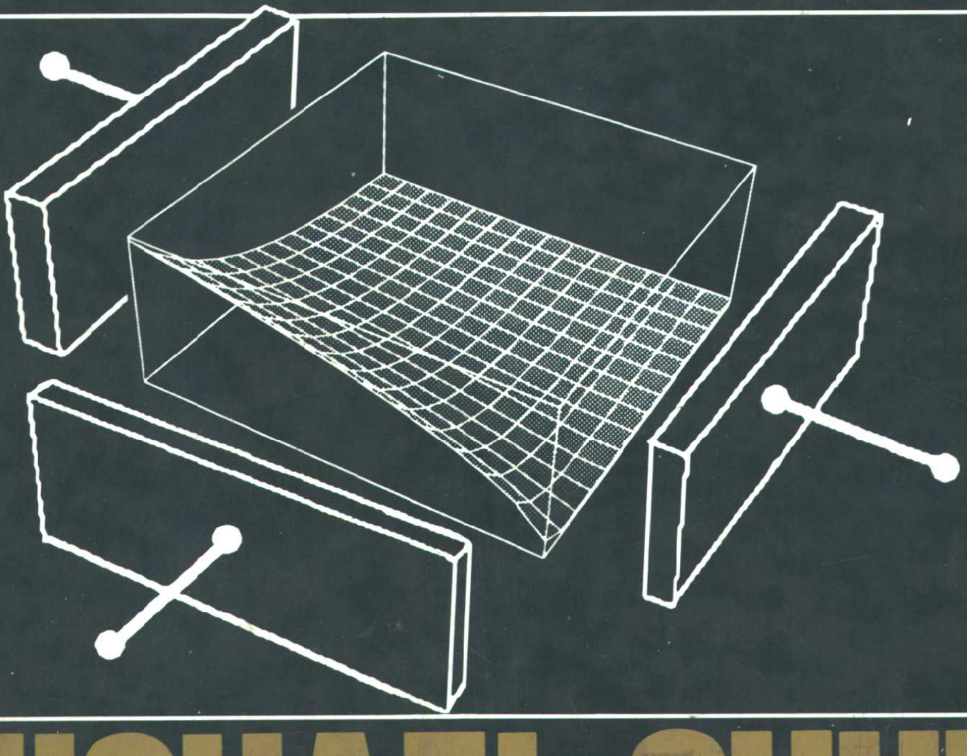
PHYSICS OF SEMICONDUCTOR DEVICES



MICHAEL SHUR

PRENTICE HALL SERIES IN SOLID STATE PHYSICAL ELECTRONICS
Nick Holonyak, Jr., Series Editor

Physics of Semiconductor Devices

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	Silicon	**Gallium Arsenide**
Crystal Structure	Diamond	Zinc blende
Breakdown field (V/cm)	$\sim3.0\mathrm{x}10^{5}$	$\sim4.0\mathrm{x}10^{5}$
Density (g/cm^3)	2.329 (at 298K)	5.3176 (at 298K)
Dielectric Constant	11.7	12.9 (at 300K) (κ_o) 10.89 (at 300K)
Diffusion Constant (cm^2/s)	37.5 (electrons) (at 300 K)	207 (electrons) (at 300 K)
	13 (holes) (at 300 K)	10 (holes) (at 300 K)
Effective density of states in the conduction band (cm^{-3})	$2.8\mathrm{x}10^{19}$ (at 300 K)	$4.7\mathrm{x}10^{17}$ (at 300 K)
Effective density of states in the valence band (cm-3)	$1.04\mathrm{x}10^{19}$ (at 300 K)	$7.0\mathrm{x}10^{18}$ (at 300 K)
Effective electron mass (in unit of m_e)	longitudinal : 0.92 (at 1.26K)	0.063 (300 K)
	transverse : 0.19 (at 1.26K)	
Effective hole mass (in unit of m_e)	heavy hole 0.49 (at 300K)	0.50 (at 300K)
	light hole 0.16 (at 300 K)	0.076 (at 300K)
Energy gap (eV)	1.12 (at 300K)	1.424 (at 300K)
Lattice constant (Å)	5.43107 (at 298.2K)	5.6533 (at 300K)
Melting point (^{o}C)	1412	1240
Mobility (cm^2/V-s)	1450 electron (at 300K)	8500 (at 300 K)
	500 hole	400 (at 300 K)
Optical phonon energy (eV)	0.063	0.035
Specific heat (J/g-^{o}C)	0.7	0.35
Thermal conductivity (W/cm-^{o}C)	1.31 (at 300K)	0.46
Thermal diffusivity (W/cm-^{o}C)	0.9	0.44
Thermal expansion,linear (^{o}C^{-1})	$2.6\mathrm{x}10^{-6}$ (at 300K)	$6.86\mathrm{x}10^{-6}$ (at 300K)

$$\left[-\frac{\hbar^2\nabla^2}{2m_e}+U(\mathbf{r})\right]\Phi = i\hbar\frac{\partial\Phi}{\partial t} \qquad a_B = \frac{4\pi\varepsilon_o\hbar^2}{m_e q^2} \qquad E_B = \frac{q^2}{8\pi\varepsilon_o a_B}$$

$$j = \mu_n n\frac{dE_{Fn}}{dx} + \mu_p p\frac{dE_{Fp}}{dx}$$

$$L_{Dn} = \left(\frac{\varepsilon V_{th}}{qN_D}\right)^{1/2} \qquad x_{dn} = \left[\frac{2\varepsilon(V_{Bi}-V)}{qN_D}\right]^{1/2}$$

$$D_a = \frac{\mu_p p_n D_n + \mu_n n_n D_p}{\mu_n n_n + \mu_p p_n} \qquad \mu_a = \frac{\mu_n\mu_p(n_n - p_n)}{\mu_n n_n + \mu_p p_n}$$

$$D_d\frac{\partial^2 p_n}{\partial x^2} - \mu_a F\frac{\partial p_n}{\partial x} + G - R = 0$$

$$\beta^{-1} = \frac{D_p W^2 I_c}{qD_n{}^2 N_{de} x_e S} + \frac{D_p N_{ab} W}{D_n N_{de} x_e} + \frac{W\,n_i}{\mu_n F_{np} n_{bo}\,\tau_{rec}\,[WI_c/(qD_n n_{bo} S)]^{(1-1/m_{re})}} + \frac{W^2}{2L_{nb}}$$

$$I_{dsat} = \beta V_{sl}{}^2\frac{(1+2\beta R_s V_{gst} + V_{gst}{}^2/V_{sl}{}^2)^{1/2} - 1 - \beta R_s V_{gst}}{1-\beta^2 R_s{}^2 V_{sl}{}^2}$$

$$I = I_L + I_s\left[1 - \exp\left(\frac{V + R_s I}{m_{id} V_{th}}\right)\right] - V/R_{sh}$$

$$\omega = -kv(F_o) - i\left[\frac{1}{\tau_{md}(F_o)} + D_n k^2\right]$$

$$D = m/(\pi\hbar^2)$$

$$k_o d_o = n\pi - \arcsin\{\gamma E/[V_o + (\gamma-1)E]\}^{1/2} - \arcsin\{\gamma E/[V_o + V_a + (\gamma-1)E]\}^{1/2}$$

PRENTICE HALL SERIES IN SOLID STATE PHYSICAL ELECTRONICS

Nick Holonyak, Jr., Editor

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To students of electrical engineering who enter this field
with dedication and vigor, who challenge their professors
and advisors, and who are our hope for a better future.

List of Symbols

a_1, a_2, a_3	primitive base vectors
a_B	Bohr radius
A	active layer thickness
A^*	Richardson constant
A_o	width of space charge region
A_d	depletion layer width of Schottky contact
$A_{dS,D}$	depletion layer width of Schottky contact at source/drain end of the gate
$\mathbf{B}$	magnetic field
BV_{cb}	collector-base breakdown voltage
BV_{ce}	collector-emitter breakdown voltage
c	normalizing constant
C	energy gap produced by the ionic potential
C_d	capacitance of the depletion layer
C_{dom}	domain capacitance
C_{geom}	geometric capacitance
C_{gd}	internal gate-to-drain capacitance

C_{gs}	internal gate-to-source capacitance
D_a	ambipolar diffusion coefficient
D_n	electron diffusion coefficient
D_p	hole diffusion coefficient
D_{xy}	diffusion coefficient tensor
E	energy
E_1	acoustic deformation potential
E_a	acceptor level energy
E_B	Bohr energy
E_{ba}	energy gap between the bonding and antibonding state
E_c	energy at bottom of conduction band
E_d	donor level energy
E_{ij}	energy of intervalley scattering phonon
E_F	Fermi energy level
E_g	energy gap
E_h	energy gap produced by the covalent part of the potential
E_i	carrier critical ionization energy
E_n	electron energy
E_o	energy of optical phonon
E_{on}	energy of non-polar optical phonon
E_v	energy at ceiling of valence band
f	Fermi-Dirac distribution (occupation) function
f_n	Fermi-Dirac electron occupation function
f_p	Fermi-Dirac hole occupation function
$\mathbf{F}$	electric field
F_b	built in electric field in base
F_{br}	breakdown field strength
F_m	maximum electric field
F_p	peak electric field
F_s	velocity saturation field
F_s	force constant in lattice vibrations
g_a	acceptor degeneracy factor
g_d	donor degeneracy factor
g_m	transconductance
G	generation rate of electron-hole pairs
h	Planck constant

$\hbar$	reduced Planck constant
I	total current
I_b	base current
I_{br}	base recombination current
I_c	collector current
I_{CBO}	common base collector saturation current
I_{CEO}	common emitter collector saturation current
I_e	emitter current
I_{gc}	generation current in depletion region of collector-base junction
I_i	intercept current
I_{nb}	base electron current
I_{nc}	collector electron current
I_{ne}	emitter electron current
I_{pe}	emitter hole current
I_{pc}	collector hole current
I_{re}	recombination current in depletion region of emitter-base junction
I_t	tunneling current
j	current density
j_1	small signal diode current density
j_F	total forward current density
j_{gen}	generation current density
j_n	electron current density
j_p	hole current density
j_R	reverse current density
j_s	diode saturation current
$\mathbf{k}$	wave vector
$\mathbf{K}_1, \mathbf{K}_2, \mathbf{K}_3$	primitive vectors of the reciprocal lattice
k_B	Boltzmann constant
k_F	Fermi wave vector
K_i	heat conductivity of electron gas in i-th valley
κ_s	low frequency dielectric constant
κ_o	high frequency dielectric constant
l	orbital quantum number
L	Lorentz number
L	device length

L	gate length of a field effect transistor
L_{bn}	diffusion length of electrons in the base region
L_D	Debye radius
L_{cp}	diffusion length of holes in the collector region
L_{ep}	diffusion length of holes in the emitter region
L_n	electron diffusion length
L_p	hole diffusion length
L_s	length of carrier velocity saturation region under the gate of a field effect transistor
L_T	transfer length
m	magnetic quantum number
m_{dn}	effective mass of the density of states' electrons
m_{dp}	effective mass of the density of states' holes
m_e	free electron mass
m_i	ideality factor
m_l	longitudinal effective electron mass
m_{lp}	effective mass for light holes
m_n	conductivity electron effective mass
m_{pn}	reduced effective mass
m_r	factor in recombination current exponent
m_t	transverse effective electron mass
M	collector multiplication factor
M	atomic mass
M_n	multiplication factor for electrons
M_p	multiplication factor for holes
n	principal quantum number
n	electron concentration
n_b	electron concentration in the base
n_{bo}	equilibrium electron concentration in the base
n_{bc}	electron concentration in the base at the collector-base junction
n_{be}	electron concentration in the base at the emitter-base junction
n_i	intrinsic carrier concentration
n_{ib}	intrinsic carrier concentration in the base region
n_{ic}	intrinsic carrier concentration in the collector region
n_{ie}	intrinsic carrier concentration in the emitter region
n_{po}	equilibrium concentration of electrons in p-region

N_a	concentration of acceptors
N_{ab}	acceptor concentration in the base
N_c	effective density of states in the conduction band
N_d	donor concentration
N_{dc}	donor concentration in the collector
N_{de}	donor concentration in the emitter
N_I	impurity concentration
N_s	density of surface states
N_{sub}	substrate doping density
N_v	effective density of states in the valence band
$\mathbf{p}$	momentum
p_b	hole concentration in the base
p_c	hole concentration in the collector
p_{co}	equilibrium hole concentration in the collector
p_e	hole concentration in the emitter
p_{eo}	equilibrium hole concentration in the emitter
$\mathbf{p}_i$	electron momentum in the i-th valley
p_{no}	equilibrium concentration of holes in the n region
q	elementary charge
$\mathbf{q}_i$	heat flow vector
Q_b	Gummel number
Q_d	charge in depletion layer
r	distance
R	recombination rate
R_b	bulk resistance
R_c	contact resistance
R_{chc}	channel sheet resistance
R_{end}	end resistance
R_p	resistance of interconnect wires
$\mathbf{R}$	space vector
R_{ch}	channel resistance
R_d	series drain resistance
R_g	series gate resistance
R_{sh}	drain-to-source shunt resistance
$\mathbf{R}_{k,l,m}$	coordinates of points belonging to the crystal lattice
R_s	series source resistance
s	spin

S	device cross-section
t	time
t_s	electron free flight time
T	temperature
T_e	effective electron temperature
T_{po}	Einstein temperature
u	sound velocity
u_k	Bloch amplitude
U	potential energy
U_m	amplitude of atomic displacement
U_M	atom velocity
U_R	generation-recombination rate
v_d	average drift velocity
V	crystal potential
V_A	Early voltage
V_{bi}	built-in voltage
V_{bisb}	built-in potential of channel-substrate junction
V_{eb}	emitter-base voltage
V_{cb}	collector-base voltage
V_{ch}	channel potential
V_{ds}	intrinsic drain-to-source voltage
V_g	gate potential
$V_{gs} = V_g - V_s$	intrinsic gate-to-source voltage
$V_{gd} = V_g - V_d$	intrinsic gate-to-drain voltage
$V_{po} = V_{bi} - V_T$	ideal pinch-off voltage
$V_{s,d}$	channel potential at source/drain ends
V_T	threshold voltage
V_{th}	thermal voltage
W	base width of bipolar junction transistor
W	gate width of field effect transistor
$W(\mathbf{k},\mathbf{k}')$	transition probability
W_i	kinetic energy density
x,y,z	space coordinates
x_c	width of the collector region
x_e	width of the emitter region
x_d	width of depletion layer
X_m	work function of metal

X_s	work function of semiconductor
Y	small-signal impedance
Z	atomic number
α	common-base current gain
α_T	base transport factor
β	common-emitter short-circuit current gain
γ	emitter injection efficiency of a bipolar junction transistor
δ_i	average length of electron travel in electric field
δ_{ox}	thickness of interfacial layer
ε_o	permittivity of vacuum
ε_s	static dielectric permittivity
ε_∞	high frequency dielectric constant
ϕ_b	barrier height
ϕ_o	neutral level
λ	scattering rate
λ_b	characteristic length of the exponential doping profile in the base
λ_e	intervalley scattering rate between equivalent valleys
μ	low field mobility
μ_a	ambipolar mobility
μ_n	electron mobility
μ_p	hole mobility
ρ	space charge density
σ_n	electron capture cross-section
σ_p	hole capture cross-section
τ	relaxation time
τ_{ac}	acoustic scattering relaxation time
τ_A	Auger recombination lifetime
τ_F	effective minority carrier lifetime for forward current
τ_{gen}	effective generation time
τ_{ii}	ionized impurity scattering relaxation time
τ_{ni}	neutral impurity scattering relaxation time
τ_{npo}	non-polar optical scattering relaxation time
τ_{pe}	piezoelectric scattering relaxation time
τ_{po}	polar optical scattering relaxation time

τ_{rec}	effective recombination time in emitter-base depletion region
τ_{R}	effective minority carrier lifetime for reverse current
ψ	wave function
ψ_{a}	antibonding orbital
ψ_{b}	bonding orbital
ψ_{k}	Bloch wave function
ω	frequency
ω_{a}	frequency of acoustic lattice vibrations
ω_{o}	frequency of optical lattice vibrations

Preface

The rapid development of semiconductor devices and integrated circuits has been accompanied by an enormous increase of information in the field of semiconductor physics and electronics. New ideas, new theories, new models, new devices, and new circuits have not only led to numerous practical applications but have also created opportunities for further and, perhaps, even more exciting developments. To work in this rapidly growing field is a challenge that attracts and inspires many researchers and students.

This book is intended to serve as a text for a three-quarter or two-semester sequence of courses on semiconductor devices for first year graduate students and qualified seniors. Some background in solid state physics and quantum mechanics may be helpful (but not required) for the students using this book. In addition to material typically found in textbooks on semiconductor devices, this book describes new important developments, such as amorphous silicon, compound semiconductor technologies, and novel heterostructure transistors. Theories and models presented in the book are implemented in microcomputer programs that make a "toolbox" for modeling and simulation of semiconductor devices. Appendices include information on semiconductor parameters. These device models and material parameters allow students to solve practical problems related to analysis, design, and characterization of different semiconductor devices. This book includes nearly 150 of such problems—from simple to advanced—with a detailed solution manual available for instructors. The book also gives many references that can serve as a material for further reading. These features should make this book useful for engineers and researchers working on semiconductor devices and also for students encountering this exciting field for the first time.

Chapter 1 starts from a brief discussion of semiconductor physics that introduces Schrödinger's equation, atomic states, chemical bonds, crystal structure, energy bands, semiconductor statistics, transport properties, and basic semiconductor equations. In addition, Chapter 1 includes more advanced topics, such as the Boltzmann transport equation, Monte Carlo simulation, and high electric field transport. These topics may be omitted from a typical course on semiconductor materials and devices, and the corresponding sections, 1-13, 1-14, and 1-15 (marked by asterisks in the Table of Contents) can be used as material for further reading.

Chapter 2 deals with the semiconductor junctions and contacts which are present in every semiconductor device. I have also included a section describing heterojunctions formed at the interfaces of dissimilar semiconductor materials. Because heterojunction devices have become extremely important for a variety of different applications—from light sources to ultrafast switching and microwave devices—the reader will find this section especially beneficial in understanding new devices emerging from research laboratories. Section 2-8-2 (marked by an asterisk in the Table of Contents) includes a more detailed analysis of avalanche breakdown than may be required for a typical course on physics of semiconductor devices. This Section can be used as a material for further study.

Chapter 3 describes bipolar junction transistors. In addition to the conventional material, I have included a description of the Gummel-Poon model and a section on heterojunction bipolar transistors. The Gummel-Poon model is required for realistic modeling of a bipolar junction transistor and is widely used in popular circuit simulators, such as SPICE developed at Berkeley. Heterojunction bipolar transistors have the potential to become one of the fastest solid-state technologies, both in the analog and digital worlds.

Chapter 4 treats field-effect transistors. The silicon field-effect transistor, considered in this chapter, is a work horse of modern electronics. Chapter 4 also describes compound semiconductor devices, such as gallium arsenide field-effect transistors, as well as amorphous silicon Thin Film Transistors (TFTs). Amorphous silicon TFTs have emerged as a very promising technology for driving flat screen displays and for applications in electronic copiers and printers.

Chapter 5 deals with photonic devices—solar cells, light-emitting diodes, semiconductor lasers, and integrated optoelectronic circuits. In particular, I discuss amorphous silicon solar-cell technology which has become the most practical solar cell technology because of its combination of high solar energy conversion efficiency with relatively low fabrication and material costs.

Chapter 6 covers microwave diodes—the most powerful solid-state sources of microwave energy. Some of these diodes utilize the negative differential resistance found in gallium arsenide in high electric fields. The physical mechanisms that lead to negative differential resistance are also discussed in Chapter 6.