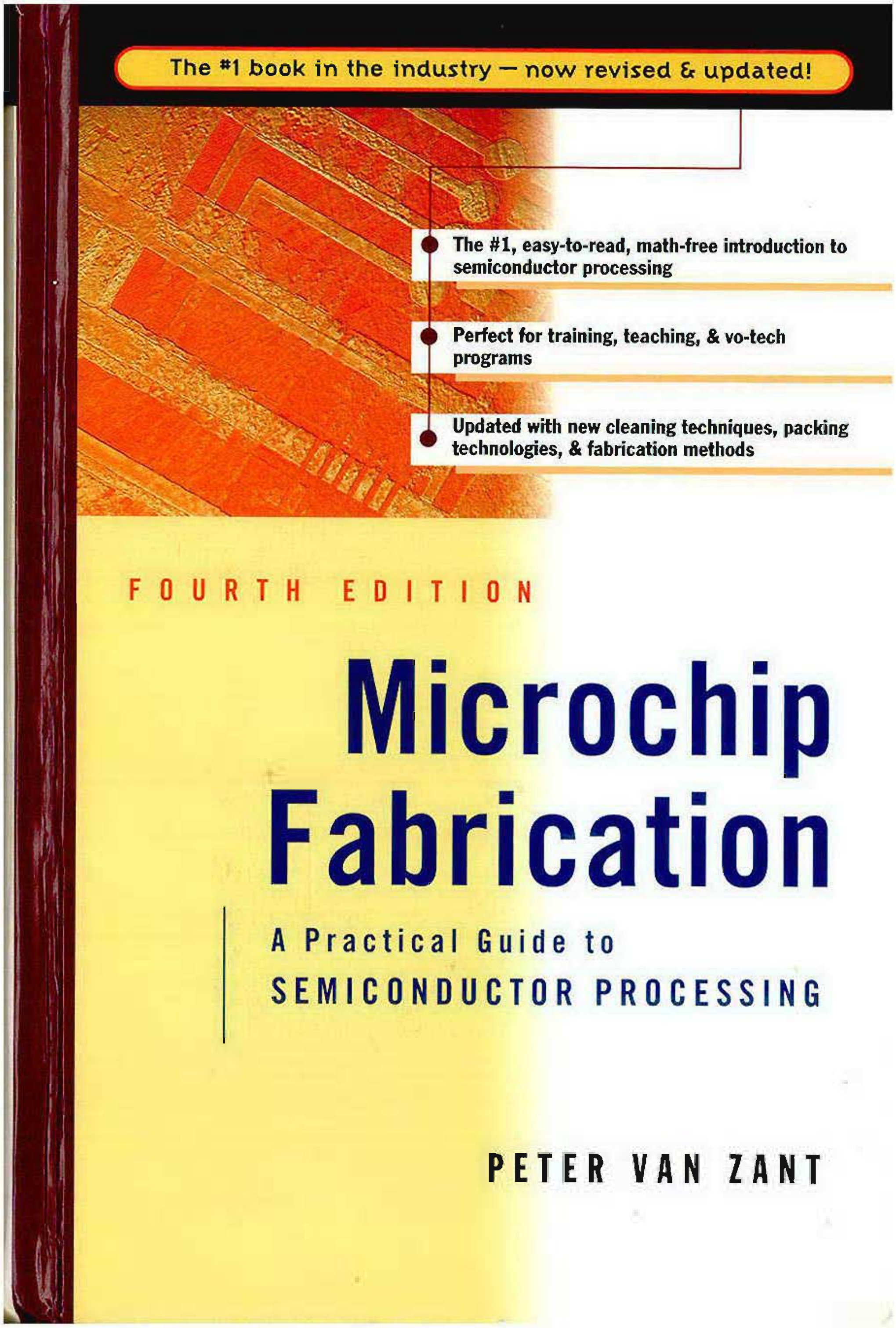

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FOURTH EDITION

Microchip Fabrication

A Practical Guide to SEMICONDUCTOR PROCESSING

PETER VAN ZANT

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Peter Van Zant

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Chapter

1

The Semiconductor Industry

Overview

In this chapter, you will be introduced to the Semiconductor industry via a brief history, as well as by the importance of the industry in the world economy, an overview of the significant technical developments, and the trends that have made the industry the world's leading industrial segment. The major manufacturing stages are introduced by product types, and transistor building structures along with integration levels will be explained.

Objectives

Upon completion of this chapter you should be able to:

1. Describe the difference between discrete devices and integrated circuits.
2. Define the terms "solid state," "planar processing" and "N" and "P" type semiconducting materials.
3. List the four major stages of semiconductor processing.
4. Explain the Integration Scale and the implications of processing circuits of different levels of integration.
5. List the major process and device trends in semiconductor processing.

Birth of an Industry

The electronic signal processing industry got its jump start with the discovery of the audion vacuum tube in the 1906 by Lee Deforest.[1] It made possible the radio, television, and other consumer electronics. It also was the brains of the world's first electronic computer, named the Electronic Numeric Integrator and Calculator (ENIAC), first demonstrated at the Moore School of Engineering in Pennsylvania in 1947.

This ENIAC hardly fits the modern picture of a computer. It occupied some 1500 square feet, weighed 30 tons, generated large quantities of heat, required the services of a small power station, and cost $400,000 in 1940 dollars. The ENIAC was based on 19000 vacuum tubes along with thousands of resistors and capacitors (Fig. 1.1).

A vacuum tube consists of three elements, two electrodes separated by a grid in a glass enclosure (Fig. 1.2). Inside the enclosure is a vacuum, required to prevent the elements from burning up, and to allow the easy transfer of electrons.

Tubes perform two important electrical functions, switching and amplification. Switching refers to the ability of an electrical device to turn a current on or off. Amplification is a little more complicated. It is the ability of a device to receive a small signal (or current) and amplify it while retaining its electrical characteristics.

Vacuum tubes suffer from a number of drawbacks. They are bulky, prone to loose connections and vacuum leaks, fragile, require rela-

Size, ft	30 × 50
Weight, tons	30
Vacuum Tubes	18,000
Resistors	70,000
Capacitors	10,000
Switches	6000
Power Requirements, W	150,000
Cost (in 1940)	$400,000

Figure 1.1 Eniac statistics. (*Foundations of Computector Technology, J. G. Giarratano, Howard W. Sams & Co., Indianapolis, Ind., 1983.*)

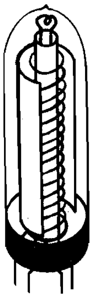


Figure 1.2 Vacuum tube.

tively large amounts of power to operate, and their elements deteriorate rather rapidly. One of the major draw backs to the ENIAC and other tube-based computers was a limited operating time due to tube burn-out.

These problems were the impetus leading many laboratories around the country to seek a replacement for the vacuum tube. That effort came to fruition on Dec. 23, 1947 when three Bell Lab scientists demonstrated an electrical amplifier formed from the semiconducting material Germanium (Fig. 1.3).

This device offered the electrical functioning of a vacuum tube, but with the advantages of the solid state (no vacuum), small and light weight, low power requirements and long lifetime. First named a transfer resistor, the new device soon became known as the *transistor*.

The three scientists, John Bardeen, Walter Brattin and William Shockley were awarded the 1956 Nobel Prize in physics for their invention.

The Solid State Era

That first transistor was a far distance from the high density integrated circuit of today. But it was the component that gave birth to the solid state electronics era with all its famous progeny. Besides transistors, solid state technology is also used to create diodes, resistors and capacitors. Diodes are two-element devices that function in a circuit as a switch. Resistors are monoelements devices that serve to limit current flow. Capacitors are two-element devices that store charge in a circuit. In some circuits, the technology is used to create fuses. Refer to Chapter 14 for an explanation of these concepts and a explanation of how these devices work.

These devices, containing only one device per chip, are called discrete devices (Fig 1.4). Most discrete devices have less demanding operational and fabrication requirements than integrated circuits. In

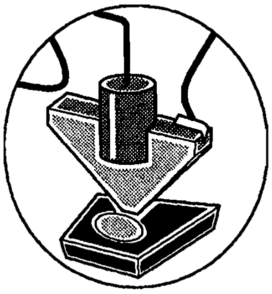


Figure 1.3 The first transistor.

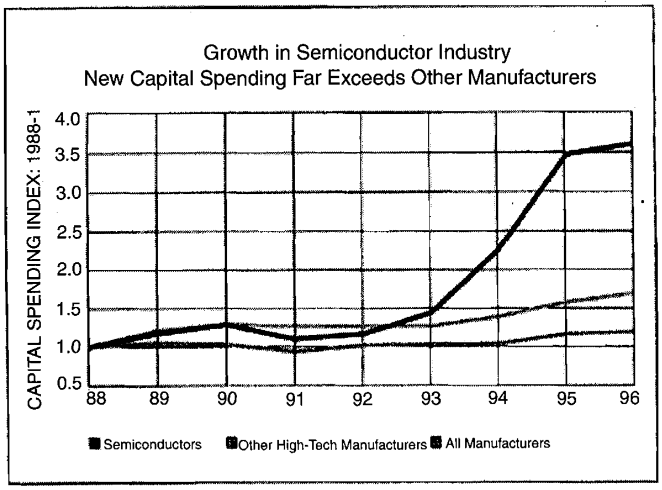


Figure 1.18 Growth of semiconductor industry-capital spending (*Courtesy of Semiconductor Industry Association*)

ket. Captive suppliers are firms whose final product is a computer, communications system, etc., and produce chips in-house for their own products. Some firms produce chips for in-house use and also sell on the open market, and others produce specialty chips in-house and buy others on the open market. During the 1980's, the trend has been to a greater percentage of chips being fabricated in captive fab areas.

Stages of Manufacturing

Solid state devices are manufactured in four distinct stages (Fig. 1.19). They are: material preparation, crystal growing and wafer preparation, wafer fabrication, and packaging.

In the first stage, material preparation (see Chapter 2), the raw semiconducting materials are mined and purified to meet semiconductor standards. For silicon, the starting material is sand, which is converted to pure silicon with a polysilicon structure. (Fig. 1.21).

In stage two, the material is formed into a crystal with specific electrical and structural parameters. Next, thin disks called wafers, are cut from the crystal and surface treated (Fig. 1.21) in a process called

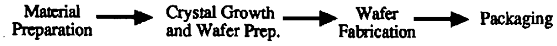


Figure 1.19 Stages of semiconductor manufacturing.

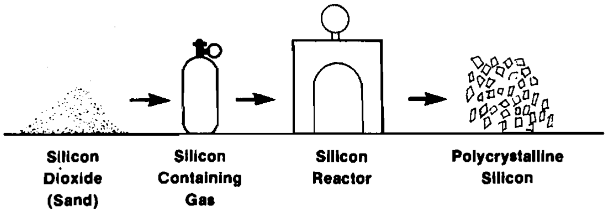


Figure 1.20 Conversion of silicon dioxide to semiconductor grade silicon.

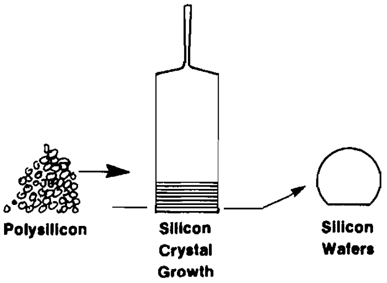


Figure 1.21 Crystal growth and wafer preparation.

crystal growth and wafer preparation (see Chapter 3). The industry also makes devices and circuits from germanium, and compounds of different semiconductor materials.

It is in stage three (Fig. 1.22), wafer fabrication, that the devices or integrated circuits are actually formed in and on the wafer surface. Up to several thousand identical devices can be formed on each wafer, although two to three hundred is a more common number. The area on the wafer occupied by the discrete device or integrated circuit is called a chip or die. The wafer fabrication process is also called fabrication, fab, chip fabrication or microchip fabrication. While a wafer fabrication operation may take several thousand individual steps there are two major activities. In the front end of the line (FEOL), the transistors and other devices are formed in the wafer surface. In the back end of the line (BEOL), the devices are wired together with metalization processes and the circuit is protected with a final sealing layer.

Following wafer fabrication, the chips on the wafer are complete, but untested and still in wafer form. Next comes an electrical test (called wafer sort) of every chip to identify those that meet customer specifications. Wafer sort may be the last step in the wafer fabrication or the first step in the *packaging* process.

Packaging (Fig. 1.23) is the series of processes that separates the wafer into individual die, and places them into protective packages. A

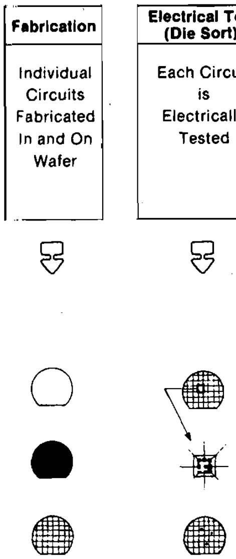


Figure 1.22 Wafer fabrication (and electrical test).

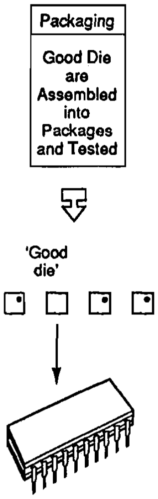


Figure 1.23 Packaging stage.

protective chip package is necessary to protect the chip from contamination and abuse, and to provide a durable and substantial electrical lead system to allow connection of the chip onto a printed circuit board or directly into an electronic product. Packaging takes place in a dif-

Atomic Structure

The Bohr atom

The understanding of semiconductor materials requires a basic knowledge of atomic structure.

Atoms are the building blocks of the physical universe. Everything in the universe is made from the 96 stable materials and 12 unstable ones known as elements. Each element has a different atomic structure. The different structures give rise to the different properties of the elements.

The unique properties of gold are due to its atomic structure. If a piece of gold is divided into smaller and smaller pieces, eventually one arrives at the last piece that exhibits the properties of gold. That last piece is the atom.

Dividing that last piece further will yield the three parts that compose individual atoms. They are called the subatomic particles. They are protons, neutrons and electrons. These subatomic particles each have their own properties. A particular combination and structure of the subatomic particles are required to form the gold atom. The basic structure of the atom most used to understand physical, chemical and electrical differences between different elements was first proposed by the famous physicist Niels Bohr (Fig. 2.1).

The Bohr atom model has the positively charged protons and neutral neutrons located together in the nucleus of the atom. The negatively charged electrons move in defined orbits about the nucleus, similar to the movement of the planets about the sun. There is an attractive force between the positively charged protons and the negatively charged electrons. However this force is balanced by the out-

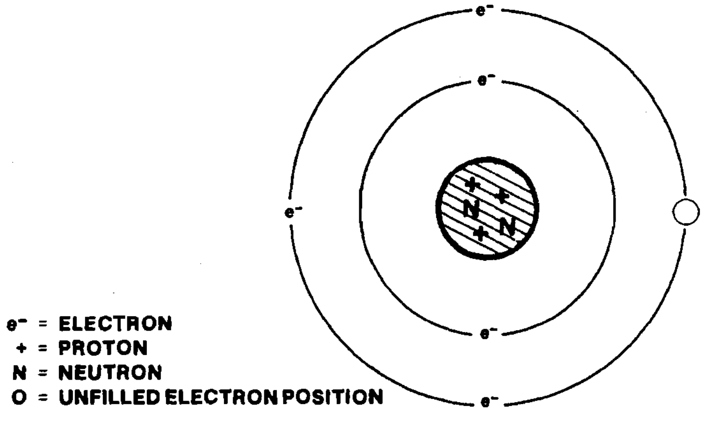


Figure 2.1 Bohr atom model.

ward centrifugal force of the electrons moving in their orbits. The net result is a structurally stable atomic structure.

Each orbit has a maximum number of positions available for electrons. In some atoms not all of the positions are filled, leaving a "hole" in the structure. When a particular electron orbit is filled to the maximum, additional electrons must go into the next outer orbit.

The Periodic Table of the Elements

The elements differ from each other in the number of electrons, protons and neutrons in their atoms. Fortunately, nature combine the subatomic particles in an orderly fashion. An examination of some of the rules governing atomic structure is helpful in understanding the properties of semiconducting materials and process chemicals. Atoms (and therefore the elements) range from the simplest, hydrogen (with one electron) to the most complicated one, lawrencium (with 103 electrons).

Hydrogen consists of only one proton in the nucleus and only one electron. This arrangement illustrates the first rule of atomic structure.

1. In each atom there is an equal amount of protons and electrons.
2. Each element contains a specific number of protons and no two elements have the same number of protons. Hydrogen has one proton in its nucleus while the oxygen atom has eight.

This fact leads to the assignment of numbers to each of the elements. Known as the "atomic number" it is equal to the number of protons (and therefore electrons) in the atom. The basic reference of the elements is the periodic table (Fig. 2.2). The periodic table has a box for each of the elements, which is identified by two letters. The atomic number is in the upper left hand corner of the box. Thus calcium (Ca) has the atomic number 20, so we know immediately that calcium has 20 protons in its nucleus and 20 electrons in its orbital system.

Neutrons are electrically neutral particles that, along with the protons, make up the mass of the nucleus.

Figure 2.3 shows the atomic structure of elements #1, hydrogen, #3, lithium, and #11, sodium. When constructing the diagrams, several rules were observed in the placement of the electrons in their proper orbits. The rule is that each orbit (n) can hold $2n^2$ electrons. Solution of the math for orbit #1 dictates that the first electron orbit can hold only two electrons. This rule forces the third electron of lithium into the second ring. The rule limits the number of electrons in the second ring to 8 and that of the third ring to 18. So, when constructing the

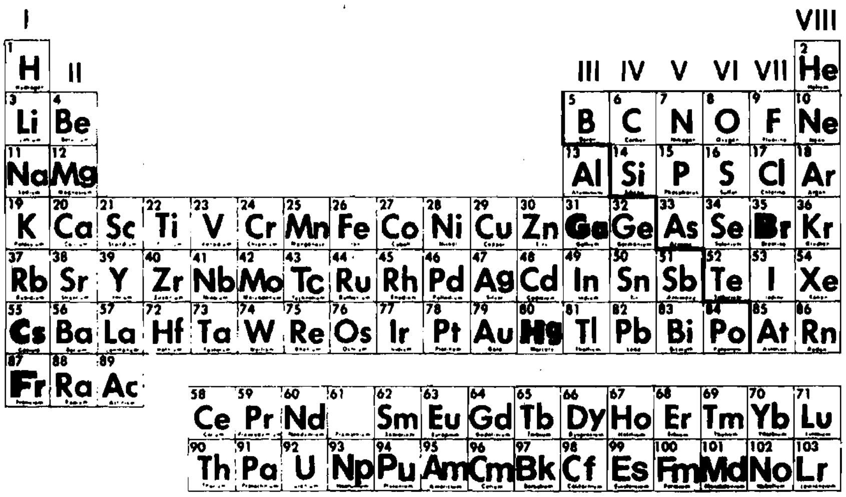
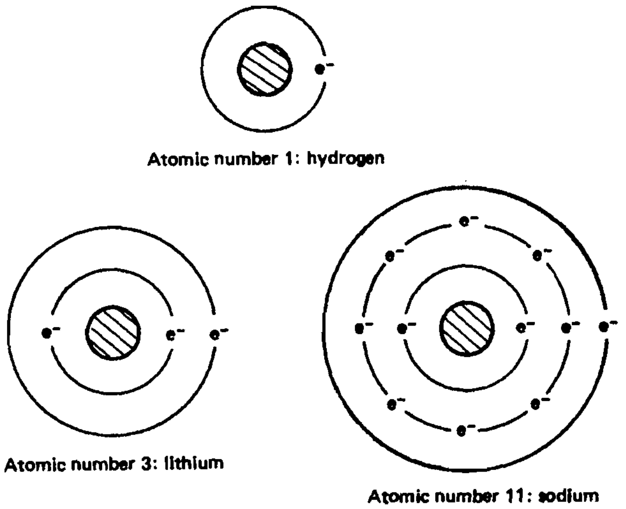


Figure 2.2 Periodic table of elements.



Atomic number 1: hydrogen

Atomic number 3: lithium

Atomic number 11: sodium

Figure 2.3 Atomic structures of hydrogen, lithium, and sodium.

diagram of the sodium atom, with 11 protons and electrons, the first two orbits take up ten electrons, leaving the eleventh in the third ring.

These three atoms have a commonalty. Each has an outer ring with only one electron in it. This illustrates another observable fact of elements.

3. Elements with the same number of outer orbit electrons have similar properties. This rule is reflected in the periodic table. Note that hydrogen, lithium and sodium appear on the table in a vertical column labeled with the Roman numeral one (I). The column number

represents the number of electrons in the outer ring and all of the elements in each column share similar properties.

It is no accident that the three best electrical conductors (copper, silver and gold) all appear in the same column (Ib) (Fig. 2.4) of the periodic table.

There are two more rules of atomic structure relevant to the understanding of semiconductors.

4. Elements are stable with a filled outer ring or with eight electrons in the outer ring. These atoms tend to be more chemically stable than atoms with partially filled rings.
5. Atoms seek to combine with other atoms to create the stable condition of full orbits or eight electrons in their outer ring.

Rules 4 and 5 influence the creation of N- and P-type semiconductor materials as explained in the section on doped semiconductors.

Electrical Conduction

Conductors

An important property of many materials is the ability to conduct electricity or support an electrical current flow. An electrical current is simply a flow of electrons. Electrical conduction takes place in elements and materials where the attractive hold of the protons on the outer ring electrons is relatively weak. In such a material, these electrons can be easily moved and set up an electrical current. This condition exists in most metals.

The property of materials to conduct electricity is measured by a factor known as conductivity. The higher the conductivity, the better the conductor. Conducting ability is also measured by the reciprocal of the conductivity which is resistivity. The lower the resistivity of a material, the better the conducting ability.

$$C = 1/\rho$$

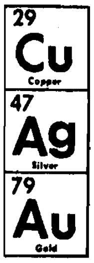


Figure 2.4 The three best electrical conductors.

where C = conductivity
ρ = resistivity in ohms-centimeter (Ω-cm)

Dielectrics and Capacitors

At the opposite end of the conductivity scale are materials that exhibit a large attractive force between the nucleus and the orbiting electrons. The net effect is a great deal of resistance to the movement of electrons. These materials are known as dielectrics. They have low conductivity and high resistivity. In electrical circuits and products, dielectric materials such as silicon dioxide (glass) are used as insulators.

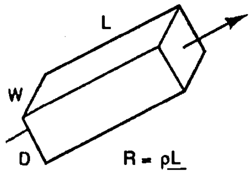
An electrical device known as a *capacitor* is formed whenever a dielectric layer is sandwiched between two conductors. In semiconductor structures, capacitors are formed in MOS gate structures, between metal layers and silicon subatrates separated by dielectric layers, and other structures (see Chapter 16). The practical effect of a capacitor is that it stores electrical charges. Capacitors are used for information storage in memory devices to prevent unwanted charges to build up in conductors and silicon surfaces, and to form the working parts of field effect (MOS) transistors. Capacitance ability of a film is relative to the area and thickness and a property parameter known as the dielectric constant. Semiconductor metal conduction systems need high conductivity and, therefore, low resistance and low capacitance materials. These are referred to as low-k dielectrics. Dielectric layers used as insulators between conducting layers need high capacitances or high-k dielectrics.

$$C = \frac{k\,E_0\,A}{t}$$

C = capacitance
k = dielectric constance of material
E_0 = permitivity of free space (free space has the highest "capacitance")
A = area of capacitor
t = thickness of dielectric material

Resistors

An electrical factor related to the degree of conductivity (and resistivity) of a material is the electrical resistance of a specific volume of the material. The resistance is a factor of the resistivity and dimensions of the material. Resistance to electrical flow is measured in ohms as illustrated in Fig. 2.5.



R = Resistance
L = Length
W = Width
D = Depth
A = Cross sectional area = WxD
ρ = Resistivity of material

$$R = \frac{\rho L}{A}$$

$$R = \frac{\rho L}{W \times D}$$

Figure 2.5 Resistance of rectangular bar.

The formula defines the electrical resistance of a specific volume of a specific material (in this illustration, the volume is a rectangular bar with dimensions X, Y and Z). The relationship is analogous to density and weight, *density* being a material property and *weight* being the force exerted by a specific volume of the material.

Electric current flow is analogous to water flowing in a hose. For a given hose diameter and water pressure, only a given amount of water will flow out of the hose. The resistance to flow can be reduced by increasing the hose diameter, shortening the hose, and/or increasing the pressure. In an electrical system, the electron flow can be increased by increasing the cross section of the material, shortening the length of the piece, increasing the voltage (analogous to pressure), and/or decreasing the resistivity of the material.

Intrinsic Semiconductors

Semiconducting materials, as the name implies, are materials that have some natural electrical conducting ability. There are two elemental semiconductors—silicon and germanium—both found in column IV (Fig. 2.6) of the periodic table. In addition, there are some tens of material compounds (a compound is a material containing two or more chemically bound elements) that also exhibit semiconducting properties. These compounds come from elements found in columns III and V, such as gallium arsenide and gallium phosphide. Others are compounds from elements shown in columns II and VI.

The term intrinsic refers to these materials in their purified state and not contaminated with impurities or other substances.

Doped Semiconductors

Semiconducting materials, in their intrinsic state, are not useful in solid state devices. However, through a process called doping, specific

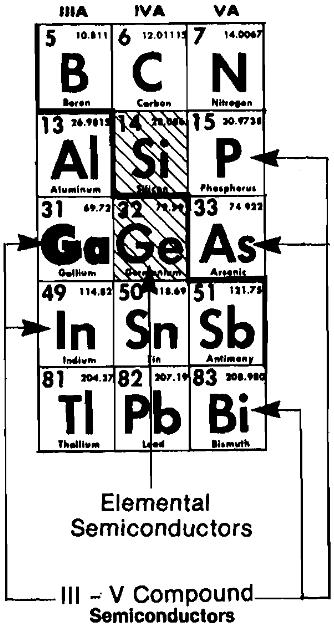


Figure 2.6 Semiconductor materials.

elements can be introduced into intrinsic semiconductor materials. These elements increase the conductivity of the intrinsic semiconductor material. The doped material displays two unique properties that *are* the basis of solid state electronics. The two properties are:

1. Precise resistivity control through doping
2. Electron and hole conduction

Resistivity of doped semiconductors

Metals have a conductivity range limited to 10^4 to 10^6/ohm-cm. The implications of this limit is illustrated by an examination of the resistor represented in Fig. 2.5. Given a specific metal with a specific resistivity, the only way to change the resistance of a given volume is to change the dimensions. In a semiconducting material, the resistivity can be changed, giving another degree of freedom in the design of the resistor. Semiconductors are such a material. Their resistivity can be extended over the range of 10^{-3} to 10^3 by the addition of dopant atoms.

Semiconducting materials can be doped into a useful resistivity range by elements that make the material either electron rich (N-type) or hole rich (P-type).

Figure 2.7 shows the relationship of the doping level to the resistivity of silicon. The x-axis is labeled the carrier concentration because the electrons or holes in the material are called carriers. Note that there are two curves: N-type and P-type. That is due to the different amount of energies required to move an electron or a hole through the material. As the curves indicate, it takes less of a concentration of N-type dopants than P-type dopants to create a given resistivity in silicon. Another way to express this phenomenon is that it takes less energy to move an electron than move a hole.

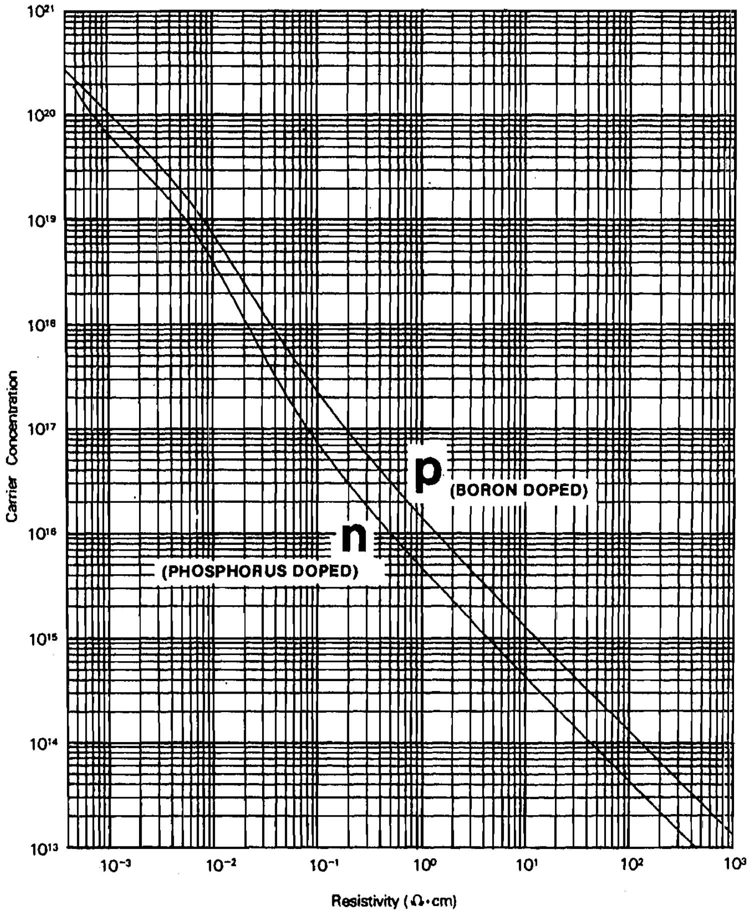


Figure 2.7 Silicon resistivity versus doping (carrier) concentration. (*After Thurber et al., Natl. Bur Standards Spec. Publ. 400-64, May 1981, tables 10 and 14.)*

It takes only 0.000001% to 0.1% of a dopant to bring a semiconductor material into a useful resistivity range. This property of semiconductors allows the creation of regions of very precise resistivity values in the material.

Electron and Hole Conduction

Another limit of a metal conductor is that it conducts electricity only through the movement of electrons. Metals are permanently N-type. Semiconductors can be made either N- and P-type by doping with specific dopant elements. N- and P-type semiconductors can conduct electricity by either electrons or holes. Before examining the conduction mechanism, it is instructive to examine the creation of free (or extra) electrons or holes in a semiconductor structure.

To understand the situation of N-type semiconductors, consider a piece of silicon (Si) doped with a very small amount of arsenic (As) as shown in Fig. 2.8. Assuming even mixing, each of the arsenic atoms would be surrounded by silicon atoms. Applying the rule from section 2.3.2 that atoms attempt to stabilize by having eight electrons in their outer ring, the atom is shown sharing four electrons from its neighboring silicon atoms. However, arsenic is from column V which means it has five electrons in its outer ring. The net result is that four of them pair up with electrons from the silicon atoms, leaving one left over. This one electron is available for electrical conduction.

Considering that a crystal of silicon has millions of atoms per cm^3, there are lots of electrons available to conduct an electrical current. In silicon, the elements arsenic, phosphorus and antimony create N-type conditions.

An understanding of P-type material is approached in the same manner (Fig. 2.9). The difference is that only boron, from column III of the periodic table, is used to make silicon P-type. When mixed into the silicon, it too borrows electrons from silicon atoms. However, having only three outer electrons, there is a place in the outer ring that is not filled by an electron. It is this unfilled position that is defined as a hole.

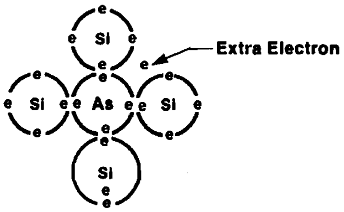


Figure 2.8 N-type doping of silicon with arsenic.

1. Chip, die, device, circuit, microchip, or bar. All of these terms are used to identify the microchip patterns covering the majority of the wafer surface.

2. Scribe lines, saw lines, streets, and avenues. These areas are spaces between the chips that allow separation of the chip from the wafer. Generally the scribe lines are blank, but some companies place alignment targets, or test structures (see photomasking) in them.

3. Engineering die, test die. These chips are different from the regular device or circuit die. They contain special devices and circuit elements that allow electrical testing during the fabrication processing.

4. Edge die. The edges of the wafer contain partial die patterns that are wasted space. The trend to increasing die sizes leads to more wasted space that is compensated by manufacturing larger diameter wafers. One of the driving forces behind larger wafer diameters is to minimize the area occupied by the edge die.

5. Wafer crystal planes. The cutaway section illustrates the crystal structure of the wafer under the circuit layers. The diagram shows that the chip edges are oriented to the wafer crystal structure.

6. Wafer flats/notches. The depicted wafer has a major and minor flat, indicating that it is a P-type ⟨100⟩ oriented wafer (see Chapter 3 for the flat code). 300mm diameter wafers use notches as crystal orientation indicators.

Basic Wafer-Fabrication Operations

There are hundreds of thousands of different microchip types and functions. However, they are made with a small number of basic structures (primarily bipolar or MOS structures, see Chapter 16) and manufacturing processes. An analogy is the auto industry. This industry produces a wide variety of products, from sedans to bulldozers. Yet the processes of metal forming, welding, painting, etc. are common to all plants. Within the plant, these basic processes are applied in different ways to produce the desired product.

The same is true in microchip fabrication. Companies use four basic operations in an infinite number of sequences and variations to produce specific microchips. They are layering, patterning, doping, and heat treatments (Fig. 4.3).

- Layering
- Patterning
- Doping
- Heat Treatments

Figure 4.3 Basic wafer-fabrication operations.

Layering

Layering is the operation used to add thin layers to the wafer surface. An examination of the simple MOS transistor structure in Fig. 4.4 shows a number of layers that have been added to the wafer surface. These layers could be insulators, semiconductors, or conductors. They are of different materials and are grown or deposited by a variety of processes.

The major techniques are grown silicon dioxide layers and deposition (Fig. 4.5) of a variety of materials. Common deposition techniques are chemical vapor deposition (CVD), evaporation, and sputtering. Figure 4.6 lists common layer materials and layering processes. The details of each are explained in the process chapters. The role of the different layers in the structures is explained in Chapter 16.

Patterning

Patterning is the series of steps that results in the removal of selected portions of the added surface layers (Fig. 4.7). After removal, a *pattern* of the layer is left on the wafer surface. The material removed may be in the form of a hole in the layer or just a remaining island of the material.

The patterning process is known by the names photomasking, masking, photolithography, and microlithography. During the wafer fabri-

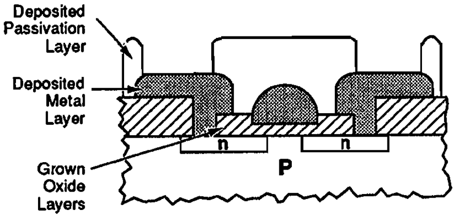


Figure 4.4 Cross section of completed metal gate MOS transistor with grown and deposited layers.

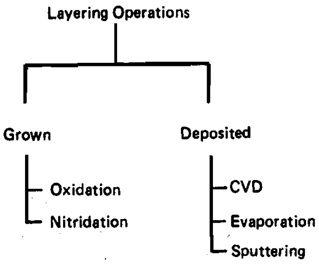


Figure 4.5 Layering operations.

Layers	Thermal Oxidation	Chemical Vapor Deposition	Evaporation	Sputtering
Insulators	Silicon Dioxide	Silicon Dioxide Silicon Nitrides		Silicon Dioxide Silicon Monoxide
Semiconductors		Epitaxial Silicon Poly Silicon		
Conductors			Aluminum Aluminum/Silicon Aluminum/Copper Nichrome Gold	Tungston Titanium Molybdenum Aluminum Aluminum/Silicon Aluminum/Copper

Figure 4.6 Table of layers, processes, and materials.

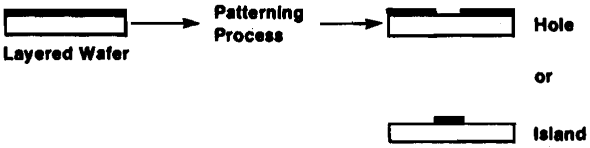


Figure 4.7 Patterning.

cation process, the various physical *parts* of the transistors, diodes, capacitors, resistors and metal conduction system are formed in and on the wafer surface. These parts are created one layer at a time by the combination of putting a layer on the surface and removing portions, with a patterning process, to leave a specific shape. The goal of the patterning operation is to create the desired shapes in the exact dimensions (feature size) required by the circuit design, and to locate them in their proper location on the wafer surface and in relation to the other *parts.*

Patterning is the most critical of the four basic operations. This operation sets the critical dimensions of the devices. Errors in the patterning process can cause distorted or misplaced patterns that result in changes in the electrical functioning of the device/circuit. Misplacement of the pattern can have the same bad results. Another problem is defects. Patterning is a high tech version of photography, but performed at incredibly small dimensions. Contamination in the process steps can introduce defects. This contamination problem is magnified by the fact that patterning operations are performed on the wafer from five to twenty or more times in the course of the wafer-fabrication process.

Doping

Doping is the process that puts specific amounts of dopants in the wafer surface through openings in the surface layers (Fig. 4.8). The

Chapter 14

Process and Device Evaluation

Overview

The wafer-fabrication process requires a high degree of precision in process control, equipment operation, and material manufacture. One mistake can render the wafer completely useless. Throughout the process, a variety of tests and measurements are made to determine both wafer and process quality. The tests take place on in-process wafers, test die and production die, and the finished circuit. Individual tests are described in this chapter. Statistical process control programs are addressed in Chapter 15.

Objectives

Upon completion of this chapter you should be able to:

1. Explain the difference between resistance, resistivity, and sheet resistance.
2. Draw a sketch of the parts and current flow in a four-point probe.
3. Compare the principles and uses of color interference, fringe counting, spectrophotometers, ellipsometers, and stylus for film thickness measurements.
4. Compare the principles and uses of groove and stain, SEM, and spreading resistance for junction depth measurements.
5. List the methods and advantages of microscope and SEM inspection of wafer surfaces.
6. Draw sketches of diodes in forward and reverse bias and their companion current-voltage curves.

7. Explain the effect of surface current leakage on a junction performance characteristic.
8. Draw sketches of a bipolar and MOS transistor in operation and their companion current-voltage characteristics.
9. List the process steps for a capacitance-voltage measurement and the principle of contamination detection.
10. Describe the principle and use of atomic force microscopes.

Introduction

Characterization of processes and circuit parameters is required for production-line control and product stability. Good characterization can warn of a process about to go out of control and device characterization is essential to analyze circuit performance and conformance to customer specifications. Consequently, every process step has a rigid set of equipment and process parameters that are controlled (temperature, time, etc.). And after every significant process step there is an evaluation of the result on the wafer or a test wafer. *Test wafers* are blank wafers or wafer pieces that are included in the process step for post process measurements. Many of the tests are destructive and cannot be performed on the device wafers or cannot be performed on the actual components in the chip. In the process chapters, the important parameters for each process were identified (film thickness, resistivity, cleanliness, etc.). Here, the basic theory, applicability, and range of sensitivity of the test methods are examined.

From the perspective of process control and improvement, there is a collection of measurements, some direct, some indirect. One group includes electrical measurements of test wafers and on the actual devices. They measure the direct effect of some of the processes, such as ion implantation. Device performance measurements are usually inclusive of several process and the results used to infer individual process parameter control. Another group directly measures physical parameters such as layer thicknesses and widths, composition, and others. This group includes defect detection. A third group measures contamination in and on the wafer and in materials.

Not surprisingly, test and measurement methods have changed along with the levels of integration and smaller image sizes. ULSI technology is ushering in nanometer- and angstrom-level inquiry, called the *nanoanalysis era*.[1] And the price of in-line testing is going up. Larger wafers and more dense circuits require more tests to properly characterize processes. High-volume processing requires real time testing and analysis to guard against scrapping volumes of production wafers. Measurement systems for ULSI circuits usually include onboard statistical analysis and data base management capabilities.

the transistor on and off (switching speed) is critical when millions of transistors are operating.

Field-effect transistors (FETs)

Metal-gate MOSFET. As early as 1948 William Shockley noted another type of transistor operation, a field-effect-actuated transistor current flow. That effect was developed into the field-effect transistor, with the MOS structure now the most popular design. An MOS transistor, like a bipolar (Fig. 16.18), has three regions, three contacts, and two junctions but in a different structure. There is a similar analogy to the water system described previously. Current travels from the source region (tank), through the dielectric gate material (valve), and into the drain (bucket) before exiting the device.

An MOSFET gate controls current flow by a different mechanism than a bipolar base. The MOS structure shown in Fig. 16.19 is a simple metal-gate type capacitor and operates the same as a capacitor. When a voltage (the gate voltage) is applied to the gate through the gate metal a *field effect* takes place in the surface of the semiconductor. The effect is either a build-up of charge or a depletion of charges in

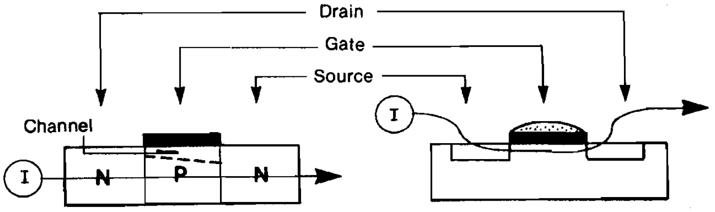


Figure 16.18 MOS transistor operation.

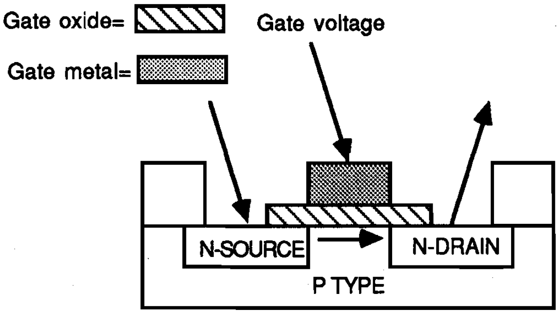


Figure 16.19 Metal gate MOS transistor.

the wafer surface under the top plate. Which event occurs depends on the doping conductivity type in the wafer under the gate and the polarity of the gate voltage.

The build-up or depletion of charge creates a channel under the gate which connects the source and drain. The surface of the semiconductor is said to be *inverted*. The source is biased with a voltage and the drain is grounded relative to the source. In this condition a current starts to flow as the inverted surface creates an electrically connecting channel. The source and drain are essentially shorted together. Applying more voltage to the gate increases the size of the channel, allowing more current to flow through the transistor (see Chapter 14). By controlling the gate voltage, an MOS transistor can be used as a switch (on/off) or as an amplifier. However, MOS transistors are voltage amplifiers, unlike the current amplification of bipolar transistors.

If the source and drain are N type formed in a P-type wafer, the channel must be of N type for conduction to occur. This type of MOS transistor is called N channel. MOS transistors with P-type sources and drains are P channel. Most high-performance MOS circuits are built around N-channel transistors due to the higher mobility of electrons in silicon. The mobility makes N-channel transistors faster and they consume less power than P-channel circuits. They often are referred to as NMOS transistors. Figure 16.20 shows the major steps in the formation of an N-channel metal-gate MOS transistor.

Silicon Gate MOS. A certain amount of voltage must be applied to the gate metal before the channel forms. This voltage is called the *threshold voltage* or *V*. The value of the threshold voltage is an important and critical circuit parameter. A lower *V* means less power supplies and faster circuits.

A primary parameter that determines the threshold voltage is the *work function* between the gate material and the doping level in the semiconductor. The work function can be thought of as a kind of electrical compatibility. The lower the work function, the lower the threshold voltage, the lower the power required to run the circuit, etc.

Deposited doped polysilicon has a lower work function than aluminum as an MOS gate material and has become the standard gate electrode material for MOS transistors. The formation of the transistor is shown in Fig. 16.21. The polysilicon is heavily doped N type to reduce its resistance. Thus doped it serves as the gate electrode and as a circuit conduction line. A polysilicon gate can withstand subsequent high-temperature processing without degradation.

An additional benefit of the silicon-gate process is the self-aligned gate. In the metal-gate process sequence, a hole for the gate oxide must be patterned between the source and drain. To ensure that the

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