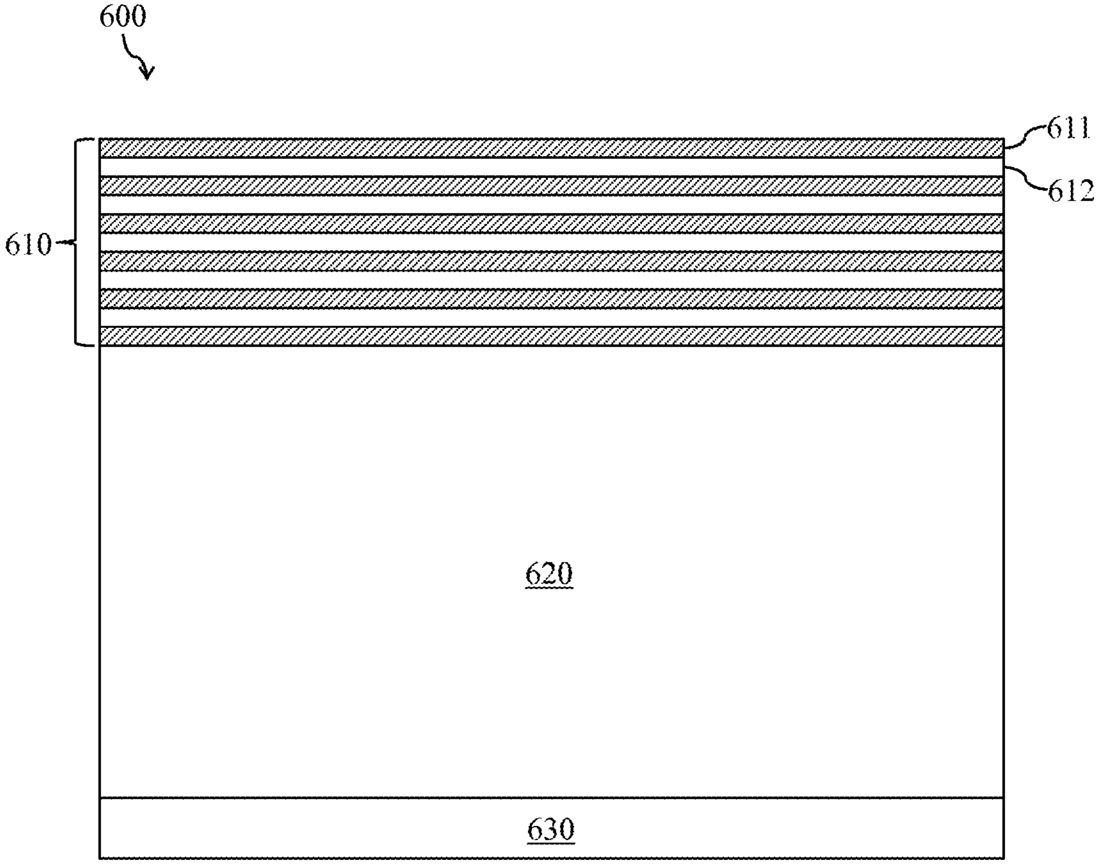


FIG. 6

Comparison of First Conventional Optical Filter and First Exemplary Optical Filter		
Property	First Conventional Optical Filter	First Exemplary Optical Filter
FWHM (nm)	66.0	46.5
Center-wavelength shift, 0° to 30° (nm)	−29.1	−12.2
Background transmittance for 2856 K blackbody (%)	14.8	9.75
Total coating thickness (nm)	24432	5688

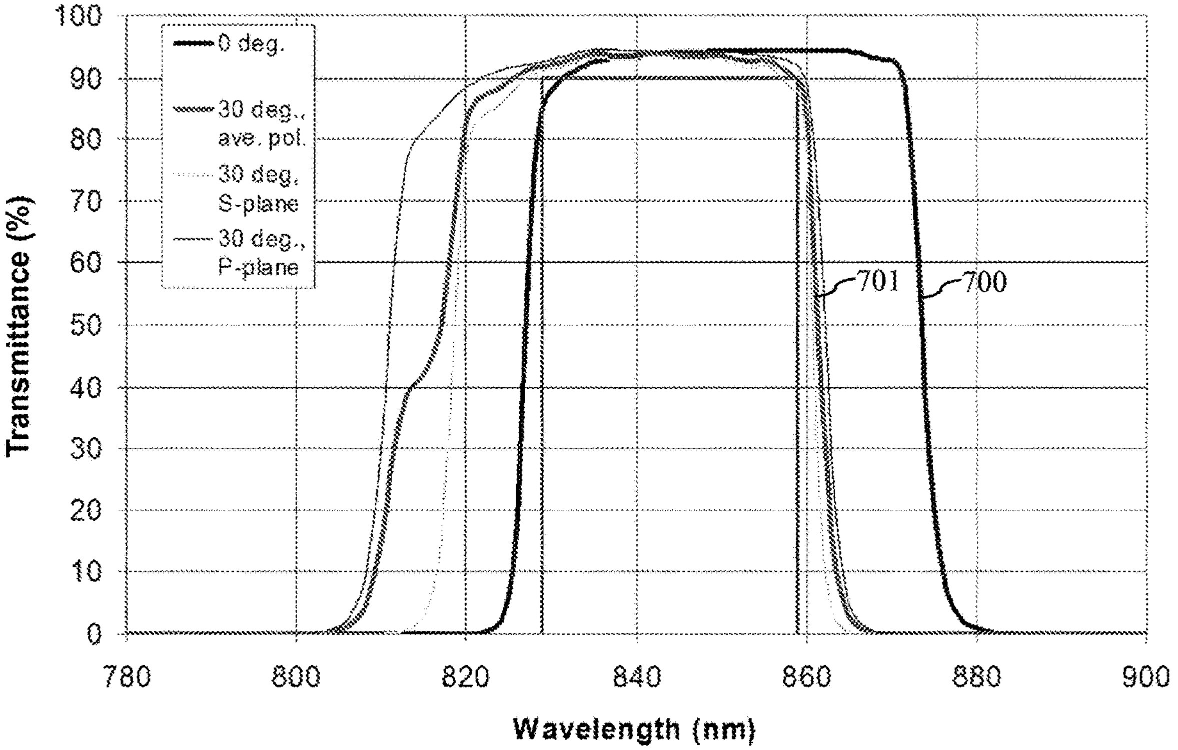
FIG. 7A

AR Coating of First Exemplary Optical Filter		
Layer No.	Material	Thickness (nm)
1	SiO_2	153.5852
2	Ta_2O_5	32.39649
3	SiO_2	47.88567
4	Ta_2O_5	112.6954
5	SiO_2	146.4009

FIG. 7B

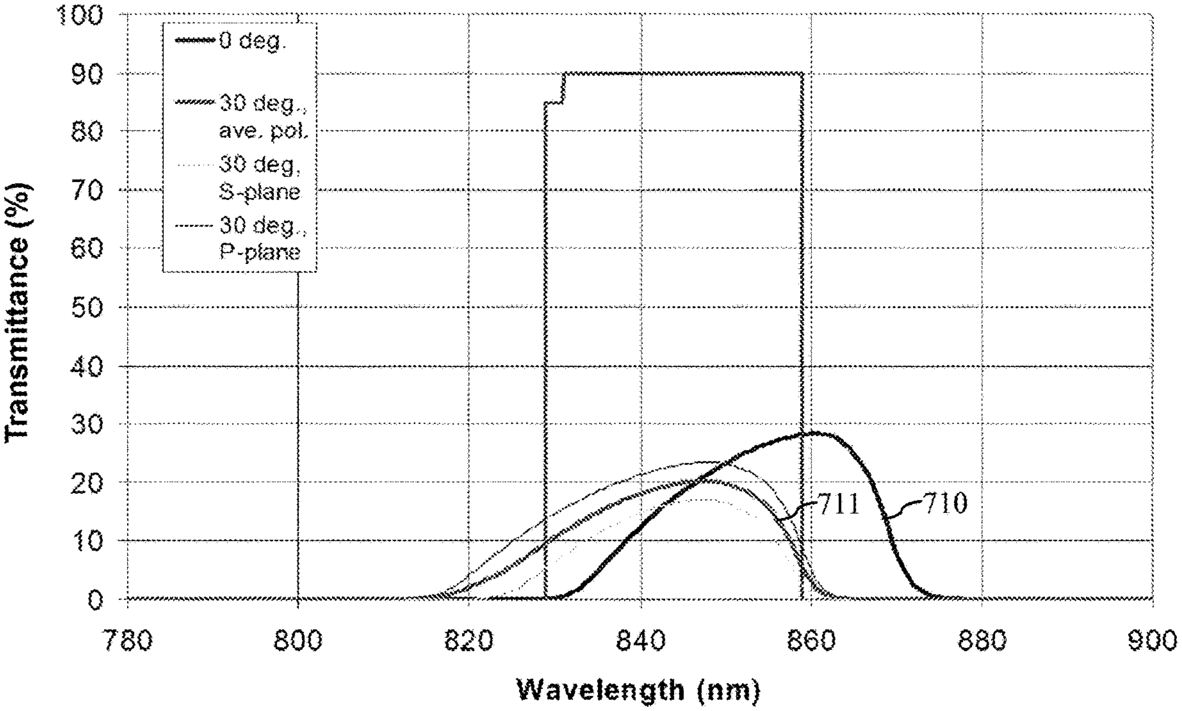
Filter Stack of First Exemplary Optical Filter					
Layer No.	Material	Thickness (nm)	Layer No.	Material	Thickness (nm)
1	Si:H	12.06225	25	Si:H	123.9279
2	SiO_2	207.0239	26	SiO_2	73.3697
3	Si:H	112.2893	27	Si:H	92.284
4	SiO_2	131.3289	28	SiO_2	93.71968
5	Si:H	58.57214	29	Si:H	57.99244
6	SiO_2	123.472	30	SiO_2	129.6102
7	Si:H	121.8488	31	Si:H	118.8611
8	SiO_2	62.37868	32	SiO_2	121.0311
9	Si:H	94.08999	33	Si:H	58.78395
10	SiO_2	91.40882	34	SiO_2	126.8949
11	Si:H	68.58871	35	Si:H	27.06202
12	SiO_2	97.34483	36	SiO_2	265.4308
13	Si:H	126.2579	37	Si:H	107.9248
14	SiO_2	65.22393	38	SiO_2	103.3531
15	Si:H	87.89165	39	Si:H	33.0597
16	SiO_2	95.32283	40	SiO_2	225.0774
17	Si:H	68.92315	41	Si:H	32.91478
18	SiO_2	96.5938	42	SiO_2	284.8275
19	Si:H	126.1687	43	Si:H	90.36095
20	SiO_2	66.16271	44	SiO_2	79.30571
21	Si:H	88.58283	45	Si:H	55.39493
22	SiO_2	96.5938	46	SiO_2	247.4205
23	Si:H	63.19303	47	Si:H	95.3999
24	SiO_2	103.7141	48	SiO_2	285.9541

FIG. 7C



0 deg.
30 deg., ave. pol.
30 deg, S-plane
30 deg., P-plane
Transmittance (%)
100
90
80
70
60
50
40
30
20
10
0
780
800
820
840
860
880
900
Wavelength (nm)
701
700

FIG. 7D



0 deg.
30 deg., ave. pol.
30 deg, S-plane
30 deg., P-plane
Transmittance (%)
100
90
80
70
60
50
40
30
20
10
0
780
800
820
840
860
880
900
Wavelength (nm)
711
710

FIG. 7E

Comparison of Second Conventional Optical Filter and Second Exemplary Optical Filter		
Property	Second Conventional Optical Filter	Second Exemplary Optical Filter
FWHM (nm)	29.1	29.6
Center-wavelength shift, 0° to 20° (nm)	−12.7	−7.8
Background transmittance for 2856 K blackbody (%)	5.84	5.54
Total coating thickness (nm)	13780	3312

FIG. 8A

Filter Stack of Second Exemplary Optical Filter					
Layer No.	Material	Thickness (nm)	Layer No.	Material	Thickness (nm)
1	SiO_2	169.8593	14	Si:H	42.95783
2	Si:H	25.36196	15	SiO_2	151.3625
3	SiO_2	169.8593	16	Si:H	108.6165
4	Si:H	108.6165	17	SiO_2	141.1964
5	SiO_2	141.1964	18	Si:H	54.30826
6	Si:H	54.30826	19	SiO_2	173.3892
7	SiO_2	173.3892	20	Si:H	22.70085
8	Si:H	22.70085	21	SiO_2	173.3892
9	SiO_2	173.3892	22	Si:H	108.6165
10	Si:H	108.6165	23	SiO_2	155.1748
11	SiO_2	141.1964	24	Si:H	38.8304
12	Si:H	54.30826	25	SiO_2	155.1748
13	SiO_2	151.3625			

FIG. 8B

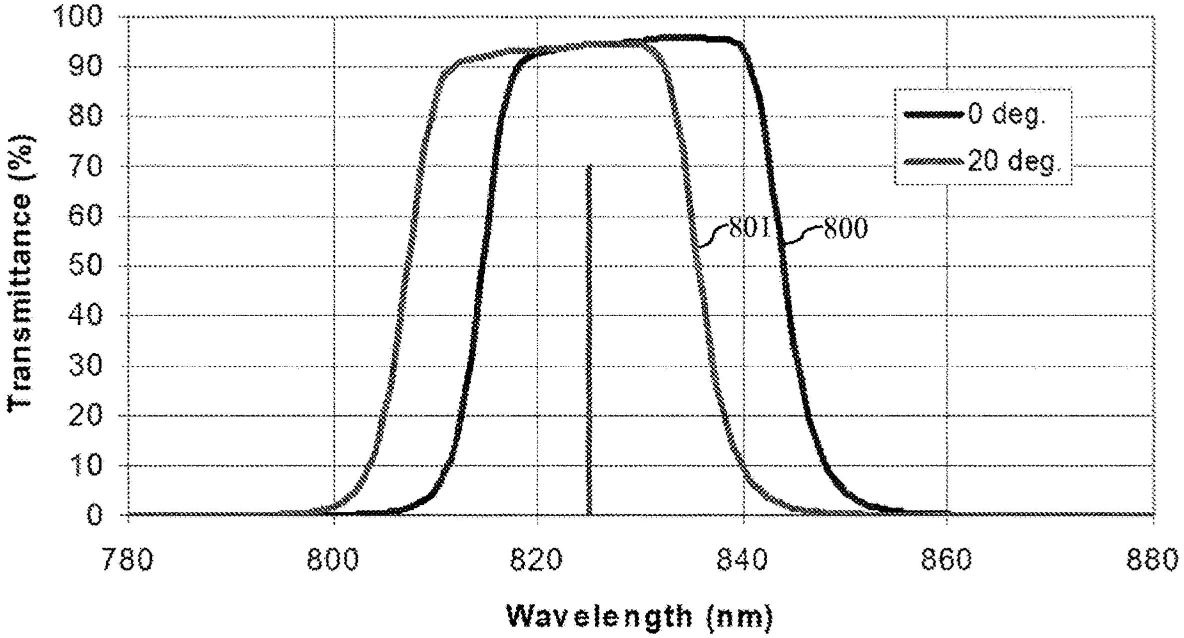

100
90
80
70
60
50
40
30
20
10
0
Transmittance (%)
780
800
820
840
860
880
Wavelength (nm)
0 deg.
20 deg.
801
800

FIG. 8C

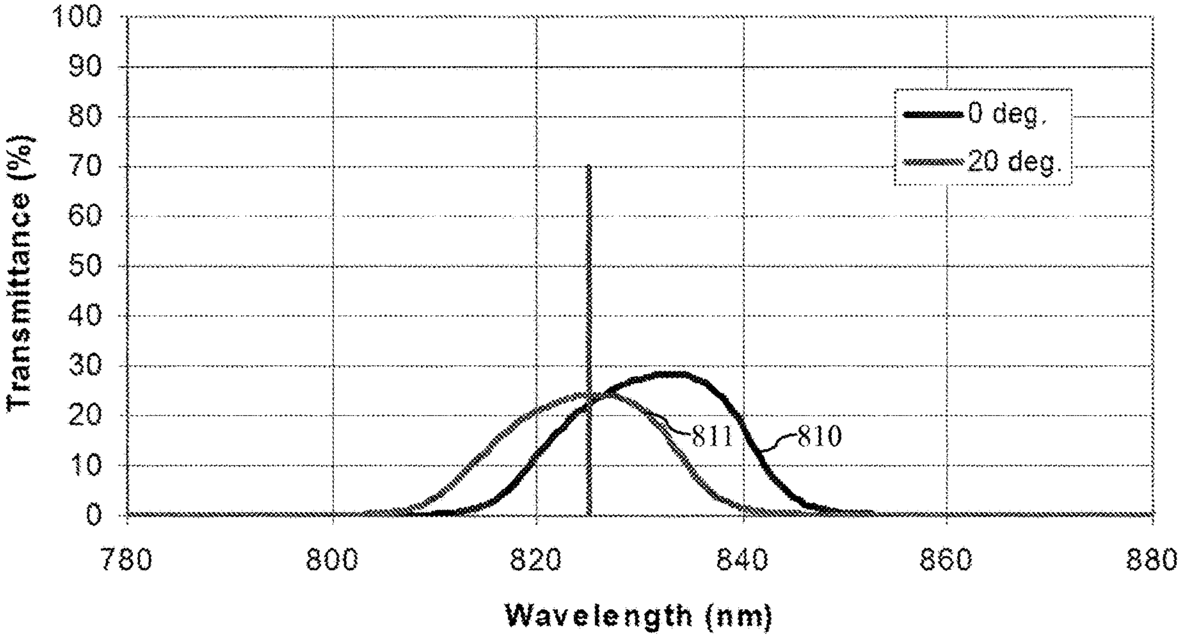

100
90
80
70
60
50
40
30
20
10
0
Transmittance (%)
780
800
820
840
860
880
Wavelength (nm)
0 deg.
20 deg.
811
810

FIG. 8D

Filter Stack of Third Exemplary Optical Filter

Layer No.	Material	Thickness (nm)	Layer No.	Material	Thickness (nm)
1	Si:H	48.99656	16	SiO_2	144.9036
2	SiO_2	27.72806	17	Si:H	172.5048
3	Si:H	261.865	18	SiO_2	144.8237
4	SiO_2	175.7108	19	Si:H	229.229
5	Si:H	67.55759	20	SiO_2	131.8658
6	SiO_2	48.09467	21	Si:H	77.24942
7	Si:H	245.3538	22	SiO_2	139.1643
8	SiO_2	157.5898	23	Si:H	225.9625
9	Si:H	53.78669	24	SiO_2	115.736
10	SiO_2	117.5423	25	Si:H	97.86642
11	Si:H	234.1488	26	SiO_2	170.7001
12	SiO_2	146.2907	27	Si:H	232.4637
13	Si:H	172.8534	28	SiO_2	168.9233
14	SiO_2	143.1595	29	Si:H	118.3322
15	Si:H	230.0482			

FIG. 9A

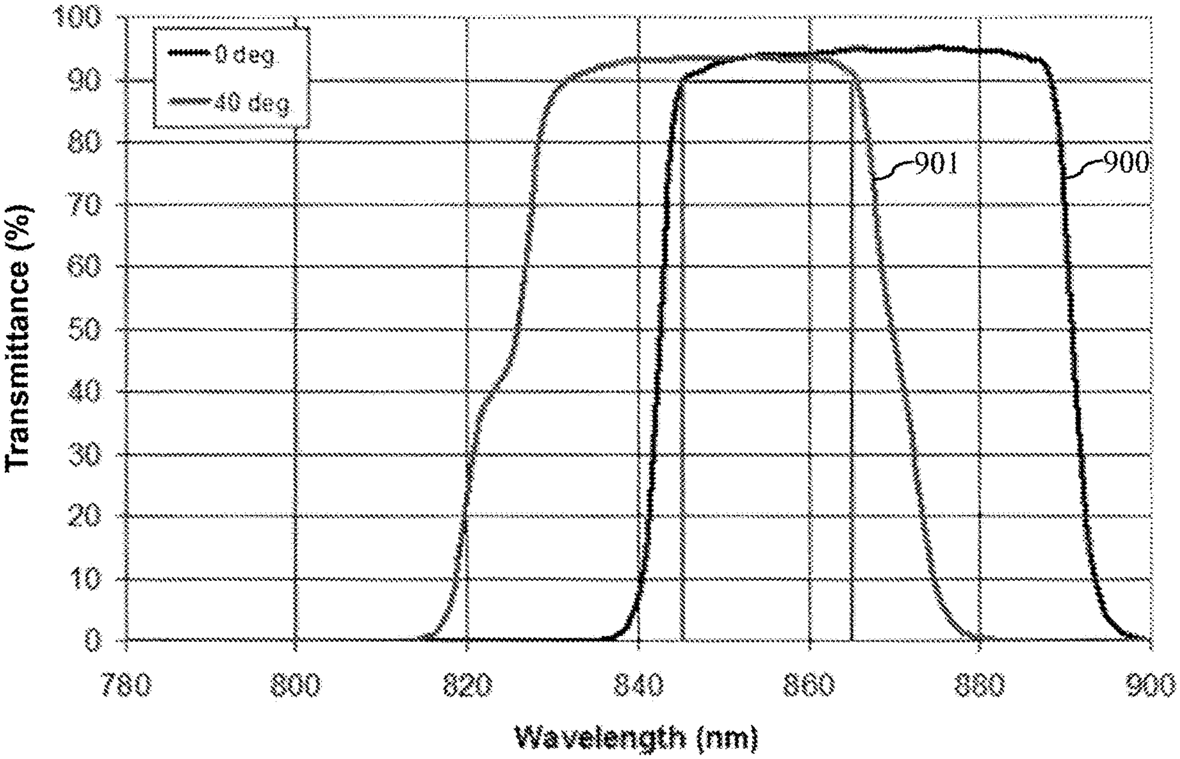

100
90
80
70
60
50
40
30
20
10
0
Transmittance (%)
780
800
820
840
860
880
900
Wavelength (nm)
0 deg.
40 deg.
901
900

FIG. 9B

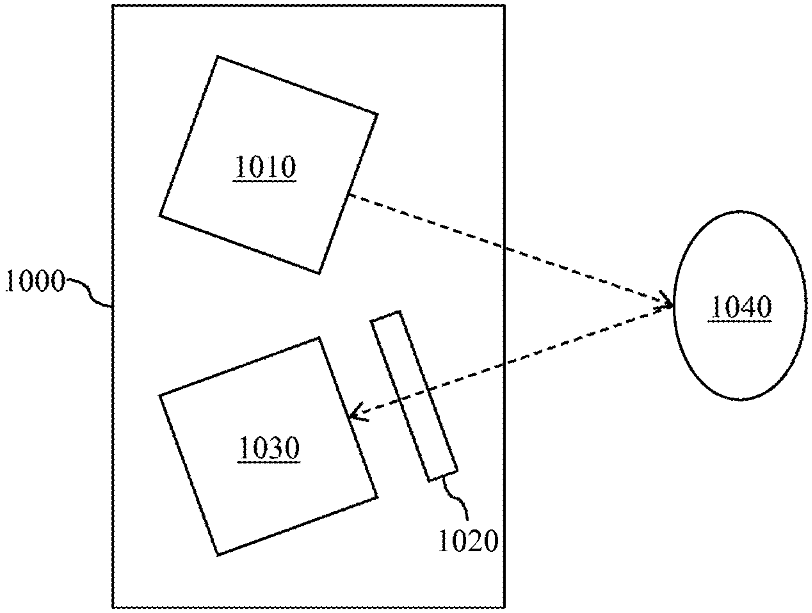


FIG. 10

OPTICAL FILTER AND SENSOR SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 15/617,654, filed Jun. 8, 2017 (now U.S. Pat. No. 10,222,526), which is a continuation of U.S. patent application Ser. No. 15/099,180, filed Apr. 14, 2016 (now U.S. Pat. No. 9,945,995), which is a continuation of U.S. patent application Ser. No. 13/943,596, filed Jul. 16, 2013 (now U.S. Pat. No. 9,354,369), which claims priority from U.S. Provisional Patent Application No. 61/672,164, filed on Jul. 16, 2012, the contents of which are incorporated herein by reference.

TECHNICAL FIELD OF THE INVENTION

The present invention relates to optical filters and to sensor systems comprising optical filters. More particularly, the present invention relates to optical filters including hydrogenated silicon layers and to sensor systems comprising such optical filters.

BACKGROUND OF THE INVENTION

In a typical gesture-recognition system, a light source emits near-infrared light towards a user. A three-dimensional (3D) image sensor detects the emitted light that is reflected by the user to provide a 3D image of the user. A processing system then analyzes the 3D image to recognize a gesture made by the user.

An optical filter, more specifically, a bandpass filter, is used to transmit the emitted light to the 3D image sensor, while substantially blocking ambient light. In other words, the optical filter serves to screen out ambient light. Therefore, an optical filter having a narrow passband in the near-infrared wavelength range, i.e., 800 nm to 1100 nm, is required. Furthermore, the optical filter must have a high transmittance level within the passband and a high blocking level outside of the passband.

Conventionally, the optical filter includes a filter stack and a blocking stack, coated on opposite surfaces of a substrate. Each of the stacks is formed of high-refractive-index layers and low-refractive-index layers stacked in alternation. Different oxides are, generally, used for the high-refractive-index layers and the low-refractive-index layers, such as TiO_2, Nb_2O_5, Ta_2O_5, SiO_2, and mixtures thereof. For example, some conventional optical filters include a TiO_2/SiO_2 filter stack and a Ta_2O_5/SiO_2 blocking stack, in which the high-refractive index layers are composed of TiO_2 or Ta_2O_5, respectively, and the low-refractive-index layers are composed of SiO_2.

In a first conventional optical filter designed to transmit light in a wavelength range of 829 nm to 859 nm over an incidence angle range of 0° to 30°, the filter stack includes 71 layers, the blocking stack includes 140 layers, and the total coating thickness is about 24 μm. Transmission spectra **100** and **101** at incidence angles of 0° and 30°, respectively, for this optical filter are plotted in FIG. **1**. In a second conventional optical filter designed to transmit light at a wavelength of 825 nm over an incidence angle range of 0° to 20°, the filter stack includes 43 layers, the blocking stack includes 82 layers, and the total coating thickness is about 14 μm. Transmission spectra **200** and **201** at incidence angles of 0° and 20°, respectively, for this optical filter are plotted in FIG. **2**. In a third conventional optical filter designed to

transmit light in a wavelength range of 845 nm to 865 nm over an incidence angle range of 0° to 24°, the filter stack includes 77 layers, the blocking stack includes 148 layers, and the total coating thickness is about 26 μm. Transmission spectra **300** and **301** at incidence angles of 0° and 24°, respectively, for this optical filter are plotted in FIG. **3**.

With reference to FIGS. **1**-**3**, the first, second, and third conventional optical filters, generally, have a high transmittance level within the passband and a high blocking level outside of the passband. However, the center wavelength of the passband undergoes a relatively large shift with change in incidence angle. Consequently, the passband must be relatively wide to accept light over the required incidence angle range, increasing the amount of ambient light that is transmitted and reducing the signal-to-noise ratio of systems incorporating these conventional optical filters. Furthermore, the large number of layers in the filter stacks and blocking stacks increases the expense and coating time involved in fabricating these conventional optical filters. The large total coating thickness also makes these conventional optical filters difficult to pattern, e.g., by photolithography.

To enhance the performance of the optical filter in the gesture-recognition system, it would be desirable to reduce the number of layers, the total coating thickness, and the center-wavelength shift with change in incidence angle. One approach is to use a material having a higher refractive index than conventional oxides over the wavelength range of 800 nm to 1100 nm for the high-refractive-index layers. In addition to a higher refractive index, the material must have also have a low extinction coefficient over the wavelength range of 800 nm to 1100 nm in order to provide a high transmittance level within the passband.

The use of hydrogenated silicon (Si:H) for high-refractive-index layers in optical filters is disclosed by Lairson, et al. in an article entitled "Reduced Angle-Shift Infrared Bandpass Filter Coatings" (Proceedings of the SPIE, 2007, Vol. 6545, pp. 65451C-1-65451C-5), and by Gibbons, et al. in an article entitled "Development and Implementation of a Hydrogenated a-Si Reactive Sputter Deposition Process" (Proceedings of the Annual Technical Conference, Society of Vacuum Coaters, 2007, Vol. 50, pp. 327-330). Lairson, et al. disclose a hydrogenated silicon material having a refractive index of 3.2 at a wavelength of 1500 nm and an extinction coefficient of less than 0.001 at wavelengths of greater than 1000 nm. Gibbons, et al. disclose a hydrogenated silicon material, produced by alternating current (AC) sputtering, having a refractive index of 3.2 at a wavelength of 830 nm and an extinction coefficient of 0.0005 at a wavelength of 830 nm. Unfortunately, these hydrogenated silicon materials do not have a suitably low extinction coefficient over the wavelength range of 800 nm to 1100 nm.

SUMMARY OF THE INVENTION

Accordingly, the present invention relates to an optical filter having a passband at least partially overlapping with a wavelength range of 800 nm to 1100 nm, comprising: a filter stack including: a plurality of hydrogenated silicon layers each having a refractive index of greater than 3 over the wavelength range of 800 nm to 1100 nm and an extinction coefficient of less than 0.0005 over the wavelength range of 800 nm to 1100 nm; and a plurality of lower-refractive-index layers each having a refractive index of less than 3 over the wavelength range of 800 nm to 1100 nm, stacked in alternation with the plurality of hydrogenated silicon layers.

The present invention also relates to a sensor system comprising: a light source for emitting light at an emission wavelength in a wavelength range of 800 nm to 1100 nm; an optical filter having a passband including the emission wavelength and at least partially overlapping with the wavelength range of 800 nm to 1100 nm, disposed to receive the emitted light, for transmitting the emitted light while substantially blocking ambient light, comprising: a filter stack including: a plurality of hydrogenated silicon layers each having a refractive index of greater than 3 over the wavelength range of 800 nm to 1100 nm and an extinction coefficient of less than 0.0005 over the wavelength range of 800 nm to 1100 nm; and a plurality of lower-refractive-index layers each having a refractive index of less than 3 over the wavelength range of 800 nm to 1100 nm, stacked in alternation with the plurality of hydrogenated silicon layers; and a sensor, disposed to receive the emitted light after transmission by the optical filter, for detecting the emitted light.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be described in greater detail with reference to the accompanying drawings wherein:

FIG. **1** is a plot of transmittance spectra at incidence angles of 0° and 30° for a first conventional optical filter;

FIG. **2** is a plot of transmittance spectra at incidence angles of 0° and 20° for a second conventional optical filter;

FIG. **3** is a plot of transmittance spectra at incidence angles of 0° and 24° for a third conventional optical filter;

FIG. **4** is a schematic illustration of a sputter-deposition system;

FIG. **5**A is a plot of transmittance spectra for 1500-nm-thick silicon layers deposited in the presence and absence of hydrogen;

FIG. **5**B is a plot of the absorption-edge wavelength at a transmittance level of 50% against hydrogen flow rate for hydrogenated silicon (Si:H) layers before and after an annealing step;

FIG. **5**C is a plot of refractive index at wavelengths of 800 nm to 1120 nm against hydrogen flow rate for hydrogenated silicon layers;

FIG. **5**D is a plot of absorption coefficient at wavelengths of 800 nm to 880 nm against hydrogen flow rate for hydrogenated silicon layers;

FIG. **6** is a schematic illustration of a cross-section of an optical filter according to the present invention;

FIG. **7**A is a table comparing properties of the first conventional optical filter of FIG. **1** and a first exemplary optical filter according to the present invention;

FIG. **7**B is a table listing layer numbers, materials, and thicknesses for the antireflective (AR) coating of the first exemplary optical filter;

FIG. **7**C is a table listing layer numbers, materials, and thicknesses for the filter stack of the first exemplary optical filter;

FIG. **7**D is a plot of transmittance spectra at incidence angles of 0° and 30° for the first exemplary optical filter;

FIG. **7**E is a plot of transmittance spectra at incidence angles of 0° and 30° for an optical filter analogous to the first exemplary optical filter, but including an Si/SiO_2 filter stack;

FIG. **8**A is a table comparing properties of the second conventional optical filter of FIG. **2** and a second exemplary optical filter according to the present invention;

FIG. **8**B is a table listing layer numbers, materials, and thicknesses for the filter stack of the second exemplary optical filter;

FIG. **8**C is a plot of transmittance spectra at incidence angles of 0° and 20° for the second exemplary optical filter;

FIG. **8**D is a plot of transmittance spectra at incidence angles of 0° and 20° for an optical filter analogous to the second exemplary optical filter, but including an Si/SiO_2 filter stack;

FIG. **9**A is a table listing layer numbers, materials, and thicknesses for the filter stack of a third exemplary optical filter according to the present invention;

FIG. **9**B is a plot of transmittance spectra at incidence angles of 0° and 40° for the third exemplary optical filter; and

FIG. **10** is a block diagram of a sensor system according to the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention provides an optical filter including hydrogenated silicon (Si:H) layers, which is particularly suitable for use in a sensor system, such as a proximity sensor system, a three-dimensional (3D) imaging system, or a gesture-recognition system.

The optical filter of the present invention uses an improved hydrogenated silicon material, which has both a high refractive index and a low absorption coefficient over a wavelength range of 800 nm to 1100 nm, i.e., in the near-infrared wavelength range. Typically, the hydrogenated silicon material is amorphous. The hydrogenated silicon material is, preferably, produced by pulsed direct current (DC) sputtering. A sputter-deposition system suitable for producing the hydrogenated silicon material is described in U.S. Pat. No. 8,163,144 to Tilsch, et al., issued on Apr. 24, 2012, which is incorporated herein by reference.

With reference to FIG. **4**, a typical sputter-deposition system **400** used to produce the hydrogenated silicon material includes a vacuum chamber **410**, a substrate **420**, a cathode **430**, a cathode power supply **440**, an anode **450**, a plasma activation source (PAS) **460**, and a PAS power supply **470**. The cathode **430** is powered by the cathode power supply **440**, which is a pulsed DC power supply. The PAS **460** is powered by the PAS power supply **470**, which is a radio frequency (RF) power supply.

The cathode **430** includes a silicon target **431**, which is sputtered in the presence of hydrogen (H_2), as well as an inert gas such as argon, to deposit the hydrogenated silicon material as a layer on the substrate **420**. The inert gas is introduced into the vacuum chamber **410** through the anode **450** and the PAS **460**. Alternatively, the walls of the vacuum chamber **410** may serve as the anode, and the inert gas may be introduced at a different location.

Hydrogen is introduced into the vacuum chamber **410** through the PAS **460**, which serves to activate the hydrogen. Activated hydrogen is more chemically reactive and is, therefore, more likely to create Si—H bonds, which are thought to be responsible for the optical properties of the hydrogenated silicon material. The PAS **460** is located very close to the cathode **430**, allowing the PAS plasma and the cathode plasma to overlap. Both atomic and molecular species of activated hydrogen are believed to be present in the plasmas. The use of the PAS **460** allows the hydrogenated silicon layer to be deposited at a relatively high deposition rate with a relatively low hydrogen content. Typically, the hydrogenated silicon layer is deposited at a deposition rate of 0.05 nm/s to 1.2 nm/s, preferably, at a deposition rate of about 0.8 nm/s. Alternatively, the cathode plasma alone may be used for hydrogen activation.

The optical properties of the hydrogenated silicon material depend primarily on the hydrogen content in the vacuum chamber **410** and, therefore, on the hydrogen flow rate. However, they are also influenced by other parameters, such as the flow rate of the inert gas, the PAS power level, the cathode power level, and the deposition rate.

FIG. **5**A shows transmission spectra **500** and **501** for 1500-nm-thick silicon layers deposited in the presence of hydrogen, at a hydrogen flow rate of 139 sccm, and in the absence of hydrogen, respectively. The silicon layer deposited in the presence of hydrogen, i.e., the hydrogenated silicon layer, has a significantly higher transmittance level over the wavelength range of 800 nm to 1100 nm.

FIG. **5**B shows curves **510** and **511** of the absorption-edge wavelength at a transmittance level of 50% against hydrogen flow rate for hydrogenated silicon layers before and after an annealing step, respectively. For the as-deposited hydrogenated silicon layers, the absorption-edge wavelength decreases with increasing hydrogen flow rate. Generally, the absorption-edge wavelength varies approximately logarithmically with hydrogen flow rate. The absorption-edge wavelength is decreased further by the annealing step, which was carried out at a temperature of about 300° C. for about 60 minutes. Typically, when an optional post-coating annealing step is performed, the hydrogenated silicon layers are annealed at a temperature of up to 350° C. for up to 120 minutes, preferably, at a temperature of 250° C. to 350° C. for 30 to 90 minutes. In some instances, more than one annealing step may be performed.

Thus, the absorption-edge wavelength of the hydrogenated silicon material can be tuned by adjusting the hydrogen flow rate and, optionally, by annealing. Likewise, the refractive index and the absorption coefficient of the hydrogenated silicon material can also can be tuned by adjusting the hydrogen flow rate and, optionally, by annealing. Typically, the hydrogenated silicon layers are deposited with a hydrogen flow rate of greater than 80 sccm, preferably, a hydrogen flow rate of about 80 sccm. However, it should be noted that the hydrogen content associated with this flow rate will depend on the pumping speed of the vacuum system.

FIG. **5**C shows a plot of refractive index at wavelengths of 800 nm to 1120 nm against hydrogen flow rate for as-deposited hydrogenated silicon layers. The refractive index decreases with increasing hydrogen flow rate. Generally, the refractive index varies approximately linearly with hydrogen flow rate. In particular, the refractive index of the hydrogenated silicon layer produced at a hydrogen flow rate of 80 sccm is greater than 3.55 over the wavelength range of 800 nm to 1120 nm.

FIG. **5**D shows a plot of absorption coefficient at wavelengths of 800 nm to 880 nm against hydrogen flow rate for as-deposited hydrogenated silicon layers (the absorption coefficient is less than 0.0001 at wavelengths of 920 nm to 1120 nm). The absorption coefficient decreases with increasing hydrogen flow rate. Generally, the absorption coefficient varies approximately exponentially with hydrogen flow rate. In particular, the absorption coefficient of the hydrogenated silicon layer produced at a hydrogen flow rate of 80 sccm is less than 0.0004 over the wavelength range of 800 nm to 1120 nm.

The improved hydrogenated silicon material, tuned to have suitable optical properties, is used in the optical filter of the present invention. With reference to FIG. **6**, the optical filter **600** includes a filter stack **610**, which is disposed on a first surface of a substrate **620**. In most instances, the substrate **620** is a free-standing substrate, typically, a glass substrate, e.g., a borofloat glass substrate. Alternatively, the substrate **620** may be a sensor or another device. When the substrate **620** is a free-standing substrate, an antireflective (AR) coating **630** is often disposed on a second surface of the substrate **620** opposite the first surface. Typically, the AR coating **630** is a multilayer interference coating, e.g., a Ta_2O_5/SiO_2 coating. Also typically, the AR coating **630** has a thickness of 0.1 μm to 1 μm.

The filter stack **610** includes a plurality of hydrogenated silicon layers **611**, which serve as higher-refractive-index layers, and a plurality of lower-refractive-index layers **612** stacked in alternation. Usually, the filter stack **610** consists of a plurality of hydrogenated silicon layers **611** and a plurality of lower-refractive-index layers **612** stacked in a sequence of $(H/L)_n$, $(H/L)_nH$, or $L(H/L)_n$. Typically, the filter stack **610** includes a total of 10 to 100 layers, i.e., $5 \leq n \leq 50$. Also typically, the hydrogenated silicon layers **611** and the lower-refractive-index layers **612** each have a thickness of 3 nm to 300 nm, and the filter stack **610** has a thickness of 1 μm to 10 μm. Generally, the layer numbers and thicknesses are selected according to a particular optical design. Preferably, the optical filter **600** has a total coating thickness, i.e., the thickness of the filter stack **610** and the AR coating **630**, of less than 10 μm.

The hydrogenated silicon layers **611** are composed of the improved hydrogenated silicon material tuned to have a refractive index of greater than 3 and an extinction coefficient of less than 0.0005 over the wavelength range of 800 nm to 1100 nm. Preferably, the hydrogenated silicon material has a refractive index of greater than 3.5 over the wavelength range of 800 nm to 1100 nm, e.g., a refractive index of greater than 3.64, i.e., about 3.6, at a wavelength of 830 nm. A higher refractive index is usually desirable. However, generally, the hydrogenated silicon material has a refractive index of less than 4.5 over the wavelength range of 800 nm to 1100 nm.

Preferably, the hydrogenated silicon material has an extinction coefficient of less than 0.0004 over the wavelength range of 800 nm to 1100 nm, more preferably, an extinction coefficient of less than 0.0003 over the wavelength range of 800 nm to 1100 nm. Typically, the hydrogenated silicon material has an extinction coefficient of greater than 0.01 at wavelengths of less than 600 nm, preferably, an extinction coefficient of greater than 0.05 at wavelengths of less than 650 nm. Because the hydrogenated silicon material is relatively strongly absorbing at wavelengths of less than 600 nm, an additional blocking stack is not necessary in the optical filter **600**.

The lower-refractive-index layers **612** are composed of a lower-refractive-index material having a refractive index lower than that of the hydrogenated silicon layers **611** over the wavelength range of 800 nm to 1100 nm. Typically, the lower-refractive-index material has a refractive index of less than 3 over the wavelength range of 800 nm to 1100 nm. Preferably, the lower-refractive-index material has a refractive index of less than 2.5 over the wavelength range of 800 nm to 1100 nm, more preferably, a refractive index of less than 2 over the wavelength range of 800 nm to 1100 nm.

A lower refractive index is usually desirable for the lower-refractive-index layers **612** to increase the width of the blocking wavelength range, i.e., the stopband, of the optical filter **600**, allowing the same blocking level to be achieved with fewer layers in the filter stack **610**. However, in some instances, a somewhat higher refractive index that is still lower than that of hydrogenated silicon layers **611** may be desirable to reduce the center-wavelength shift with change in incidence angle, i.e., angle shift, of the optical filter **600**.

In most instances, the lower-refractive-index material is a dielectric material, typically, an oxide. Suitable lower-refractive-index materials include silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), titanium dioxide (TiO_2), niobium pentoxide (Nb_2O_5), tantalum pentoxide (Ta_2O_5), and mixtures thereof, i.e., mixed oxides.

The optical filter **600** may be fabricated by using a sputtering process. Typically, the substrate **620** is provided in the vacuum chamber of a sputter-deposition system similar to that illustrated in FIG. **4**. The hydrogenated silicon layers **611** and the lower-refractive-index layers **612** are then sequentially deposited on the first surface of the substrate **620** to form the filter stack **610** as a multilayer coating. Typically, the hydrogenated silicon layers **611** are deposited by pulsed-DC sputtering of a silicon target in the presence of hydrogen, as described heretofore. Also typically, the lower-refractive-index layers **612** are deposited by pulsed-DC sputtering of one or more suitable metal targets, e.g., a silicon target, an aluminum target, a titanium target, a niobium target, and/or a tantalum target, in the presence of oxygen. The AR coating **630** is deposited on the second surface of the substrate **620** in a similar fashion. It should be noted that the order of forming the filter stack **610** and the AR coating **630** is usually unimportant.

The optical filter **600** is an interference filter having a passband at least partially overlapping with the wavelength range of 800 nm to 1100 nm. The passband may include the entire wavelength range of 800 nm to 1100 nm or, more typically, only a part of the wavelength range. The passband may be restricted to part or all of the wavelength range of 800 nm to 1100 nm, or may extend beyond the wavelength range. Preferably, the optical filter **600** has a transmittance level, within the passband, of greater than 90% over the wavelength range of 800 nm to 1100 nm.

The optical filter **600** provides blocking outside of the passband, i.e., a stopband on one or both sides of the passband, typically, over a wavelength range of 400 nm to 1100 nm, preferably, over a wavelength range of 300 nm to 1100 nm. Preferably, the optical filter **600** has a blocking level, outside of the passband, of greater than OD2 over the wavelength range of 400 nm to 1100 nm, more preferably, a blocking level of greater than OD3 over the wavelength range of 300 nm to 1100 nm.

In some instances, the optical filter **600** is a long-wavelength-pass edge filter, and the passband has an edge wavelength in the wavelength range of 800 nm to 1100 nm. However, in most instances, the optical filter **600** is a bandpass filter, preferably, a narrow bandpass filter. Typically, the passband has a center wavelength in the wavelength range of 800 nm to 1100 nm. Preferably, the passband has a full width at half maximum (FWHM) of less than 50 nm. Often, the entire passband is within the wavelength range of 800 nm to 1100 nm.

Generally, the optical filter **600** has a low center-wavelength shift with change in incidence angle. Preferably, the center wavelength of the passband shifts by less than 20 nm in magnitude with a change in incidence angle from 0° to 30°. Accordingly, the optical filter **600** has a wide incidence-angle acceptance range.

The optical filter **600** may have a variety of optical designs. In general, the optical design of the optical filter **600** is optimized for a particular passband by selecting suitable layer numbers, materials, and/or thicknesses for the filter stack **610**. Some exemplary optical filters, described hereafter, include an Si:H/SiO_2 filter stack and a Ta_2O_5/SiO_2 AR coating, coated on opposite surfaces of a borofloat glass substrate.

With reference to FIG. **7**, a first exemplary optical filter is a narrow bandpass filter that is designed to transmit light in a wavelength range of 829 nm to 859 nm over an incidence angle range of 0° to 30°. The first exemplary optical filter of FIG. **7** is comparable to the first conventional optical filter of FIG. **1**, and some properties of the optical filters are compared in FIG. **7**A. Design data, i.e., layer numbers (from substrate to air), materials, and thicknesses, for the AR coating and the filter stack of the first exemplary filter are listed in FIGS. **7**B and **7**C, respectively. The filter stack includes 48 layers, the AR coating includes 5 layers, and the total coating thickness is about 5.7 μm.

Transmission spectra **700** and **701** at incidence angles of 0° and 30°, respectively, for the first exemplary optical filter are plotted in FIG. **7**D. The first exemplary optical filter has a transmittance level, within the passband, of greater than 90%, and a blocking level, outside of the passband, of greater than OD3 over a wavelength range of 450 nm to 1050 nm. The passband has a center wavelength of about 850 nm and a FWHM of about 46.5 nm at an incidence angle of 0°. With change in incidence angle from 0° to 30°, the center wavelength of the passband shifts by about −12.2 nm.

Advantageously, the first exemplary optical filter of FIG. **7** includes fewer layers and has a smaller total coating thickness than the first conventional optical filter of FIG. **1**. In particular, the total coating thickness of the first exemplary optical filter is about one quarter of the total coating thickness of the first conventional optical filter. Therefore, the first exemplary optical filter is less expensive to fabricate and is easier to pattern. Also advantageously, the first exemplary optical filter has a lower center-wavelength shift with change in incidence angle. Therefore, the passband of the first exemplary optical filter can be significantly narrower while accepting light over the same incidence angle range, improving the signal-to-noise ratio of systems incorporating the first exemplary optical filter.

The first exemplary optical filter may also be compared to an analogous optical filter including an Si/SiO_2 filter stack, i.e., a filter stack including non-hydrogenated silicon layers, instead of an Si:H/SiO_2 filter stack. Transmission spectra **710** and **711** at incidence angles of 0° and 30°, respectively, for this optical filter are plotted in FIG. **7**E. The transmittance level within the passband of this optical filter is too low to be useful.

With reference to FIG. **8**, a second exemplary optical filter is a narrower bandpass filter that is designed to transmit light at a wavelength of 825 nm over an incidence angle range of 0° to 20°. The second exemplary optical filter of FIG. **8** is comparable to the second conventional optical filter of FIG. **2**, and some properties of the optical filters are compared in FIG. **8**A. Design data for the AR coating of the second exemplary optical filter, which is the same as that of the first exemplary optical filter, are listed in FIG. **7**B. Design data for the filter stack of the second exemplary optical filter are listed in FIG. **8**B. The filter stack includes 25 layers, the AR coating includes 5 layers, and the total coating thickness is about 3.3 μm.

Transmission spectra **800** and **801** at incidence angles of 0° and 20°, respectively, for the second exemplary optical filter are plotted in FIG. **8**C. The second exemplary optical filter has a transmittance level, within the passband, of greater than 90%, and a blocking level, outside of the passband, of greater than OD2 over a wavelength range of 400 nm to 1100 nm. The passband has a center wavelength of about 829 nm and a FWHM of about 29.6 nm at an incidence angle of 0°. With change in incidence angle from 0° to 20°, the center wavelength of the passband shifts by about −7.8 nm.

Similarly to the first exemplary optical filter of FIG. **7**, the second exemplary optical filter of FIG. **8**, advantageously, includes fewer layers, has a smaller total coating thickness, and has a lower center-wavelength shift with change in incidence angle than the second conventional optical filter of FIG. **2**.

The second exemplary optical filter may also be compared to an analogous optical filter including an Si/SiO_2 filter stack instead of an Si:H/SiO_2 filter stack. Transmission spectra **810** and **811** at incidence angles of 0° and 20°, respectively, for this optical filter are plotted in FIG. **8**D. The transmittance level within the passband of this optical filter is too low to be useful.

With reference to FIG. **9**, a third exemplary optical filter is a narrow bandpass filter that is designed to transmit light over a wavelength range of 845 nm to 865 nm over an incidence angle range of 0° to 40°. The third exemplary optical filter of FIG. **9** is comparable to the third conventional optical filter of FIG. **3**. Design data for the AR coating of the third exemplary optical filter, which is the same as that of the first exemplary optical filter, are listed in FIG. **7**B. Design data for the filter stack of the third exemplary optical filter are listed in FIG. **9**A. The filter stack includes 29 layers, the AR coating includes 5 layers, and the total coating thickness is about 4.8 μm.

Transmission spectra **900** and **901** at incidence angles of 0° and 40°, respectively, for the third exemplary optical filter are plotted in FIG. **9**B. The third exemplary optical filter of FIG. **9** has substantially the same passband width as the third conventional optical filter of FIG. **3**, but has a slightly lower transmittance level within the passband. Advantageously, however, the third exemplary optical filter accepts light over a considerably larger incidence angle range of 0° to 40° than the third conventional optical filter, which accepts light over an incidence angle range of only 0° to 24°. In other words, the third exemplary optical filter has a significantly wider incidence-angle acceptance range. Also advantageously, the third exemplary optical filter includes fewer layers and has a smaller total coating thickness, about one fifth of the total coating thickness of the third conventional optical filter.

As mentioned heretofore, the optical filter of the present invention is particularly useful when it forms part of a sensor system, such as a proximity sensor system, a 3D imaging system, or a gesture-recognition system. With reference to FIG. **10**, a typical sensor system **1000** includes a light source **1010**, an optical filter **1020** according to the present invention, and a sensor **1030**. Note that other elements commonly included in a sensor system, such as optics, are omitted for simplicity of illustration.

The light source **1010** emits light at an emission wavelength in a wavelength range of 800 nm to 1100 nm. Typically, the light source **1010** emits modulated light, e.g., light pulses. Preferably, the light source **1010** is a light-emitting diode (LED), an LED array, a laser diode, or a laser diode array. The light source **1010** emits light towards a target **1040**, which reflects the emitted light back towards the sensor system **1000**. When the sensor system **1000** is a gesture-recognition system, the target **1040** is a user of the gesture-recognition system.

The optical filter **1020** is disposed to receive the emitted light after reflection by the target **1040**. The optical filter **1020** has a passband including the emission wavelength and at least partially overlapping with the wavelength range of 800 nm to 1100 nm. Typically, the optical filter **1020** is a bandpass filter, preferably, a narrow bandpass filter, as described heretofore. The optical filter **1020** transmits the emitted light from the light source **1010**, while substantially blocking ambient light. In short, the optical filter **1020** receives the emitted light from the light source **1010**, after reflection by the target **1040**, and transmits the emitted light to the sensor **1030**.

The sensor **1030** is disposed to receive the emitted light after transmission by the optical filter **1020**, i.e., the sensor **1030** is disposed behind the optical filter **1020**. In some instances, the optical filter **1020** is formed directly on the sensor **1030** and, thus, disposed on the sensor **1030**. For example, the optical filter **1020** may be coated and patterned, e.g., by photolithography, on sensors, e.g., proximity sensors, in wafer level processing (WLP).

When the sensor system **1000** is a proximity sensor system, the sensor **1030** is a proximity sensor, which detects the emitted light to sense a proximity of the target **1040**, according to methods known in the art. When the sensor system **1000** is a 3D-imaging system or a gesture-recognition system, the sensor **1030** is a 3D image sensor, e.g., a charge-coupled device (CCD) chip or a complementary metal oxide semiconductor (CMOS) chip, which detects the emitted light to provide a 3D image of the target **1040**, which, in some instances, is the user. Typically, the 3D image sensor converts the optical information into an electrical signal for processing by a processing system, e.g., an application-specific integrated circuit (ASIC) chip or a digital signal processor (DSP) chip, according to methods known in the art. For example, when the sensor system **1000** is a gesture-recognition system, the processing system processes the 3D image of the user to recognize a gesture of the user.

Of course, numerous other embodiments may be envisaged without departing from the spirit and scope of the invention.

We claim:

1. An optical device, comprising:
a near infrared band pass filter, comprising:
  a substrate having a first side and a second side;
  a first set of layers on the first side, wherein the first set of layers includes silicon and hydrogen;
  a second set of layers on the first side, wherein the second set of layers includes oxygen; and
  a third set of layers on the second side, whether the third set of layers includes oxygen.

2. The optical device of claim **1**, wherein one or both of the second set or the third set of layers includes silicon.

3. The optical device of claim **1**, wherein one or both of the second set or the third set of layers is silicon dioxide.

4. The optical device of claim **1**, wherein one or both of the second set or the third set of layers includes tantalum.

5. The optical device of claim **1**, wherein one or both of the second set or the third set of layers includes titanium.

6. The optical device of claim **1**, wherein total quantity of layers on the first side is between 25 and 48.

7. The optical device of claim **1**, wherein the optical device is configured for use in a 3D image sensing system.

8. The optical device of claim **1**, wherein the band pass filter has a center wavelength that shifts less than 15 nm in magnitude with a change in incidence angle from 0° to 30°.

9. An optical device, comprising:
a first set of layers including silicon and hydrogen; and
a second set of layers including oxygen;

wherein the optical device is a near infrared bandpass filter that has a center wavelength that shifts by less than 15 nm in magnitude with a change in incidence angle from 0° to 30°.

10. The optical device of claim **9**, wherein the second set of layers includes silicon.

11. The optical device of claim **9**, wherein the second set of layers is silicon dioxide.

12. The optical device of claim **9**, wherein the second set of layers includes tantalum.

13. The optical device of claim **9**, wherein the near infrared band pass filter has a full width half maximum (FWHM) that is less than 50 nm.

14. The optical device of claim **9**, wherein the passband shifts by less than 13 nm in magnitude with a change in incidence angle from 0° to 30°.

15. An optical system, comprising:

a light source for emitting light having a wavelength between 800-1100 nm; and

a filter comprising:

a first set of layers including silicon and hydrogen; and

a second set of layers including oxygen;

wherein the filter is designed for substantially allowing light in a wavelength range that includes the wavelength between 800-1100 nm to pass through it and exhibits a blocking level greater than OD2 between 400 nm to 1100 nm but outside of the wavelength range.

16. The optical system of claim **15**, wherein the filter has a blocking level of greater than OD3 for wavelengths between 300 nm to 1100 nm that are outside of the wavelength range.

17. The optical system of claim **15**, wherein the filter has a center wavelength that shifts by less than 20 nm in magnitude with a change in incidence angle from 0° to 30°.

18. The optical system of claim **15**, wherein the first set of layers and the second set of layers are on a first side of a substrate and an antireflective coating is on a second side of the substrate.

19. The optical system of claim **15**, wherein the first set of layers and the second set of layers are on a first side of a substrate and a third set of layers that includes oxygen is on a second side of the substrate.

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