Textbook Preface (page x)

“The purpose of the fourth edition of this book is to provide a basis for understanding the characteristics, operation, and limitations of semiconductor devices. In order to gain this understanding, it is essential to have a thorough knowledge of the physics of the semiconductor material. The goal of this book is to bring together quantum mechanics, the quantum theory of solids, semiconductor material physics, and semiconductor device physics. All of these components are vital to the understanding of both the operation of present-day devices and any future development in the field.”

Course Goals

• To gain an understanding of semiconductor physics, and apply that knowledge to comprehend the characteristics, operation, and limitations of semiconductor devices.
• To be able to use derivations, calculations, and models to acquire a basic sense of how semiconductor devices work.
• To be able to design semiconductor-based devices to meet desired performance specifications.
• To be able to recognize the mechanisms of new semiconductor devices as they materialize and evolve in the near future.

Course Objectives

Students who complete this course should be able to...

1. Describe the basic principles of quantum mechanics and solid state physics, and relate these principles to semiconductor band structure and carrier concentration using appropriate diagrams and equations.
2. Describe charge transport, and carrier generation and recombination processes in both equilibrium and non-equilibrium conditions using appropriate diagrams and equations.
3. Describe the band structure, charge distribution and electric field and potential distribution for semiconductor devices in both equilibrium and non-equilibrium conditions using appropriate diagrams and equations.
4. Relate internal characteristics of the device such as charge distribution and electric field to externally measurable properties such as current or capacitance.
5. Relate device parameters such as material choice, doping levels and dimensions to device performance, such as current-voltage relationship, including non-ideal effects.
6. Design a diode or transistor by determining dimensions, materials and doping parameters in order to meet a set of desired performance specifications.
7. Identify critical issues for semiconductor devices including the environmental and safety issues related to semiconductor manufacturing.
8. Describe current trends and future needs in the semiconductor industry and identify the educational preparation necessary to meet those needs.
9. Evaluate how a new development in semiconductor technology fits into the arc of semiconductor development and evaluate the worth and impact of that new technology.
Chapter 1: The Crystal Structure of Solids

- List the most common elemental semiconductor material
- Describe the concept of a unit cell
- Determine the volume density of atoms for various lattice structures
- Determine the Miller indices of a crystal-lattice plane
- Sketch a lattice plane given the Miller indices
- Determine the surface density of atoms on a given crystal-lattice plane
- Describe the tetrahedral configuration of silicon atoms
- Describe the various defects in a single-crystal lattice

Chapter 2: Introduction to Quantum Mechanics

- Discuss the principle of energy quanta, the wave-particle duality principle, and the uncertainty principle
- Apply Schrödinger's wave equation and boundary conditions to problems with various potential functions
- Determine quantized energy levels of bound particles
- Determine the approximate tunneling probability of a particle incident on a potential barrier
- State Pauli exclusion principle
- Discuss the results of the one-electron atom analysis, including quantum numbers and their interrelationship.

Chapter 3: Introduction to the Quantum Theory of Solids

- Discuss the concept of allowed and forbidden energy bands in a single crystal
- Discuss the splitting of energy bands in silicone
- State the definition of effective mass from the E versus k diagram
- Discuss the concept of a hole
- Discuss the characteristics of a direct and an indirect bandgap semiconductor
- Discuss the difference between a metal, an insulator, and a semiconductor in terms of energy bands
- Understand the meaning of the Fermi-Dirac distribution function and the Fermi energy

Chapter 4: The Semiconductor in Equilibrium

- Derive the equations for the thermal equilibrium concentrations of electrons and holes in terms of the Fermi energy
- Derive the equation for the intrinsic carrier concentration
- Discuss what is meant by the effective density of states for electrons and holes
- Describe the effect of adding donor and acceptor impurity atoms to a semiconductor
- Understand the concept of complete ionization
- Derive the fundamental relationship \( n_0p_0 = n_i^2 \)
- Describe the meaning of degenerate and nondegenerate semiconductor materials
- Discuss the concept of charge neutrality
- Derive the equations for \( n_0 \) and \( p_0 \) in terms of impurity doping concentrations
- Derive the equations for the Fermi energy in terms of the impurity doping concentrations
- Discuss the variation of the Fermi energy with doping concentration and temperature
Chapter 5: Carrier Transport Phenomena

- Discuss carrier drift current density
- Explain why carriers reach an average drift velocity in the presence of an applied electric field
- Discuss the mechanisms of lattice scattering and impurity scattering
- Define mobility and discuss the temperature and ionized impurity concentration dependence on mobility
- Define conductivity and resistivity
- Discuss velocity saturation
- Discuss carrier diffusion current density
- State the Einstein relation
- Describe the Hall effect

Chapter 6: Nonequilibrium Excess Carriers in Semiconductors

- Describe the concept of excess carrier generation and recombination
- Describe the concept of an excess carrier lifetime
- Describe how the time-dependent diffusion equations for holes and electrons are derived
- Describe how the ambipolar transport equation is derived
- Understand the consequence of the coefficients in the ambipolar transport equation
- Apply the ambipolar transport equation to various problems
- Understand the concept of dielectric relaxation time constant and what it means
- Calculate the quasi-Fermi levels for electrons and holes
- Calculate the excess carrier recombination rate for a given concentration of excess carriers
- Understand the effect of a surface on the excess carrier concentration

Chapter 7: The pn Junction

- Describe why and how the space charge region is formed
- Draw the energy-band diagram of a zero-biased and reverse-biased pn junction
- Define and derive the expression of the built-in potential barrier voltage
- Derive the expression for the electric field in space charge region of the pn junction
- Describe what happens to the parameters of the space charge region when a reverse-biased voltage is applied
- Define and explain the junction capacitance
- Describe the characteristics and properties of a one-sided pn junction
- Describe the avalanche breakdown mechanism in a reverse-biased pn junction
- Describe how a linearly graded junction is formed
- Define a hyperabrupt junction

Chapter 8: The pn-Junction Diode

- Describe the mechanism of charge flow across the space charge region of a pn junction when a forward-bias voltage is applied
- State the boundary conditions for the minority carrier concentrations at the edge of the space charge region
- Derive the expressions for the steady-state minority carrier concentrations in the pn junction
- Derive the ideal current-voltage relationship for a pn junction diode
- Describe the characteristics of a “short” diode
- Describe the generation and recombination currents in a pn junction
- Define high-level injection and describe its effect on the diode I-V characteristics
Define what is meant by diffusion resistance and diffusion capacitance

Chapter 9: Metal-Semiconductor and Semiconductor Heterojunctions

- Sketch the energy-band diagram of zero-biased, reverse-biased, and forward-biased Schottky diodes
- Describe the charge flow in a forward-biased Schottky barrier diode
- Explain the Schottky barrier lowering and its effect on the reverse saturation current in a Schottky barrier diode
- Explain the effect of interface states on the characteristics of a Schottky barrier diode
- Describe one effect of a larger reverse saturation current in Schottky barrier diode compared to that of a pn junction diode
- Describe what is meant by an ohmic contact
- Draw the energy-band diagram of an nN heterojunction
- Explain what is meant by a two-dimensional electron gas

Chapter 10: Fundamentals of the Metal-Oxide-Semiconductor Field-Effect Transistor

- Sketch the energy-band diagrams in the semiconductor of the MOS capacitor under various bias conditions
- Describe the process by which an inversion layer of charge is created in a MOS capacitor
- Discuss the reason the space charge width reaches a maximum value once the inversion layer is formed
- Discuss what is meant by the metal-semiconductor work function difference and why this value is different between aluminum, n+ polysilicon, and p+ polysilicon gates
- Describe what is meant by flat-band voltage
- Define threshold voltage
- Sketch the C-V characteristics of a MOS capacitor with p-type and n-type semiconductor substrates under high-frequency and low-frequency conditions
- Discuss the effects of fixed trapped oxide charge and interface states on the C-V characteristics
- Sketch the cross sections of n-channel and p-channel MOSFET structures
- Explain the basic operation of the MOSFET
- Discuss the I-V characteristic of the MOSFET when biased in the nonsaturation and saturation regions
- Describe the substrate bias effects on the threshold voltage
- Sketch the small-signal equivalent circuit, including capacitances, of the MOSFET, and explain the physical origin of each capacitance
- Discuss the condition that defines the cutoff frequency of a MOSFET
- Sketch the cross section of a CMOS structure
- Discuss what is meant by latch-up in a CMOS structure

Chapter 11: Metal-Oxide-Semiconductor Field-Effect Transistor: Additional Concepts

- Describe the concept and effects of subthreshold conduction
- Discuss channel length modulation
- Describe carrier mobility versus gate-to-source voltage and discuss the effects on the current-voltage characteristics of a MOSFET
- Discuss the effect of velocity saturation on the current-voltage relationship of a MOSFET
- Define what is meant by constant-field scaling in MOSFET device design, and discuss how device parameters change in constant-field scaling
- Describe why the threshold voltage changes as the channel length decreases and as the channel width decreases
Describe the various voltage breakdown mechanisms in a MOSFET, such as oxide breakdown, avalanche breakdown, snapback breakdown, and near punch-through effects.

Describe the advantages of lightly doped drain transistor.

Discuss the advantages and the process of threshold adjustment by ion implantation.

Chapter 14: Optical Devices

Describe the optical absorption process in semiconductors. When is optical absorption essentially zero?

Describe the basic operation and characteristics of a solar cell, including the short-circuit current and open-circuit voltage.

Discuss the factors that contribute to the solar cell conversion efficiency.

Describe the advantages and disadvantages of an amorphous silicon solar cell.

Describe the characteristics of a photoconductor, including the concept of the photoconductor gain.

Discuss the operation and characteristics of a single pn junction photodiode.

Discuss the advantages of PIN and avalanche photodiodes compared to the simple pn junction photodiode.

Discuss the operation and characteristics of a phototransistor.

Describe the operation of an LED.

Describe the operation of a laser diode.