an Introduction to Semiconductor Electronics

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Preface

Modern technology is growing at a very rapid rate, and new devices are appearing on the horizon much more frequently than before. The time between a research idea and its translation into product development is diminishing quite rapidly. There is a twofold implication of the above observations. First, the study of any field *must* be based on fundamental knowledge at sufficient depth to enable the student and the engineer to understand the new developments in the field. Second, the knowledge of the field should be presented in a form that clearly shows its interdependence on other fields.

This book attempts to acquaint the reader with semiconductor electronics, keeping the above two objectives in mind. No attempt has been made to discuss fabrication techniques, which change almost from day to day. Semiconductor theory, junction theory, and circuit theory are integrated to explain the behavior of existing devices in circuits. Approximately 70 per cent of the book is devoted to semiconductor device theory, and the remaining 30 per cent to circuits.

The first chapter introduces the reader to modern physics and quantum mechanics. No prior knowledge of modern physics is assumed. The second chapter deals with the basic semiconductor processes. These first two chapters serve as background material for the rest of the chapters. The topics covered are, it is hoped, sufficiently broad as well as deep so that they can be used to understand new and as yet undiscovered devices.

Chapters 3 through 11 develop the junction theory and circuit theory which are then applied to semiconductor diodes and transistors. Chapters 12 and 13 discuss the newer devices. Chapter 12 is devoted to tunnel devices. These last two chapters are analyzed by using the material developed in the first 11 chapters.

Throughout the book d-c phenomena are always covered before a-c phenomena, and the diode is always studied before the transistor. The diode serves as a simple case in which many of the theoretical complexities can be thoroughly explored. Many of the results are directly applicable to the multijunction case of the transistor.

The elements of the equivalent circuit are developed in terms of the fundamental parameters. The performance of a device embedded in a circuit is easily related to the device parameters. Topics on device theory and those on circuit theory are interwoven with each other. As time progresses, the roles of the circuit designer and the device designer are coming closer. In the not too distant future, whole circuits will be fabricated in single crystals. The engineers who design such devices will need to know both circuits and devices. This book attempts to give knowledge in both these areas.

Topics on circuits are meant to help the device engineer to appreciate the problems encountered when these devices are used in circuits. The circuit engineer can better design circuits if he thoroughly understands the fundamentals of how the device operates and what goes on inside it, so that he will not ask the device to do what it is impossible for it to do.

Chapter 10 presents a very exhaustive treatment of transistor transients. Transient response is analyzed from three points of view. The equivalent-circuit approach, the charge-control approach, and the diffusion-equation approach are used to analyze the transient response. The last approach is the most fundamental of the three. It helps to establish the limitations of the other points of view. In addition, it gives new results not obtainable from the other approaches.

An attempt has been made throughout the book to state clearly the assumptions behind the theories presented. The limitations of the existing theories must be adequately understood if they are not to be used in places where they are not valid. Too often advances in scientific knowledge have been retarded by inadequate awareness of the assumptions and limitations of existing theories.

It is the author's sincere hope that this book will be of value to students and engineers who seek to understand semiconductor devices of today and tomorrow and who want to know how their performance in a circuit may be predicted.

The author is greatly indebted to many of his colleagues for their help during the preparation of this book. Several of them taught courses based on the material of this book. In particular, the author wishes to acknowledge the help of Prof. C. O. Harbourt, Dr. R. Huang, and J. Baule. Particularly appreciated are the often long and always helpful discussions with Dr. R. A. Johnson regarding the subject material of Chap. 10. The author also wishes to thank Miss Mary Jo Phillips, who typed the manuscript with meticulous care and who cheerfully suffered through the many revisions in the manuscript from semester to semester.

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R. P. NANAVATI

List of Symbols

A junction area
A_c collector-junction area
A_e emitter-junction area
A_i current gain
A_{ib} common-base current gain
A_{ic} common-collector current gain
A_{ie} common-emitter current gain
A_p power gain
A_{pb} common-base power gain
A_{pc} common-collector power gain
A_{pe} common-emitter power gain
A_s effective surface area for recombination
A_v voltage gain
A_{vb} common-base voltage gain
A_{vc} common-collector voltage gain
A_{ve} common-emitter voltage gain
a $\sqrt{2mE}/\hbar$ Chap. 1
a lattice spacing Chap. 2
a charge-density gradient in the transition region of linearly graded junction
$\mathbf{a}$ acceleration
$a_{11}, a_{12}, a_{21}, a_{22}$ defined by Eqs. (4-37) to (4-40)

B average value of β, defined by Eq. (6-88)
$B(T)$ defined by Eq. (6-12)
$\mathbf{B}$ magnetic-field vector
b $\sqrt{2m(V_2 - E)}/\hbar$

c velocity of light
C_{av} average capacitor
C_{cn} defined in Eq. (7-45)
C_d diffusion capacitance

C_{en} defined in Eq. (7-43)
C_j, C_n junction capacitance
C_m minority-carrier equilibrium density
C_{lc} linear stray capacitance associated with the collector junction
C_{le} linear stray capacitance associated with the emitter junction
C_p defined by Eq. (7-16)
C_{tc}, C_{nc} collector-junction capacitance
C_{te}, C_{ne} emitter-junction capacitance

D diffusion constant for electrons or holes
D diffusion constant for the impurity grading in the base region Chap. 11
D_n diffusion constant for electrons
$D_{n,\mathrm{eff}}$ effective diffusion constant for electrons
D_p diffusion constant for holes
$D_{p,\mathrm{eff}}$ effective diffusion constant for holes
d distance between atoms or atomic planes

$\mathcal{E}$ electric field
E energy
E_1 amplitude of ON step voltage
E_2 amplitude of OFF step voltage
E_a acceptor energy level
E_c energy level at the bottom of the conduction band
E_{cn} energy level at the bottom of the conduction band on the n side
E_{cp} energy level at the bottom of the conduction band on the p side
E_d donor energy level
E_{en} electron energy of tunneling electron on the n side
E_{ep} electron energy of tunneling electron on the p side
E_f Fermi level in Chaps. 2 to 4, 6, 11, 12
E_f amplitude of step ON turnon voltage for the turnon diode transient
E_{fn} Fermi level on the n side
E_{fp} Fermi level on the p side
E_g band-gap energy
E_g gate voltage Chap. 13
E_g' reduced band gap due to degeneracy
E_i intrinsic energy level
E_k kinetic energy
E_n nth discrete energy level in an atom
E_{oc} open-circuit voltage
E_p energy level of the phonon energy
E_r recombination level Chap. 2
E_r amplitude of step reverse voltage for the turnoff diode transient
E_s recombination states on the surface Chap. 2

E_s smaller of E_1 and E_2 Chap. 12
E_v energy level at the top of the valence band
E_{vn} energy level at the top of the valence band in n-type semiconductor
E_{vp} energy level at the top of the valence band in p-type semiconductor
$E_\perp$ defined by Eq. (12-8)
$\bar{E}_\perp$ defined by Eq. (12-9)
$E_{f,max}$ the larger of E_{fp} and E_{fn}
$E_{f,min}$ the smaller of E_{fp} and E_{fn}

$F_{\frac{1}{2}}(\eta_f)$ defined by Eq. (2-99)
F_{crys} internal force due to the crystal
F_{ext} force due to sources external to the crystal
F_t total force
f defined by Eq. (11-12) Chap. 11
$f(E)$ the Fermi-Dirac probability that an available energy E is occupied by an electron
$f(e_g)$ tunnel-diode static characteristics
f_m maximum frequency of oscillation
$f_{max}{}^i$ maximum intrinsic frequency at which the tunnel diode can be usefully operated
$f_p(E)$ the Fermi-Dirac probability that an available energy E is occupied by a hole
f_t the frequency at which the common-emitter current gain is 1
f_{tc} cutoff frequency due to channel transit time in a field-effect transistor
f_α α cutoff frequency (cps)
$f_{\alpha d}$ cutoff frequency of α_d (cps)
$f_n(E_1)$ Fermi-Dirac function on the n side
$f_p(E_2)$ Fermi-Dirac function on the p side

G_{max} maximum power gain
$(GB)_i$ current-gain–bandwidth product
$(GB)_v$ voltage-gain–bandwidth product
G_c defined by Eq. (13-11)
G_e defined by Eq. (2-98)
G_h defined by Eq. (2-105)
G_n generation rate of electrons per unit volume
G_0 defined by Eq. (13-10)
G_p generation rate of holes per unit volume
G_t generation rate of carriers in the transition region
g defined by Eq. (11-40)
g defined by Eq. (12-41)
g_{11} defined by Eq. (9-31)
g_{22} defined by Eq. (9-32)

$g_{11}, g_{12}, g_{21}, g_{22}$ defined by Eqs. (5-15), (5-16) Chap. 5
g_c defined by Eq. (9-86)
g_{cm} number of ellipsoids in the conduction band
g_{dd} diffusion conductance of a forward-bias *p-n* diode
g'_{lc} collector leakage conductance
g_m defined by Eq. (9-85)
g_{md} defined by Eq. (11-85)
g_{mf} defined by Eq. (13-24)
g_{ms} defined by Eq. (13-36)
$g_n(Z_n)$ defined by Eq. (6-84)
$g_p(Z_p)$ defined by Eq. (6-75)

H Hamiltonian
h Planck's constant
$\hbar$ $h/2\pi$
$h_{11}, h_{12}, h_{21}, h_{22}$ *h* parameters, defined by Eqs. (4-68), (4-69)
$h_{11b}, h_{12b}, h_{21b}, h_{22b}$ common-base *h* parameters
$h_{11e}, h_{12e}, h_{21e}, h_{22e}$ common-emitter *h* parameters

I_b total a-c amplitude of base current
I_{b1} amplitude of ON step base current
I_{b2} amplitude of OFF step base current
I_{bs} base current just necessary to saturate the transistor
I_{bx} base current in excess of I_{bs}
I_{c1} amplitude of ON step collector current
I_{c2} amplitude of OFF step collector current
I_{cf} current emitted from the collector
I_{cm} maximum collector current
I_{c0} back saturation current of the collector junction
I_{cr} current collected at the collector
I_c^* total a-c amplitude of collector current including the perturbing term
I_{e1} amplitude of ON step emitter current
I_{e2} amplitude of OFF step emitter current
I_e^* total a-c amplitude of the emitter current including perturbing term
I_{ef} current emitted from the emitter
I_{em} maximum emitter current
I_{er} current collected at the emitter
I_{es} emitter current to just saturate the transistor
I_{ex} emitter current in excess of I_{es}
I_f forward current during diode turnon transient
I_j junction-capacitance current
I_L load current

I_{n1} a-c amplitude of electron current
I_{p1} a-c amplitude of hole current
I_{peak} peak current in a tunnel diode
I_q quiescent current
I_r reverse current during diode turnoff transient
I_s back saturation current of a *p-n* junction
I_s' defined by Eq. (10-23)
I_{sc} short-circuit current Chap. 6
I_{sc} back saturation current for the collector junction
I_{se} back saturation current for the emitter junction
ΔI_{on} ON current over and above the peak current in a tunnel diode
I_x excess current
$\mathcal{I}$ defined by Eq. (12-12)
i_B d-c base current
i_C d-c collector current
i_D defined by Eq. (11-51)
i_E d-c emitter current
i_{nC} d-c electron current crossing the collector junction
i_{nd} electron current due to diffusion
i_{nE} d-c electron current crossing the emitter junction
i_{nf} electron current due to the field in the transition region
i_{pC}, I_{pC} d-c hole current crossing the collector junction
i_{pc} a-c hole current crossing the collector junction
i_{pd} hole current due to diffusion
i_{pE}, I_{pE} d-c hole current crossing the emitter junction
i_{pe} a-c hole current crossing the emitter junction
i_{pf} hole current due to the field in the transition region
i_R recombination current
i_{SR} surface-recombination current
i_{VR} volume-recombination current

J current density
J^* current density in a band completely full except for the absence of an electron
J_c^* total amplitude of a-c current density crossing the collector junction
J_e^* total amplitude of a-c current density crossing the emitter junction
J_n electron-current density
J_{ne}^* a-c amplitude of the electron-current density crossing the emitter junction
J_p hole-current density
J_p^* a-c amplitude of hole-current density in the base including the effects of the perturbing term

J^*_{pc} a-c amplitude of collector hole-current density including the perturbing term
J^*_{pe} a-c amplitude of emitter hole-current density including the perturbing term
J_s back-saturation-current density of a p-n-junction diode
J_t tunneling-current density in a tunnel diode
j $\sqrt{-1}$
j_C d-c current density crossing the collector junction
j_E d-c current density crossing the emitter junction
j_n electron-current density
j_{nC}, J_{nC} d-c electron-current density crossing the collector junction
$j_{nC}(x)$ d-c electron-current density as a function of x in the collector
j_{nE}, J_{nE} d-c electron-current density crossing the emitter junction
$j_{nE}(x)$ d-c electron-current density as a function of x in the emitter
$\tilde{j}_p$ hole-current density in the base due to perturbation
j_{p1} hole-current density in the base without perturbation
j_{p0} d-c hole-current density
j^*_p total a-c hole-current density including the perturbing term
j_{pt} total hole-current density in the base including a-c, d-c, and perturbing terms

k Boltzmann constant
k_a defined by Eq. (3-104)
k_{ac} coefficient for collector step-junction capacitance
k_{ae} defined by Eq. (10-3)
k_c wave number corresponding to the crystal momentum $\hbar\mathbf{k}_c$
$\mathbf{k}_c$ wave vector corresponding to the crystal momentum $\hbar\mathbf{k}_c$
k_{cen} wave number corresponding to a tunneling electron on the n side
k_{cep} wave number corresponding to a tunneling electron on the p side
k_g defined by Eq. (3-114)
k_{gc} coefficient for a collector graded-junction capacitance
k_{ge} coefficient for an emitter graded-junction capacitance
k_p wave number for a phonon

L diffusion length for electrons or holes
L_d diffusion length associated with impurity grading
L_n diffusion length for electrons
L_{nc} diffusion length for electrons in the collector
L_p diffusion length for holes
l length
l_s tunnel-diode series inductance

M avalanche multiplication factor
M_0 defined by Eq. (B-7)

m mass
m_2 defined by Eq. (B-16)
m^* effective mass
m_e^* effective mass of electrons
m_h^* effective mass of holes
m_l^* longitudinal effective mass for electrons in the conduction band
m_0 rest mass
m_t^* transverse effective mass for electrons in the conduction band
m_x reduced effective mass for electrons

$N(E)$ density-of-states function
N_a density of acceptor atoms
N_c defined by Eq. (2-75)
$N_c(E)$ density of states in the condution band
N_d density of donor atoms
N_0 defined by Eq. (2-97)
N_x density of occupied band-gap states above the valence band
N_v defined by Eq. (2-77)
$N_v(E)$ density of states in the valence band
n electron density
n_a electron density in the acceptor states
n_C defined by Eq. (4-26)
$n_C(x)$ electron density as a function of x in the collector region
n_d electron density in the donor states
n_d^- density of unoccupied donor states
n_E defined by Eq. (4-25)
$n_E(x)$ electron density as a function of x in the emitter region
n_i carrier density in an intrinsic semiconductor
n_n thermal-equilibrium value of electrons in an n-type semiconductor
n_0 thermal-equilibrium value of electrons
n_p thermal-equilibrium value of electron density in a p-type semiconductor
n_{pc} thermal-equilibrium value of electrons in the p-type collector
n_{pe} thermal-equilibrium value of electrons in the p-type emitter
n_r defined by Eq. (2-122)
n_x density of electrons in the conduction band due to donors
n_{xtn} electron density at the edge of the transition region on the n side
P power
$P_{C,\max}$ maximum collector power dissipation
P_0 defined by Eq. (11-36)
P_r rate at which carriers are produced due to photoconductivity
P_x tunneling probability of electrons from N_x to the valence band
p hole density

p' — $p - p_n$
p_1 — hole density in valence band 1
$p_1(x, t)$ — a-c hole density in the base region assuming no variation of the collector-boundary position
p_2 — hole density in valence band 2
$p_0(x, t)$ — total hole density in the base region assuming no variation of the collector-boundary position
$\tilde{p}(x, t)$ — hole density in the base due to collector-boundary-position variation with time
p_C — defined by Eq. (4-12)
p_c — a-c hole density at the collector end of the base region
p_E — defined by Eq. (4-11)
p_e — a-c hole density at the emitter end of the base region
p_{init} — initial hole density
p_k — generalized momentum
p_n — thermal-equilibrium value of holes in n-type semiconductor
p_{nc} — thermal-equilibrium value of holes in n-type collector
p_{ne} — thermal-equilibrium value of holes in n-type emitter
p_{ne} — thermal equilibrium value of holes at the emitter in the n-type base Chap. 11
p_0 — thermal-equilibrium value of holes
$p_0(x)$ — d-c hole density in the base region
p_p — thermal-equilibrium value of holes in p-type semiconductor
p_{pc} — thermal-equilibrium value of holes in p-type collector
p_{pe} — thermal-equilibrium value of holes in p-type emitter
p_r — defined by Eq. (2-123)
p_x — density of holes in the valence band due to acceptors
p_{xtn} — hole density at the edge of the transition region on the n side

Q — charge on the junction capacitance
Q_b — base control charge
Q_{bs} — base charge when the transistor is just saturated
Q_{bx} — base charge in excess of Q_{bs} while in saturation
q — electronic charge
q_k — generalized space coordinates

R — Hall coefficient
R_c — reciprocal of G_c
R_H — the Rydberg (constant)
R_L — load resistance
R_s — source resistance
R_λ — total blackbody emissive power per unit area per unit wavelength
R_r — rate of direct recombination (cm^{-3} sec^{-1})
$\mathbf{r}$ — position vector

r' extrinsic bulk resistance
r_1, r_2 defined by Eq. (B-21)
$r_{11}, r_{12}, r_{21}, r_{22}$ defined by Eqs. (5-6), (5-7)
r_b leakage resistance of a *p-n* junction in Chap. 3
r_b base resistance in the *T* equivalent circuit
r_b' extrinsic base resistance
r_c collector resistance in the *T* equivalent circuit
r_{cf} forward resistance associated with the collector-base junction
r_c' extrinsic collector bulk resistance
r_d $r_c(1 - \alpha)$
r_{dd} diffusion resistance of a forward-bias *p-n* diode
r_e emitter resistance in the *T* equivalent circuit
r_e' extrinsic emitter bulk resistance
r_{eb} back resistance of the emitter-base junction
r_f forward bulk resistance of a *p-n*-junction diode
r_{in} input resistance
r_l' extrinsic leakage resistance of a *p-n* junction
r_{lc}' extrinsic leakage resistance for the collector junction
r_{le}' extrinsic leakage resistance for the emitter junction
r_n *n*th Bohr radius
r_{out} output resistance

S_i current-stability factor
S_v voltage-stability factor
s surface-recombination velocity defined by Eq. (2-127)
s $\sigma + j\omega$ Chaps. 9 and 10

T absolute temperature
$T_c°$ temperature in degrees centigrade
$T(t)$ time-coordinate solution to the separated Schrödinger equation
T_b defined by Eq. (10-103)
T_{bv} defined by Eq. (10-115*b*)
T_c defined by Eq. (10-104)
T_e defined by Eq. (10-102)
T_f defined by Eq. (10-146)
T_{fd} t_{fd}/τ_p
T_p defined by Eq. (10-134)
T_s defined by Eq. (10-105)
T_{sd} defined by Eq. (10-141*a*)
T_t transmission coefficient Chap. 12
t time
$\bar{t}$ mean free time for carriers
t_d total output delay time
t_{do} output delay time due to input capacitors discharging

t_{dcb} output delay time due to input-capacitor discharging time in a common-base circuit
t_{dce} output delay time due to input-capacitor discharging time in a common-emitter circuit
t_f fall time
t_{fbc} output fall time in a common-base circuit
t_{fc} collector fall time
t_{fco} output fall time in a common-collector circuit
t_{fd} diode fall time
t_{fe} emitter fall time
t_{feo} output fall time in a common-emitter circuit
t_{fi} input fall time
t_{fo} output fall time
$\bar{t}_n$ mean free time for electrons
t_0 the period with which the electron cycles repeatedly through the Brillouin zone
$\bar{t}_p$ mean free time for holes
t_r rise time
t_{ri} input rise time
t_s storage time
t_{sc} output storage time when the collector recovers first
t_{scb} output storage time when the collector recovers first in a common-base circuit
t_{scc} output storage time when the collector recovers first in a common-collector circuit
t_{sce} output storage time when the collector recovers first in a common-emitter circuit
t_{sd} diode storage time
t_{seb} input storage time (i.e., recovery time of the emitter junction) when the emitter recovers first in a common-base circuit
t_{sec} input storage time when the emitter recovers first in a common-collector circuit
t_{see} input storage time when the emitter recovers first in a common-emitter circuit
t_{si} input storage time
t_{so} output storage time

u carrier velocity

V potential energy
V_c a-c amplitude of collector voltage
V_{ce} a-c amplitude of collector-to-emitter voltage
V_e a-c amplitude of emitter voltage
V_0 stopping voltage in the photoelectric experiment

v velocity in Chaps. 1, 2
v voltage in all other chapters except Chaps. 1, 2
v_b built-in voltage across the junction
v_{be} emitter-to-base voltage
v_C d-c collector-to-base voltage
v_E d-c emitter-to-base voltage
v_e a-c emitter voltage
v_{fn} voltage corresponding to the Fermi level on the n side
v_{fp} voltage corresponding to the Fermi level on the p side
v_g band-gap voltage
$v_g(r)$ voltage across the junction in a field-effect transistor
v_{gco} pinch-off voltage
v_n electron velocity
$v_{n,\mathrm{th}}$ thermal velocity of excess electrons
v_0 total external voltage including the voltage drop in the bulk due to high injection
v_p hole velocity
$v_{p,\mathrm{th}}$ thermal velocity of excess holes
v_t total voltage across the p-n junction (including v_b)
v_{th} thermal velocity of carriers
v_{peak}, v_p peak voltage in the tunnel-diode characteristics
v_{valley}, v_v valley voltage in the tunnel-diode characteristics

$w(t)$ total base width
w_0 average base width
w_1 a-c amplitude of the base-width variation with time
w_1 width constant of the junction Chap. 12

X defined by Eq. (10-135)
x distance
x_0 tunneling-barrier width
x_t transition-region width
x_{tc} collector transition-region width
x_{te} emitter transition-region width
x_{tn} edge of the transition region on the n side of the junction
x_{tp} edge of the transition region on the p side of the junction

Y_{ee}^i, Y_{ec}^i, Y_{ce}^i, Y_{cc}^i intrinsic common-base admittance parameters defined by Eqs. (8-39), (8-40)
Y_{ee}, Y_{cc} emitter and collector admittances including the extrinsic parameters
Y'_{lc} extrinsic collector-junction leakage admittance
Y'_{le} extrinsic emitter-junction leakage admittance

Z_b' extrinsic base impedance
Z_n defined by Eq. (6-85)
Z_p defined by Eq. (6-70)

α short-circuit current gain for common-base circuit
α^* collector multiplication factor
α' short-circuit current gain for common-base circuit when $|Z_{12}| \ll |Z_{21}|, |Z_{22}|$
α_d short-circuit current gain in a drift transistor operated in the common-base mode
α_{d0} low-frequency value of α_d
α_i ionization rate in the transition region of the p-n junction
α_N, α_0 low-frequency value of α for a normal transistor
$\alpha_i(j\omega)$ short-circuit common-base current gain for a transistor operated inversely
α_I low-frequency value of $\alpha_i(j\omega)$

β short-circuit current gain for common-emitter mode of transistor operation
β^* base transport factor
β_0 low-frequency value of β
β_0^* low-frequency value of β^*
β_g constant defined by Eq. (2-111)
β_M defined by Eq. (13-41)

γ emitter efficiency
γ_0 emitter efficiency at low frequencies

δ defined by Eq. (11-42)
$\delta(E)$ delta function
δ_0 defined by Eq. (11-41)

ϵ permittivity
ϵ defined by Eq. (11-57) Chap. 11
ϵ' defined by Eq. (11-58) Chap. 11

λ wavelength

μ mobility
μ_{bc} defined by Eq. (8-56)
μ_{d1} drift mobility of holes in valence band 1
μ_{d2} drift mobility of holes in valence band 2
μ_{dn} drift mobility of electrons
μ_{dp} drift mobility of holes
μ_{hn} Hall mobility of electrons

μ_{hp}	Hall mobility of holes
μ_n	electron mobility
μ_p	hole mobility
ν	frequency in cycles per second
ρ	charge density Chap. 3
ρ	defined by Eq. (10-8)
ρ'	defined by Eq. (10-23)
ρ_B	base resistivity
ρ_C	collector resistivity
ρ_E	emitter resistivity
σ	conductivity
σ_B	base conductivity
σ_C	collector conductivity
σ_E	emitter conductivity
σ_n	conductivity of *n*-type semiconductor
σ_{nc}	conductivity of the *p*-type collector due to electrons only
σ_{nr}	capture cross section for electrons
σ_p	conductivity of the *p*-type semiconductor
σ_{pc}	collector conductivity due to majority carriers only
σ_{pr}	capture cross section for holes
σ_r	capture cross section for recombination (cm^2)
σ_s	constant associated with the Stefan-Boltzmann law
τ	lifetime for electrons or holes
τ_b	lifetime in the base
τ_c	lifetime in the collector
τ_e	lifetime in the emitter
τ_i	lifetime in an intrinsic semiconductor
τ_n	lifetime for electrons
τ_{nd}	direct-recombination lifetime for electrons
τ_{ne}	electron lifetime in *p*-type emitter
τ_{n0}	defined by Eq. (2-125)
τ_0	defined by Eq. (12-55)
τ_0	average lifetime of the newly created carriers due to photoexcitation
τ_p	lifetime for holes
τ_{pd}	direct-recombination lifetime for holes
τ_{p0}	defined by Eq. (2-124)
τ_s	lifetime associated with the surface recombination
τ_t	transit time across the channel in a field-effect transistor
ϕ	($q\phi$) is work function
ϕ_f	Fermi potential