Transistors, Diodes, and Solar Cells:

An Introduction to the Semiconductor Devices That Run the World

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Rising Dragon Books.

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DEDICATION

I dedicate this book to my parents, who taught me to think.

I dedicate this book to my brothers and sisters, cousins, aunts, uncles, and grandparents, who taught me the value of family.

I dedicate this book to my wife, who has always encouraged and supported me in everything that I do.

I dedicate this book to my children, who bring great joy and happiness to my life.

Finally, I dedicate this book to all my students and colleagues who have asked me questions that forced me to find better answers.

PREFACE

There are many books on semiconductor devices. Why would I write one?

When teaching, I found that there were some topics that were hard for students to understand, so I supplemented with my own notes. Then I wanted to make sure my students had some material that was more up to date than what is found in the existing books, so I had to write some more notes. After a few years of teaching, I found myself with Chapters 4, half of Chapter 7, and Chapters 9, 10, and 11. I also had short, 1-2 page sets of notes on other topics. With a book half-written before I had even started, it only seemed natural to complete the book. I believe this is how many textbooks are written.

I wrote the book "Operating Principles of Semiconductor Devices," which is what this book is based on. There was only a print version and limited availability. Having taught using that book for many years, I also learned how I could improve the writing to make some topics easier to understand. Thus, I wrote this book to replace it. This book is greatly expanded over the original with more examples. In addition, there are now both print and ebook versions.

In this book, I tried to make the material as clear as I could. I have tried to be somewhat detailed when deriving equations, and I have included a number of example calculations. I always include equations for both the NMOS and PMOS transistor, and I don't expect the reader to figure out how to transform the equations to go from one to another.

Solar panels have become quite prevalent, and I find that my students pay more attention and ask more questions when I cover photovoltaics than when I teach any other topic. I did not include any political or regulatory information on photovoltaics in this book because they are constantly changing, but I highly recommend that any instructor supplement with a short discussion on the societal impact of solar panels for the simple reason that the students love to hear about photovoltaics, and you will be a very popular instructor.

Chapter 10 explains the economics of making ICs because the driving force for making transistors smaller is the economics of small transistors, not the performance enhancement. The performance enhancement is important, but the rate at which transistor become smaller would have been much slower if the economics didn't favor small transistors. I find that this is a good topic for motivating students and may be taught at any time in a semester. There is only one problem at the end of the chapter, but I feel that it is a very educational problem.

This book does not introduce the BJT. I know that every other book on semiconductor devices includes a chapter on BJTs, but BJTs are rarely used anymore and I see no reason to teach it.

There is a chapter on IGBTs because these have replaced BJTs for power applications. IGBTs are not covered in most introductory books. An IGBT has a built-in BJT, but the chapter is written such that the reader doesn't need to know anything about the BJT.

I would like to acknowledge the help of my wife, Kerridwen Mangala McNamara, who has read through portions of the manuscript and provided valuable feedback, as well as helping with the formatting of the book.

Shamus McNamara
2024

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Nomenclature

$\blacksquare_n$	When a variable is subscripted with the letter 'n', it refers to a property of the electrons. For example, the mobility of electrons is μ_n.	
$\blacksquare_p$	When a variable is subscripted with the letter 'p', it refers to a property of the holes. For example, the mobility of holes is μ_p.	
$\blacksquare_N$	When a variable is subscripted with the capital letter 'N', it refers to a property in the n-region of a device. For example, the physical width of the n-region is W_N.	
$\blacksquare_P$	When a variable is subscripted with the capital letter 'P', it refers to a property in the p-region of a device. For example, the physical width of the p-region is W_P.	
$\boldsymbol{\alpha}$	This symbol serves multiple purposes as described below.	
	α	Temperature Coefficient of Resistance (TCR). This parameter is used to describe the change in resistance for a change in temperature. Units: (K^{-1}) or $(°C^{-1})$.
	α	A parameter that is used for calculating yield using a binomial distribution to account for clustering of defects. This parameter is normally fit to experimental data and typical numbers are between 3 and 4.
	α	Absorption coefficient. This describes how rapidly light is absorbed and is the inverse of the absorption length. Units: (cm^{-1})
$\boldsymbol{\beta}$	Internal current gain of an IGBT. The ratio of the collector current divided by the drain current due to the MOSFET built into the IGBT.	
$\boldsymbol{\Delta n}$	Excess electron concentration in the conduction band. $\Delta n = n - n_0$. The excess electron concentration can be positive or negative.	

Δp	Excess hole concentration in the valence band. $\Delta p = p - p_0$. The excess hole concentration can be positive or negative.	
χ	Electron affinity of a semiconductor. Electron affinity is defined as $\chi = E_{\text{vac}} - E_C$. Units: (eV)	
ϵ	Dielectric constant or permittivity (two names for the same thing). This can be either a relative dielectric constant, which is unitless, or it can be the dielectric constant of free space, which has units of (F/cm).	
	ϵ_0	Permittivity of free space. $\epsilon_0 = 8.854 \times 10^{-14}$ F/cm
	ϵ_S	Relative dielectric constant of a semiconductor.
	ϵ_i	Relative dielectric constant of an insulator.
$\mathcal{E}$	Electric field. The electric field is technically a vector, but in this book we will only use the electric field in one dimension, making it a scalar. Units: (V/cm)	
	$\mathcal{E}_x$	One dimensional electric field in the x-direction. Units: (V/cm)
	$\mathcal{E}_S$	Critical electric field that separates the drift velocity between the non-velocity saturated regime and the velocity saturated regime.
	$\mathcal{E}_{crit}$	Electric field at which Avalanche breakdown occurs.
	$\mathcal{E}_m$	Maximum electric field in a p-n junction.
ϕ	Electric potential within a semiconductor. Units are (V).	
	ϕ_i	Electric potential of the middle of the band gap. This is related to E_i.
	ϕ_F	Electric potential of the Fermi level of the semiconductor. This is related to E_F.
	ϕ_B	In a MOSFET, the Body potential of the Fermi level relative to the intrinsic level.
	ϕ_{SB}	Potential at the surface of a MOSFET, relative to the potential deep in the substrate. In many books the subscript 'B' is implied.
	ϕ_{bi}	Built-in electric potential of a p-n junction.
Φ	Work function in terms of electric potential. Units are volts (V).	
	Φ_G	Work function of the gate.

	Φ_B	Work function of the semiconductor substrate (body).
	Φ_{GB}	Work function difference between the gate and the semiconductor substrate (body).
$\boldsymbol{\gamma}$	Injection efficiency. The ratio of the hole current being injected into the base of an IGBT from the collector divided by the total current into the base.	
$\boldsymbol{\kappa}$	Thermal conductivity. Units: $\left(\frac{\mathrm{W}}{\mathrm{m \cdot K}}\right)$	
$\boldsymbol{\mu}$	Mobility of an electron or hole. Units: $(\mathrm{cm}^2/\mathrm{V \cdot s})$	
	μ_n	Electron mobility. Units: $(\mathrm{cm}^2/\mathrm{V \cdot s})$
	μ_p	Hole mobility. Units: $(\mathrm{cm}^2/\mathrm{V \cdot s})$
$\boldsymbol{\rho}$	Charge density per unit volume. Units: $(\mathrm{C/cm}^3)$.	
$\boldsymbol{\varrho}$	Resistivity. Units: $(\Omega \cdot \mathrm{cm})$ Unfortunately, both charge density and resistivity traditionally use the same symbol. To differentiate, the symbol for resistivity used in this book is a variant of the Greek letter rho.	
$\boldsymbol{\sigma}$	Conductivity. Units: $\left(\frac{1}{\Omega \cdot \mathrm{cm}}\right)$	
$\boldsymbol{\Theta}$	Flux of particles moving through a cross-sectional area per unit time. Normally this will be a flux of electrons or holes used to describe diffusion. Units: $(\mathrm{cm}^{-2}\mathrm{s}^{-1})$	
	Θ_n	Flux of electrons.
	Θ_p	Flux of holes.
$\boldsymbol{\tau}$	Lifetime of an electron or hole. This is the average time before the electron or hole recombines.	
$\boldsymbol{A}$	Area. Units: (cm^2)	
	A	Commonly used for the cross-sectional area through which current flows. The area may be width x height.
	A_{Die}	Area of one die on a substrate.
$\boldsymbol{B}$	Base transport factor. The percentage of electrons (or holes) that make it through the base of an IGBT without recombining. Unitless.	

C	Capacitance per unit area: Units: (F/cm^2)	
	C_i	Gate capacitance per unit area due to the gate insulator on a MOSFET. Units: (F/cm^2)
	C_D	Depletion capacitance per unit area. This variable can be associated with multiple types of devices, including MOSFETs and diodes. Units: (F/cm^2)
	C_G	Total gate capacitance per unit area. This includes C_i and C_D. Units: (F/cm^2)
	C_{TOT}	Total capacitance, including the area. $C_{TOT} = C \cdot A$. Units: (F)
D	This symbol does double duty, as described below.	
	D	Defect density on a substrate. Units: # defects/area, or (cm^{-2}).
	D_n	Diffusion coefficient for electrons. Units: $\left(\frac{\text{cm}^2}{\text{V·s}}\right)$
	D_p	Diffusion coefficient for holes. Units: $\left(\frac{\text{cm}^2}{\text{V·s}}\right)$
E	Energy. Units are electron-volts, (eV). Note that all energies are relative, similar in manner to how voltages are relative.	
	E_{12}	When more than one subscript is present, this presents the difference between two energies. The convention is $E_{12} = E_1 - E_2$.
	E_C	Energy level of the bottom of the conduction band.
	E_V	Energy level of the top of the valence band.
	E_F	Energy of the Fermi level. A quantum state with an energy equal to the Fermi level has a 50% change of being occupied by an electron.
	E_i	Energy of the middle of the band gap.
	E_G	Band gap of a semiconductor. This is equal to $E_C - E_V$. The band gap is a material property.
	E_{vac}	Vacuum level of a material. This is the energy of an electron that is not bound by an atomic orbital.
	E_{ph}	Energy of a photon.

$\boldsymbol{f(E)}$	Distribution function. Often, when there is no subscript, it will refer to the Maxwell-Boltzmann distribution function.	
	$f_{FD}(E)$	Fermi-Dirac distribution function. This is the most accurate distribution function that represents how electrons are distributed as a function of energy.
	$f_{MB}(E)$	Maxwell-Boltzmann distribution function. This function is a good approximation for the Fermi-Dirac distribution function and is much easier to handle for hand calculations.
$\boldsymbol{F}$	Force. Force is technically a vector, but in this book we will only need to use the force in one dimension. Units: (N)	
	F_x	Force in the x-direction. Units: (N)
$\boldsymbol{G}$	Generation rate. This is the rate at which electrons and holes are generated per volume. Units: ($cm^{-3}s^{-1}$)	
$\boldsymbol{H}$	Height of a cross-sectional area. Units: (cm)	
$\boldsymbol{I}$	The current into a semiconductor device. Units: (A)	
	I_D	Drain current in a MOSFET.
	I_{DS}	Drain current in a MOSFET. This is the same as I_D. Although the subscript 'S' isn't required, sometimes it is written this way to emphasize that the current flows from the drain into the source.
	I_G	Gate current in a MOSFET. This is normally either zero, or very close to zero.
	I_C	Collector current in an IGBT.
	I_E	Emitter current in an IGBT.
$\boldsymbol{J}$	Current density within the semiconductor. The current density is current divided by cross-sectional area: $J = I/A$. Units are (A/cm^2)	
	J_{diff}	Diffusion current density. This does not include the drift current density, but does include both electron and hole diffusion current densities.
	J_{drift}	Drift current density. This does not include diffusion current density, but does include both electron and hole drift current densities.
	J_n	Electron current density. This does not include hole current density, but does include both diffusion and drift current densities.

	J_p	Hole current density. This does not include electron current density, but does include both diffusion and drift current densities.
	J_{TOT}	Total current density. This is often just written as J, but the subscript may be used to emphasize that components of the current density were summed up. For example: $J_{TOT} = J_{\text{diff}} + J_{\text{drift}}$ $J_{TOT} = J_n + J_p$
	J_S	Reverse saturation current density of a p-n junction. This is the amount of current that flows under reverse bias.
	J_{op}	Optical current density. This current density is due to light incident on a semiconductor p-n junction.
	J_{sc}	Short-circuit current in a p- junction illuminated with light (photovoltaic cell).
	J_{ECB}	Tunneling current density where the electrons tunnel into the conduction band.
	J_{EVB}	Tunneling current density where the electrons tunnel into the valence band.
k	Wave number of an electron. Units: (cm^{-1})	
$\boldsymbol{k_B}$	Boltzmann's constant: $1.38 \times 10^{-23}\,\frac{\text{J}}{\text{K}} = 8.62 \times 10^{-5}\,\frac{\text{eV}}{\text{K}}$	
L	Length of a layer. Units: (cm)	
	L	In a MOSFET, L will refer to the length of the gate; the distance from the source to the drain.
	L_{drawn}	In a MOSFET, L_{drawn} is the distance between the source and drain as indicated on a CAD program, and is normally the drawn length of the gate metal. This length may be different than the effective gate length of a MOSFET.
	L_n	Diffusion length for electrons. This is the average distance an excess electron travels before recombination.
	L_p	Diffusion length for holes. This is the average distance an excess hole travels before recombination.

	L_A	Absorption length. This is the average distance light travels in a semiconductor before it is absorbed. The absorption length depends on the wavelength of the light.
$\boldsymbol{n}$	Concentration of electrons in the conduction band. Units are electrons per volume, or (cm^{-3}).	
	n_0	Equilibrium concentration of electrons in the conduction band.
	n_i	Intrinsic (undoped) concentration of electrons in the conduction band. This variable is commonly used in equations, and the intrinsic value should be used even if the semiconductor is doped.
$\boldsymbol{N}$	Concentration or number density. This is used for the number density of quantum states and for the number density of dopant atoms. Units are number per volume, or (cm^{-3}).	
	N_A	Concentration of acceptor atoms. Units are (cm^{-3}). Sometimes this is written as N_A^- to emphasize that these atoms are negatively ionized.
	N_D	Concentration of donor atoms. Units are (cm^{-3}). Sometimes this is written as N_D^+ to emphasize that these atoms are positively ionized.
	N_C	Effective density of states for electrons in the conduction band. Units are (cm^{-3}). This is a material property.
	N_V	Effective density of states for holes in the valence band. Units are (cm^{-3}). This is a material property.
	N_{SS}	Density of surface states on the semiconductor surface for a MOSFET. Units: (cm^{-2})
	N_{TI}	Threshold adjust Implant density. This is the atomic density introduced by an ion implanter used to adjust the threshold voltage of a MOSFET.
$\boldsymbol{p}$	Concentration of holes in the valence band. Units are holes per volume, or (cm^{-3}).	

	p_0	Equilibrium concentration of holes in the valence band.
	p_i	Intrinsic (undoped) concentration of holes in the valence band. This variable is not normally used in equations because its value is the same as n_i.
P	Power. This can be electrical power or optical power. The optical power will always have a subscript. Units: (W)	
	P_{ph}	Optical power. Units: (W)
q	Charge of an electron or hole. The constant q is always a positive number. The equations that use q have a positive or negative sign to represent that charge, as appropriate. $q = 1.6 \times 10^{-19}$ C.	
Q	Charge density per unit area. Units: (C/cm^2)	
	Q_D	Depletion charge per unit area.
	Q_S	Charge per unit area in the semiconductor.
	Q_G	Charge per unit area on the gate of a MOSFET.
	Q_i	Inversion charge per unit area in the channel region of a MOSFET.
	Q_{SS}	Charge density due to the surface states on a semiconductor surface. This charge is always positive. $Q_{SS} = qN_{SS}$
	Q_{TI}	Threshold adjust Implant charge density. This is a surface charge density introduced by an ion implanter used to adjust the threshold voltage of a MOSFET.
R	The letter *R* does double duty, as shown below.	
	R	Resistance. Units: (Ω).
	R_N	Resistance of the n- region.
	R_P	Resistance of the p- region.
	R_{eq}	Equivalent resistance.
	R	Recombination rate. The rate at which electrons and holes recombine, per volume. Units: (cm^{-3}s^{-1})
S	The so-called sub-threshold slope for a MOSFET. This is the voltage required to obtain a 10x change in current when the MOSFET is in cutoff.	

$\boldsymbol{t}$	Time. Units: (s)	
$\boldsymbol{t_i}$	Thickness of the insulating layer on a MOSFET. Units: (cm)	
$\boldsymbol{t_{Si}}$	Thickness of a silicon layer, especially in a SOI MOSFET or FinFET. Units: (cm)	
$\boldsymbol{T}$	Absolute temperature. Units: (K)	
$\boldsymbol{v_d}$	Drift velocity of an electron or hole. This is the average velocity of the carrier due to an electric field. Units: (cm/s)	
$\boldsymbol{V}$	An externally applied voltage. Unfortunately, conventions require that subscripts are sometimes repeated, such as reusing V_B for the base of a BJT and the body of a MOSFET. This book will ensure that the subscripts are unique for any given device. Units are volts (V).	
	V_{12}	When more than one subscript is present, this presents a voltage between two points. The convention is $V_{12} = V_1 - V_2$.
	V_G	Gate voltage on a MOSFET.
	V_D	Drain voltage on a MOSFET.
	V_D	Applied voltage on a diode when modeling the diode with a series resistor. The voltage across the depletion region, V_{pn}, is smaller than the voltage applied to the electrodes, V_D.
	V_S	Source voltage on a MOSFET. In most equations the source will be the reference voltage, and the other terminal voltages will be written as V_{DS}, V_{GS}, and V_{BS}.
	V_B	Body (or substrate) voltage on a MOSFET.
	V_T	Threshold voltage for a MOSFET. This is the voltage that must be applied to the gate to turn on a MOSFET.
	V_{FB}	Flat band voltage for a MOSFET. This is the voltage that must be applied to the gate to make the energy bands flat within the semiconductor.
	V_{app}	Voltage applied to a semiconductor.
	V_{pn}	Voltage applied between the anode (p-region) and cathode (n-region) of a p-n junction.

	V_E	Emitter voltage on an IGBT.
	V_C	Collector voltage on an IGBT.
	V_{oc}	Open-circuit voltage in a p-n junction illuminated with light (photovoltaic cell).
$\boldsymbol{W}$	Width of a layer. Units: (cm)	
	W	In a MOSFET, W refers to the width of the gate.
	W_D	Width of the depletion layer. In a p-n junction, W_D refers to the total depletion layer width of both the p- and n- regions. Units: (cm)
	W	Width of a cross-sectional area.
	W_P	Physical width of the p- region, including any depletion regions.
	W_N	Physical width of the n- region, including any depletion regions.
$\boldsymbol{x}$	Coordinate axis. Sometimes x is subscripted to indicate specific points on the coordinate axis.	
	x_N	In a p-n junction, x_N is the width of the depletion region in the n- region. The edge of the depletion region is located at $x = x_N$.
	x_P	In a p-n junction, x_P is the width of the depletion region in the p- region. The edge of the depletion region is located at $x = -x_P$. Thus x_P is a positive number.
$\boldsymbol{Y}$	Yield. The percent of good die on a wafer. This is unitless, but commonly expressed as a percentage.	

1 Introduction

Semiconductors are present everywhere in modern society. The reason semiconductors are so prevalent is because the electrical properties are easily modified through design and through other physical effects. In addition, making electronic devices out of semiconductors is economical.

Semiconductors are not special because they conduct electricity poorly. Many materials conduct electricity poorly. In fact, we can take a thin wire of copper and make it very long so that it will have a high resistance. The resistance can then be higher than the resistance of a short length of a semiconductor. So what, then, makes a semiconductor special? Semiconductors are special because their resistivity can be changed with light or an applied voltage on demand. A comparison is shown in the following table.

	Conductor	**Semiconductor**	**Insulator**
Example material	Copper	Silicon	Glass
Resistivity	Low	High	High
Conductivity	High	Low	Low
Resistivity change with:			
Light	None	Large	None
Voltage	None	Large	None
Temperature	Small	Large	Small

It is the large change in resistivity with voltage that will be used most often throughout this book because it permits us to create diodes, transistors, and power transistors. Solar cells will take advantage of the change in resistivity of both voltage and light.

1.1 Uses of Semiconductors

Semiconductors are used all around us. They make up our computers, cell phones, and tablet computers. They are integral to the television screens that we watch. They are used in the home appliances that we utilize, such as the microwave oven, refrigerator, oven, dishwasher, and clothes dryer. They are integral to the cars we drive, as well as controlling the traffic lights that direct traffic. They are used in LEDs that are used in lighting for computer screens, traffic lights, Christmas tree lights, and other lights. They are used in all solar panels on homeowners' rooftops, commercial buildings, and in large industrial solar plants. Semiconductors are used wherever you see a blinking light: on DVD players, MP3 players, wrist watches, fitness bands, exit signs, and more. Finally, they are integral to the Internet, from electronic interfaces such as Wi-Fi and Ethernet, to the semiconductor laser diodes and detectors that are used in fiber optic communications.

1.2 Understanding Concepts

In this book, it is very important to learn concepts. In many engineering courses, a small number of concepts are taught and you learn how to apply these concepts to a variety of situations. For example, in a Circuits Course, you learn Ohm's law, Kirchhoff's current and voltage laws, and a few equations for inductors and capacitors. From these basic laws, an entire semester's worth of RCL circuits are analyzed.

In this book many, many concepts will be introduced, and only a few applications will be shown. This is the exact opposite of most engineering courses, in which a few concepts are used to explore a large variety of applications. Thus, it will be imperative for the reader to spend a lot of time reviewing the concepts. While an attempt will be made to introduce each concept in a simple manner such that concepts build on each other, it will be found that many concepts interact with other concepts. This book will try to help with the understanding by re-introducing concepts periodically, assuming that the reader has a better understanding of the underlying concepts and will better grasp the concepts being reviewed. But the reader of the book will find it is beneficial to re-read portions of the book a second time to gain a thorough understanding of the concepts. The author has taught this subject many times over the years, and it is his experience that the concepts must be reviewed more than once to gain a good understanding.

1.3 Outline of the book

This book starts with an introduction to the physics of semiconductors, including band diagrams, doping, resistivity, and current flow. Other semiconductor physics, such as optical absorption, E-k diagrams, continuity equations, generation, and recombination are deferred until they are needed for specific semiconductor devices. The philosophy of the book is to get to the device operation as quickly as possible, and learn the physics along the way.

MOSFETs are introduced as the first device because they are so important, and because it provides a great opportunity to describe what happens when energy bands bend: depletion regions and inversion regions are formed. Using a MOSFET, a depletion region can be introduced without worrying about the concept of current flow through the depletion region.

Then diodes are introduced, which requires a good understanding of minority carriers, diffusion current, carrier recombination, and the continuity equation.

Solar cells follow diodes because solar cells are a special type of diode. The chapter on solar cells covers the physics of how semiconductors absorb light. Similarly, LEDs and lasers follow solar cells because they are special types of diodes. This chapter covers the physics of how semiconductors emit light.

Now the reader is ready for advanced MOSFET topographies. Sub 100-nm MOSFETs are described because they are commonly used in industry and are state of the art. These devices also look and behave very differently from the long-channel MOSFET introduced earlier.

The final chapter covers power transistors. The power MOSFET and IGBT are covered. It is covered to provide the reader with an introduction to power semiconductor devices, which are used to control

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the flow of power to other devices. For example, they are used in power supplies, USB chargers, and motor controllers.

1.4 Homework Problems

1. Consider a slab of silicon with a resistivity of $10\ \Omega \cdot \text{cm}$. It has a length of 5 cm, width of 1 cm, and a thickness of 1 cm. Current flows along the length of the silicon.
   a. What is the resistance of the silicon?
   b. If I were to replace the silicon with copper (resistivity = $1.68 \times 10^{-6}\ \Omega \cdot \text{cm}$), what thickness gives the same resistance as you obtained in part (a)?

   Note #1: Using a technique called atomic layer deposition (ALD), it is possible to get copper just a few atoms thick. Therefore, your answer is reasonable. Look up Atomic Layer Deposition!

   Note #2: The resistivity of copper increases when the thickness is much smaller than a typical grain size due to increased scattering. We did not take this into account.

This chapter is a brief outline of the uses of different types of semiconductors. The purpose of this chapter is to motivate the reader to take an interest in the subject material. The reader may not be familiar with some concepts used in this chapter, but the author hopes that this material is sufficiently general to pique the interest of the reader. After learning more about semiconductors in later chapters, the reader may wish to re-visit this chapter.

2.1 Silicon

Silicon (Si) is the most widely used semiconductor. It has been said that we have gone through the Stone Age, the Bronze Age, the Iron Age, …

and that we are now in the Silicon Age. Silicon easily makes up over 99% of the semiconductor market.

Silicon is used to make transistors for analog circuits, digital circuits, and power circuits. Silicon can be grown as a single crystal with relative ease and incredible purity, and thus is available at a lower cost than any other semiconductor. Further, it is stable at high temperatures, engineers know how to introduce dopants with nanometer precision, and a stable insulator can be readily added that introduces very few defects. These advantages cannot be met by any other semiconductor. The manufacturing knowledge that has been built up over the past 50+ years creates a huge market barrier to the introduction of a new semiconductor material to replace silicon.

Silicon is used to create VLSI circuits that consist of billions of transistors on an integrated circuit. The reason silicon is used for VLSI is that the transistors can be made very small and use much less power than the transistors used with any other semiconductor. When there are 1 billion transistors on a chip, 1 μA of leakage current per transistor is equal to 1000 Amps of total wasted current.

Silicon is used for most solar cells. For solar cells, silicon comes in three forms: amorphous, polycrystalline, and single crystal. The efficiency improves as the silicon is made more crystalline, but the cost also increases. Single crystal solar cells are widely available with efficiencies over 20 %.

Silicon is used for power diodes, MOSFETs and IGBTs. Power BJTs were made of silicon, but the IGBT has largely displaced the BJT market.

Silicon is not the fastest semiconductor, but the faster semiconductors cannot compete in terms of power consumption, and the other semiconductors do not have a sufficiently large speed advantage to overcome the problems with power consumption for most applications.

If you look at your computer, cell phone, tablet, electronics in your car, electronics in your appliances, etc., you will find that it is almost all silicon based.

2.2 Germanium

Germanium (Ge) was used to create the first transistor, but it is much harder to work with germanium than silicon. The natural oxide, germanium oxide, is water soluble making manufacturing much more difficult. Germanium has a smaller band gap than silicon leading to higher leakage currents. These disadvantages led to the rapid adoption of silicon as the semiconductor of choice.

Germanium, with its small band gap, may be for infrared detectors.

2.3 SiGe

Silicon germanium (SiGe) is sometimes used on a silicon substrate because it can be readily grown on the silicon substrate with few defects. By changing the amount of germanium, the band gap can be changed and a built-in electric field can be generated. This is used to provide very fast heterojunction bipolar transistors that are faster than silicon MOSFETs. These transistors often used in high frequency RF applications, such as the RF interface on a cell phone.

2.4 GaAs

Gallium Arsenide (GaAs) has a higher electron mobility than silicon, and thus transistors made of GaAs are significantly faster. Two major disadvantages of GaAs are: (1) GaAs is much more expensive to manufacture, and (2) the power consumption is high. For a time, there was great interest in researching GaAs to replace silicon as the semiconductor of choice, but these disadvantages could never be overcome. Today, GaAs is used for high frequency RF applications, such as the RF interface on a cell phone.

GaAs is also a great light emitter, and is thus commonly used for making LEDs and laser diodes. By changing the chemical composition of GaAs, such as by adding Aluminum or Phosphorus, the wavelength of the emitted light may be modified. When you see a LED, or use a laser pointer, it is almost always made using GaAs.

2.5 GaN

Gallium Nitride (GaN) is a wide band gap semiconductor that readily emits blue light. At the time this is written, the defect density of GaN is many orders of magnitude higher than silicon, and extensive research efforts are underway to discover a method of creating inexpensive GaN substrates with lower defect densities. GaN laser diodes are used in Blu-Ray readers.

Despite the high defect density, GaN has attracted great interest for power transistors because of its high breakdown voltage and faster switching speed compared to silicon.

GaN LEDs make white LEDs possible since GaAs cannot produce blue light. White-light LEDs have become an economical solution for lighting applications as GaN substrates become less expensive.

GaN is also used for High Electron Mobility Transistors (HEMT) for high frequency RF applications.

2.6 SiC

Silicon carbide (SiC) is a wide band gap semiconductor that is used for power semiconductor devices. Having a large band gap, SiC has the same advantages as GaN for power devices: higher breakdown voltage, faster switching speed, and lower switching losses compared to silicon. But SiC also benefits from being very similar to silicon in terms of fabrication, making it very attractive from a manufacturing perspective. SiC is more expensive than silicon, but the reduced power losses make SiC transistors the best solution for many high power applications.

2.7 Bismuth Telluride

Bismuth Telluride (Bi_3Te_4) is a small band gap semiconductor that has good thermoelectric properties. By running a current through it, one side gets hot while the other side gets cold. This property can be used to cool electronics without any moving parts. The efficiency is not as great as a refrigerator or AC unit, so that market penetration is not large, but the simplicity and small size makes it attractive for some applications.

2.8 Diamond

Diamond is a form of carbon. It is commonly considered an insulator, but some researchers are investigating its use as a wide band gap semiconductor. Diamond has a very high thermal conductivity, making it potentially useful for power electronics where it will be much easier to cool the chip. Its thermal conductivity of 2200 W/m·K is about 5x greater than copper. Theoretically, diamond can provide very fast electronics with low leakage currents. The difficulties that must be overcome include problems with the manufacture of defect free diamond and problems with doping diamond. Until a manufacturing breakthrough occurs, diamond is not likely to be widely used as a semiconductor material.

2.9 Graphene

By itself, graphene is not technically a semiconductor because it has zero band gap. However, a band gap usually arises when other materials are added to graphene. Graphene is the subject of intense research because it is a 2 dimensional material. That is, graphene is made up of a single atomic layer of carbon atoms. This creates many unique physical, electronic, optical, and magnetic properties that are under investigation.

It is unclear what the future holds for graphene. The unique electronic properties mean that it is unlikely that graphene-based transistors will look like their silicon counterparts.

In addition to graphene, there are numerous other 2D materials that are under investigation, many of which have a natural band gap. This is a ripe area for research.

2.10 Organic Semiconductors

There is great interest in making semiconductors out of organic materials instead of inorganic materials. Organic materials are typically less expensive and processed at lower temperatures. However, the organic materials developed thus far have much lower electron mobility and hole mobility than silicon, and thus are much slower and cannot be used for power devices. Organic semiconductors have started to be commercialized, such as for OLED displays.

2.11 Problems

1. Do some investigating and find a typical cost for a substrate of the following semiconductors: Si, Ge, GaAs, and GaN.
   a. Make a table with the following five columns: semiconductor type (e.g., Si), wafer diameter, wafer cost, cost per cm^2, and your reference.

      Note: You should find that silicon is the least expensive per area.

   b. Explain why silicon is a popular semiconductor for manufacturing.