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SEMICONDUCTOR DEVICES

BJTS, JFETS, MOSFETS, and Integrated Circuits

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PREFACE

Since the interval between the discovery of new phenomena and their engineering applications is rapidly diminishing, knowledge of fundamental theory is essential to understanding not only electronic devices of today but also those that will be developed in the future. Therefore I have tried to balance the discussion of semiconductor devices in this book with a presentation of theory in sufficient depth. Basic assumptions are stated, as are the approximations used to obtain the final results. Moreover, the presentation is given in enough depth so that the theories developed here may be extended as necessary. Because of this emphasis on principles, almost all the material in this book has been covered satisfactorily by juniors in the electrical engineering department at Syracuse University.

Included are all the important semiconductor devices, including the bipolar junction transistor (BJT), the junction field effect transistor (FET), and the metal-oxide semiconductor field effect transistor (MOSFET). Since the device models are, by and large, equivalent circuits, each element may be expressed in terms of functional parameters, and desirable changes in the parameters may be readily related to the necessary performance of the device in a given circuit application. In certain cases more sophisticated models need to be considered. To predict the time taken by a transistor to turn off in a given circuit, for example, it is necessary to know the detailed distribution of minority carriers in the base region, as shown in Chapter 6.

Integrated circuits have revolutionized the electronics world, and their impact will be felt not only in electrical engineering education but also in medical practice, international communication, computers, banks, governmental operations, outer space exploration, and a host of other areas. There is sufficient material in the areas of semiconductor device physics and fabrication technology to enable the student to grasp the essentials of integrated circuits.

Chapter 1 covers the ideas of modern physics, assuming no prior knowledge, and Chapter 2 describes band theory and semiconductor processes. These two chapters constitute a broad foundation for the theories developed in the remainder of the book. Chapters 3 through 7 deal with the device theory of *p-n* junctions and the bipolar junction transistor. In Chapter 6 both the wide band steady state is analysed and transient analysis of junction transistors is carried out.

Chapters 8 and 9 develop the theory of FETS and MOSFETS respectively. Chapter 11 goes into the details of modern fabrication technology. The integrated circuit and the technology behind it are also introduced in this chapter. Extensions of the junction theory are considered in Chapter 12. These go somewhat beyond the junior level, but are included in the interest of completeness.

In Chapter 10 a number of additional semiconductor devices are considered, demonstrating that the material in the first 9 chapters enables the reader to understand many present day devices and those that may be developed in the future.

Chapter 11 can be covered as early as after Chapter 3. Alternatively, it can be introduced after Chapter 7, 8, or 9. Vacuum tube physics is covered in an extensive appendix E.

The reader will note that some chapters have equations numbering in several hundreds. This is done to aid clarity in the presentation as well as to make it easier to refer to specific steps in the development. Equations are numbered separately in each worked out example beginning with one. Only those results obtained in the examples which are generally true and valuable are given a number prefixed by the chapter number.

The photo-micrographs of integrated circuits provided by Fairchild Semiconductor, Mountain View, California; and by the Texas Instruments Corporation add considerably to the book. The author is deeply grateful to them.

Without the patience and encouragement of my wife and the forebearance of my two daughters over many weekends and countless evenings, this book would have been impossible to write.

Most of the manuscript typing was done by Mrs. Stephanie Micale, Mrs. Elka Bolich, Mrs. Linda Lopez and Mrs. Sue Garner whose help deserves special mention.

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LIST OF SYMBOLS

A	area
A_b	cross-sectional area through which the base current flows
A_c	cross-sectional area of the collection junction
A_e	cross-sectional area of the emitter junction
A_i	current gain
A_p	power gain
A_s	area over which surface recombination takes place
A_v	voltage gain
A_{v0}	low frequency voltage gain
a	lattice constant; or acceleration in Chapter 2; doping gradient in the transition region of linearly graded junctions in Chapter 3; half channel width in FET shown in Fig. 8–1.
$a_{11}, a_{12}, a_{21}, a_{22}$	defined by Eqs. (4–76) and (4–77)
B	magnetic field density Chapters 1, 2; volume of the charge depleted transition region
B_c	volume of the charge neutral channel region
b	defined by Eq. (12–104); channel width defined on Fig. 8–1
b_t	tunneling barrier width in a tunnel diode
c	velocity of light
c_1	a numerical factor defined in Eq. (12–67)
C	volume density of chemical impurities Chapter 11; input gate capacitance of FET (Chapter 8)
C_{av}	average linear capacitance which displaces the same amount of charge as the nonlinear junction capacitance

C_{cp}	defined by Eq. (6–18)
C_{ep}	defined by Eq. (6–19)
C_d	diffusion capacitance
C_{dc}	defined by Eq. (6–211)
C_{de}	defined by Eq. (6–210)
C_{ds}	capacitance between drain and source
C_{gd}	capacitance between gate and drain
C_{gch}	gate to channel capacitance
C_{gs}	capacitance between gate and source
C_i	input capacitance Eq. (9–82)
C_j	junction capacitance
C_{jd}	junction capacitance between drain and substrate
C_{js}	junction capacitance between source and substrate
C_ℓ	linear stray capacitance of the *p-n* junction
$C_{\ell c}$	linear stray capacitance associated with the collector junction
$C_{\ell e}$	linear stray capacitance associated with the emitter junction
C_n	defined by Eq. (5–8)
C_{nc}	collector junction capacitance
C_{ne}	emitter junction capacitance
C_o	output capacitance Eq. (9–83)
C_{ox}	oxide capacitance
c_{ox}	oxide capacitance per unit area
C_p	defined by Eq. (5–7)
C_s	surface concentration of doping impurities
C_{tc}	collector junction capacitance
C_{te}	emitter junction capacitance
D	diffusion constant
D_n	electron diffusion constant
D_p	hole diffusion constant
$D_{p,\text{eff}}$	effective diffusion constant for holes taking account of high injection affects
d_1	channel width in MOSFETs
E	energy
E_a	energy of acceptor levels
E_c	energy at the bottom of the conduction band
E_{cn}	conduction band edge energy on the *n*-side
E_{cp}	conduction band edge energy on the *p*-side
$\mathscr{E}$	electric field
$\mathscr{E}_b$	built-in field

$\mathscr{E}_e$	electric field in the epitaxial region
$\mathscr{E}_{ox}$	electric field in the oxide
$\mathscr{E}_{TL}$	electric field defined by Eq. (9–56)
E_f	Fermi level
E_{fm}	Fermi level in a metal
E_{fs}	Fermi level in a semi-conductor
E_g	band gap
E_n	quantized or discrete energy level
E_i	intrinsic energy
E_k	kinetic energy
E_r	recombination center energy
E_v	energy at the top of the valence band
E_{vn}	valence band edge on the n-side
E_{vp}	valence band edge on the p-side
E_t	trap energy
E_x	energy gap through which the electron tunnels
E_1	defined by Eq. (10–45)
F	force
$F_{\frac{1}{2}}$	Fermi–Dirac integral
F_{ext}	external force
F_{in}	internal force
f	field factor defined by Eq. (7–19)
$f(E)$	Fermi–Dirac distribution function
$f(b)$	defined by Eq. (12–103)
f_m	maximum frequency of oscillation for transistor
f_{maxd}	defined by Eq. (7–120)
f_T'	defined by Eq. (7–111)
f_T^*	defined by Eq. (7–118)
f_t	fraction of traps occupied by electrons
f_{tc}	cut-off frequency due to transit time effect in FET
f_{tp}	fraction of traps occupied by holes
G_c	generation rate of carriers
G_e	defined by Eq. (2–63)
G_n	generation rate of electrons
G_0	channel conductance with gate to source voltage zero in FET.
G_p	generation rate of holes
$(GB)_v$	voltage gain-bandwidth product
$(GB)_{ic}$	current gain-bandwidth product for cascaded current gain
g	defined by Eq. (7–47)

g_{cc}	defined by Eq. (6–199)
g_D	channel conductance, Chapters 7, 8
g_d	diffusion conductance
$g'_{d\ell}$	leakage conductance between gate to drain
g_{ee}	defined by Eq. (6–198)
g'_ℓ	leakage conductance
$g'_{\ell c}$	leakage conductance of the collector junction
$g'_{\ell e}$	leakage conductance of the emitter junction
$g'_{\ell s}$	leakage conductance between the gate and source
g_m	defined by Eq. (6–257); tranconductance of a MOSFET in Chapter 9
g_h	defined by Eq. (10–8)
g_n	defined by Eq. (12–213)
$g_n(Z_n)$	defined by Eq. (12–213)
$g_p(Z_p)$	defined by Eq. (12–210)
h	Planck's constant; channel depth in Chapters 8, 9
$h_{11e}, h_{12e}, h_{21e}, h_{22e}$	common emitter h–parameters
$\hbar$	h/π
h_{fb}	forward short circuit current gain in the common base circuit
h_{fc}	forward short circuit current gain in the common emitter circuit
I	current
I_B	d-c base current
I_C	d-c collector current
I_{CM}	maximum collector current
I_{CO}	collector current when the emitter current is zero
I_{DO}	drain current in saturation
I_D	photo-diode current Chapter 10, drain current for Chapter 7, Chapter 8; given by Eq. (7–57)
I_E	d-c emitter current
I_{EM}	maximum emitter current
I_{EPD}	defined by Eq. (7–55)
I_{CPD}	defined by Eq. (7–56)
I_P	peak current
I_{PH}	photon generated diode current
I_S	back saturation current for p-n junction diodes
I_{SC}	photodiode short circuit current
I_V	valley current
I_c	amplitude of the a-c collector current
I_e	amplitude of the a-c emitter current

I_f	feedback current
I_{bs}	base current which just saturates the transistor
I_{bx}	base current in excess of I_{bs}
I_{nC}	d-c electron current crossing the collector junction
I_{nE}	d-c electron current crossing the emitter junction
I_{ne}	a-c electron current crossing the emitter junction
I_{n0}	d-c electron current crossing the *p-n* junction
I_{cf}	forward collector current
I_{cr}	reverse collector current
I_{cf}	forward emitter current
I_{er}	reverse emitter current
I_m	defined by Eq. (8–67)
I_{es}	emitter current to just saturate the transistor
I_p	hole current
I_{pC}	d-c hole current crossing the collector junction
I_{pE}	d-c hole current crossing the emitter junction
I_{pe}	a-c hole current crossing the emitter junction
I_{p0}	d-c hole current crossing the *p-n* junction
I_{SE}	back saturation current of the emitter junction
I_{SR}	surface recombination current
I_{VR}	volume recombination current
I_{tc}	total a-c current crossing the collector junction
I_{te}	total a-c current crossing the emitter junction
J	current density
J_c	collector current which equals the current in the epitaxial region
J_{pC}	d-c hole current density crossing the collector junction
J_{pE}	d-c hole current density crossing the emitter junction
J_{ptc}	total a-c current density crossing the collector junction
J_{pte}	total a-c current density crossing the emitter junction
J_0	defined by Eq. (12–236)
j	$\sqrt{-1}$
j_n	electron current density
j_p	hole current density
j_{p1}	unperturbed a-c minority carrier current density in the base region
j_{pt}	total hole current density including the contribution of the perturbed solution
j_{p0}	d-c minority carrier current density in the base due to d-c voltages across the emitter and collector junctions
k	Boltzmann's constant

k_a	defined by Eq. (3–94)
k_{at}	defined by Eq. (3–99)
$\mathbf{k}_c$	wave vector
k_c	wave number
k_ℓ	defined by Eq. (3–105)
k_v	defined by Eq. (8–65)
L	diffusion length; channel length in Chapters 8, 9
L_d	distance over which the transition regions meet at the drain end Chapters 8, 9; distance constant associated with the impurity grading in the base region Chapter 7
L_n	diffusion length for electrons
L_{cn}	diffusion length for electrons in the type collector
L_{ne}	diffusion length for electrons in the *p*-type emitter
L_p	diffusion length for holes
L_{pc}	diffusion length for holes in the *n*-type collector
L_{pe}	diffusion length for holes in the *n*-type emitter
L_s	effective channel length
ℓ	a quantum number in Chapter 1; length of a resistive path
M	multiplication factor
MAG	maximum available power gain
m	mass; quantum number in Eq. (1–56)
m_e	electron mass
m^*	effective mass
m_e^*	effective mass of electrons
m_h^*	effective mass of holes
m_ℓ^*	longitudinal effective mass
m_t^*	transverse effective mass
m_0	rest mass of electron
$N(E)$	density of states function
$N_c(E)$	density of states function in the conduction band
N_c	defined by Eq. (2–74)
N_a	volume density of acceptors
N_d	volume density of donor atoms
N_0	defined by Eq. (2–62)
N_{eff}	effective net doping density
$N_v(E)$	density of states function in the valence band
N_v	defined by Eq. (2–78)
N_x	density of occupied band gap states above the top of valence band

n_1	density of electrons in the conduction band when the Fermi level is at the trap level
n	integer and quantum number corresponding to energy; also electron volume density; optimum transformer turns ratio in Chapter 6
n_a	density of electrons in the acceptor states
n_d	density of electron in the donor states
n_i	intrinsic volume density
n_{inj}	injected electrons
n_n	thermal equilibrium electron density in an *n*-type crystal
n_p	thermal equilibrium density of electron density in a *p*-type crystal
n_{pc}	thermal equilibrium electron density in the *p*-type collector
n_{pe}	thermal equilibrium hole density in the *p*-type emitter
n_{xtn}	electron density at x_{tn} density in the *p*-type material
P	momentum in Chapters 1, 2; hole density in other chapters except in Chapter 8 where it is defined by Eq. (8–68)
$\tilde{p}$	perturbed solution
P	probability
P_x	probability of electrons tunneling from band gap states to the valence band
$p_0(x)$	steady state hole density
$p_1(x)$	a-c amplitude of the sinusoidally varying hole density
p_1	hole density in the valence bands when the Fermi level is at the trap level
p_i	intrinsic hole density
p_{inj}	injected holes density
p_n	thermal equilibrium density of holes in an *n*-type crystal
p_p	thermal equilibrium density of holes in a *p*-type crystal
p_{pe}	thermal equilibrium density of holes in the *p*-type emitter
p_{pc}	thermal equilibrium hole density in the *p*-type collector
P_t	total hole density solution including the perturbed solution
p_C	defined by Eq. (4–3)
p_{xtn}	hole density at x_{tn}
p_E	defined by Eq. (4–2)
p_e	a-c emitter boundary condition

P_{in}	input power
P_0	defined by Eq. (7–42)
P_{out}	output power
Q	charge
Q_b	excess minority carrier base charge
Q_{bi}	initial base charge
Q_{bss}	steady-state base charge
Q_{bs}	base minority carrier charge just at saturation
Q_{bx}	base minority carrier charge in excess of Q_{bs}
Q_n	free electron charge in the inverted region
Q_{tot}	total charge
q	magnitude of the electronic charge
s	spin quantum number Chapters 1, 2; surface recombination velocity
T_b	defined by Eq. (6–425)
T_{bv}	defined by Eq. (6–444)
T_c	defined by Eq. (6–427)
T_d	time for which the base is exposed to doping impurities from infinite source
T_e	defined by Eq. (6–426)
T_{fd}	diode fall time
T_p	normalized time, Eq. (6–427)
T_s	defined by Eq. (6–417)
T_s^*	defined by Eq. (6–416)
T_{sd}	normalized diode storage time
T	absolute temperature; time constant; duration of "on" pulse in Chapter 6.
T_0	defined by Eq. (5–30) low frequency of mid-band gain
$\bar{t}$	mean free time
$\bar{t}_n$	mean free time for electrons
$\bar{t}_p$	mean free time for holes
t_d	delay time
t_{dc}	delay time due to capacitor charge readjustment time
t_{dcb}	delay time due to capacitor charge readjustment time in common base circuit
t_{dce}	delay time due to capacitor charge readjustment time in common emitter circuit
t_{dp}	propagation delay time
t_f	fall time
t_{fb}	common base circuit fall time

t_{fc}	common collector circuit fall time
t_{fe}	common emitter circuit fall time
$t_{f\min}$	minimum fall time
t_{ox}	oxide thickness
t_r	rise time
t_{rb}	common base circuit rise time
t_{rc}	common collector circuit rise time
t_{re}	common emitter circuit rise time
t_s	storage time
t_{sb}	common base circuit storage circuit
t_{sc}	common collector circuit storage time
t_{se}	common emitter circuit storage time
U	recombination rate
U_{cn}	rate of recombination of electrons
U_{cp}	rate of recombination of holes
U_{ct}	capture rate of conduction band electrons by available traps
U_r	recombination rate in a reverse biased *p-n* junction
U_{tc}	rate of electron emission from traps to conduction band
U_{tv}	rate of hole emission from traps to valence band
U_{vt}	rate of arrival of holes from the valence band to the traps
u	velocity
u_n	electron velocity
u_p	hole velocity
V	potential energy in Chapter 1; voltage in other chapters
V_B	d-c base voltage
V_{BD}	breakdown voltage
V_{BI}	built-in voltage
V_{BIC}	built-in voltage of collector junction
V_{BIE}	built-in voltage of emitter junction
V_{BO}	defined by Eq. (10–2)
V_C	d-c collector voltage with respect to the base due to an external source
V_c	a-c amplitude of collector to base voltage
V_{DS}	d-c drain to source voltage
V_{DSO}	d-c drain to source voltage at the onset of saturation
V_E	d-c emitter voltage with respect to the base due to an external source
V_e	a-c amplitude of emitter to base voltage
V_F	final voltage

$V_{f\max}$	maximum between V_{fn} and V_{fp}
$V_{f\min}$	minimum between V_{fn} and V_{fp}
V_{fn}	voltage difference between the Fermi level and conduction band edge
V_{fp}	voltage difference between the valence band edge and Fermi level
V_A	avalanche breakdown voltage
V_{D1}	defined by Eq. (12–138)
V_G	d-c gate voltage
V_{GD}	d-c gate to drain voltage
V_{GS}	d-c gate to source voltage
V_{GSeff}	defined by Eq. (9–62)
V_I	initial voltage
V_d	defined by Eq. (7–5)
V_m	defined by Eq. (12–23a)
V_0	defined by Eq. (12–139)
V_{OC}	photo-diode open circuit voltage
V_P	peak voltage in Chapter 10; pinch-off voltage defined by Eq. (8–9) in FET
V_T	threshold voltage
V_V	valley voltage
V_t	total voltage across the transition region
v	volume in Chapter 1; voltage in other chapters
v_1	amplitude of a-c voltage
v_0	d-c voltage
v_c	a-c collector to base voltage
v_C	total collector junction voltage
v_e	a-c emitter to base voltage
v_g	voltage corresponding to the band gap energy
x	position coordinate
x_o	tunneling barrier width in Chapter 1. Oxide thickness in Chapter 9
x_t	transition region width
x_{tc}	collector transition region
x_{te}	emitter transition region
$x_{t\max}$	maximum value of transition region width in MOSFETS
x_{tn}	transition region on the *n*-side of the junction
x_{tp}	transition region edge on the *p*-side of the junction
Y	admittance
$Y_{11}, Y_{12}, Y_{21}, Y_{22}$	admittance parameters

Y^i	intrinsic admittance
$Y^i_{cc}, Y^i_{ce}, Y^i_{ec}, Y^i_{ee}$	common base intrinsic admittances
$Y^i_{ccd}, Y^i_{ced}, Y^i_{ecd}, Y^i_{eed}$	common base intrinsic admittances for drift transistors
Y_{cc}	defined by Eq. (6–163)
$Y_{\ell c}$	leakage admittance of the collector junction
$Y_{\ell e}$	leakage admittance of the emitter junction
Y_m	defined by Eq. (7–93)
Z	impedance
Z'_b	extrinsic base impedance
Z_c	collector impedance
Z_e	emitter impedance
Z_n	high injection parameter for *n-p-n* transistors
Z_p	high injection parameter Eq. (12–20) for *p-n-p* transistors
z_1, z_2	defined by Eq. (12–105)
α	short-circuit current gain for common-base circuit
α^*	collector multiplication factor
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. (2–102)
γ	injection efficiency
γ_0	low frequency value of the injection efficiency
γ_{SS}	charge per unit area at the oxide–semiconductor interface
γ_u	injection efficiency for the unijunction transistor

ε	permittivity
ε_d	defined by Eq. (7–44)
ε_g	defined by Eq. (7–65)
ε_{ox}	permittivity of the oxide
ε_g	defined by Eq. (7–66)
η_c	normalized conduction band edge
η	E/kT normalized energy defined by Eq. (2–64) in Chapter 2; capacitance ratio defined by Eq. (6–325)
η_f	E_f/kT normalized Fermi level (Chapter 2)
η_a	E_a/kT normalized acceptor energy (Chapter 2)
η_d	E_d/kT normalized donor energy (Chapter 2)
η_g	E_g/kT (Chapter 2)
θ_h	Hall angle
θ_n	Hall angle in an *n*-type semiconductor
θ_p	Hall angle in a *p*-type semiconductor
λ	wavelength
μ	mobility
μ_{d1}	drift mobility of holes in valence band 1
μ_{d2}	drift mobility of holes in valance band 2
μ_{dn}	drift mobility of electrons
μ_{dp}	drift mobility of holes
μ_{hn}	Hall mobility of electrons
σ	defined by Eq. (7–49)
σ_0	defined by Eq. (7–48)
σ_B	base conductivity
σ_C	collector conductivity
σ_E	conductivity of the emitter
σ_i	conductivity of the intrinsic semiconductor
σ_n	conductivity due to electrons
σ_p	conductivity due to holes
σ_{nc}	conductivity of *p*-type collector due to only electrons
σ_{pc}	conductivity of *p*-type collector due to only holes
τ	base transit time
τ_B	defined by Eq. (7–113)
τ_C	defined by Eq. (7–114)
τ_{CB}	defined by Eq. (7–115)
τ_E	defined by Eq. (7–112)