Home work problems

Dr. M. Radmanesh

(1)

*9. Derive Eq. 17. (Hint: In the valence band, the probability of occupancy of a state by a hole is $[1 - F(E)]$.)

10. At room temperature (300 K) the effective density of states in the valence band is 2.66×10^{19} cm^{-3} for silicon and 7×10^{18} cm^{-3} for gallium arsenide. Find the corresponding effective masses of holes. Compare these masses with the free-electron mass.

11. Calculate the location of E_i in silicon at liquid nitrogen temperature (77 K), at room temperature (300 K), and at 100°C (let $m_p = 1.0\ m_0$ and $m_n = 0.19\ m_0$). Is it reasonable to assume that E_i is in the center of the forbidden gap?

12. Find the kinetic energy of electrons in the conduction band of a nondegenerate n-type semiconductor at 300 K.

13. (a) For a free electron with a velocity of 10^7 cm/s, what is its de Broglie wavelength.

    (b) In GaAs, the effective mass of electrons in the conduction band is $0.063\ m_0$. If they have the same velocity, find the corresponding de Broglie wavelength.

14. The intrinsic temperature of a semiconductor is the temperatures at which the intrinsic carrier concentration equals the impurity concentration. Find the intrinsic temperature for a silicon sample doped with 10^{15} phosphorus atoms/cm^3.

FOR SECTION 2.7 DONORS AND ACCEPTORS

15. A silicon sample at $T = 300$ K contains an acceptor impurity concentration of $N_A = 10^{16}$ cm^{-3}. Determine the concentration of donor impurity atoms that must be added so that the silicon is n-type and the Fermi energy is 0.20 eV below the conduction band edge.

16. Draw a simple flat energy band diagram for silicon doped with 10^{16} arsenic atoms/cm^3 at 77 K, 300 K, and 600 K. Show the Fermi level and use the intrinsic Fermi level as the energy reference.

17. Find the electron and hole concentrations and Fermi level in silicon at 300 K (a) for 1×10^{15} boron atoms/cm^3 and (b) for 3×10^{16} boron atoms/cm^3 and 2.9×10^{16} arsenic atoms/cm^3.

18. A Si sample is doped with 10^{17} As atoms/cm^3. What is the equilibrium hole concentration p_0 at 300 K? Where is E_F relative to E_i?

19. Calculate the Fermi level of silicon doped with 10^{15}, 10^{17}, and 10^{19} phosphorus atoms/cm^3 at room temperature, assuming complete ionization. From the calculated Fermi level, check if the assumption of complete ionization is justified for each doping. Assume that the ionized donors is given by $n = N_D\,[1 - F(E_D)] = \dfrac{N_D}{1 + e^{(E_F - E_D)/kT}}$.

20. For an n-type silicon sample with 10^{16} cm^{-3} phosphorous donor impurities and a donor level at $E_D = 0.045$ eV, find the ratio of the neutral donor density to the ionized donor density at 77 K where the Fermi level is 0.0459 below the bottom of the conduction band. The expression for ionized donors is given in Prob. 19.

Car
Phe

3.1 CA
3.2 CA
3.3 GE
3.4 CO
3.5 TH
3.6 TU
3.7 HI(
SUMM

In this ch
The trans
emission,
(electrons
carrier co
dition whe
n_i^2. Return
is conside
operation,
is followe
closes wit
impact io
Speci
• Tl
• Tl
• O
tr
• M
ity

6

ıs.[9]

(90)

tively. This expression
n avalanche condition.

. These include drift,
and impact ionization.
: influence of an elec-
ectric field. This pro-
is the carrier diffusion
al current is the sum

ondition. Most semi-
ers can be generated
ight, and impact ion-
ı of the excess minor-
ıation or via localized
or the rate of change

As the electric field becomes higher, the drift velocity departs from its linear relationship with the applied field and approaches a saturation velocity. This effect is particularly important in the study of short-channel field-effect transistors discussed in Chapter 6. When the field exceeds a certain value, the carriers gain enough kinetic energy to generate electron-hole pair by colliding with the lattice and breaking a bond. This effect is particularly important in the study of p–n junctions. The high field accelerates these new electron-hole pairs, which collide with the lattice to create more electron-hole pairs. As this process, called impact ionization or the avalanche process, continues, the p–n junction breaks down and conducts a large current. The junction breakdown is discussed in Chapter 4.

REFERENCES

1. R. A. Smith, *Semiconductors*, 2nd ed., Cambridge Univ. Press, London, 1978.
2. J. L. Moll, *Physics of Semiconductors*, McGraw-Hill, New York, 1964.
3. W. F. Beadle, J. C. C. Tsai, and R. D. Plummer, Eds., *Quick Reference Manual for Semiconductor Engineers*, Wiley, New York, 1985.
4. (a) R. N. Hall, "Electron–Hole Recombination in Germanium," *Phys. Rev.*, **87**, 387 (1952); (b) W. Shockley and W. T. Read, "Statistics of Recombination of Holes and Electrons," *Phys. Rev.*, **87**, 835(1952).
5. M. Prutton, *Surface Physics*, 2nd ed., Clarendon, Oxford, 1983.
6. A. S. Grove, *Physics and Technology of Semiconductor Devices*, Wiley, New York, 1967.
7. J. R. Haynes and W. Shockley, "The Mobility and Life of Injected Holes and Electrons in Germanium," *Phys. Rev.*, **81**, 835 (1951).
8. D. M. Caughey and R. E. Thomas, "Carrier Mobilities in Silicon Empirically Related to Doping and Field," *Proc. IEEE*, **55**, 2192 (1967).
9. S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed., Wiley, New York, 1981.

PROBLEMS (* INDICATES DIFFICULT PROBLEMS)

FOR SECTION 3.1 CARRIER DRIFT

1. Find the resistivities of intrinsic Si and intrinsic GaAs at 300 K.
2. Assume that the mobility of electrons in silicon at T = 300 K is μ_n = 1300 cm²/V-s. Also assume that the mobility is mainly limited by lattice scattering. Determine the electron mobility at (a) T = 200 K and (b) T = 400 K.
3. Two scattering mechanisms exist in a semiconductor. If only the first mechanism is present, the mobility will be 250 cm²/V-s. If only the second mechanism is present, the mobility will be 500 cm²/V-s. Determine the mobility when both scattering mechanisms exist at the same time.
4. Find the electron and hole concentrations, mobilities, and resistivities of silicon samples at 300 K, for each of the following impurity concentrations: (a) 5×10^{15} boron atoms/cm³; (b) 2×10^{16} boron atoms/cm³ and 1.5×10^{16} arsenic atoms/cm³; and (c) 5×10^{15} boron atoms/cm³, 10^{17} arsenic atoms/cm³, and 10^{17} gallium atoms/cm³.

*5. Consider a compensated n-type silicon at T = 300 K, with a conductivity of σ = 16 $(\Omega\text{-cm})^{-1}$ and an acceptor doping concentration of 10^{17} cm^{-3}. Determine the donor the mobility ratio.

7. A four-point probe (with probe spacing of 0.5 mm) is used to measure the resistivity of a p-type silicon sample. Find the resistivity of the sample if its diameter is 200 mm and its thickness is 50 μm. The contact current is 1 mA, and the measured voltage between the inner two probes is 10 mV.

8. Given a silicon sample of unknown doping, Hall measurement provides the following information: $W = 0.05$ cm, $A = 1.6 \times 10^{-3}$ cm^2 (refer to Fig. 8), $I = 2.5$ mA, and the magnetic field is 30 nT (1 T = 10^{-4} Wb/cm^2). If a Hall voltage of +10 mV is measured, find the Hall coefficient, conductivity type, majority carrier concentration, resistivity, and mobility of the semiconductor sample.

9. A semiconductor is doped with N_D ($N_D >> n_i$) and has a resistance R_1. The same semiconductor is then doped with an unknown amount of acceptors N_A ($N_A >> N_D$), yielding a resistance of 0.5 R_1. Find N_A in terms of N_D if D_n/D_p=50.

*10. Consider a semiconductor that is nonuniformly doped with donor impurity atoms $N_D(x)$. Show that the induced electric field in the semiconductor in thermal equilibrium is given by $\mathscr{E}(x) = -\left(\frac{kT}{q}\right)\frac{1}{N_D(x)}\frac{dN_D(x)}{dx}$.

FOR SECTION 3.2 CARRIER DIFFUSION

11. An intrinsic Si sample is doped with donors from one side such that $N_D = N_0 \exp(-ax)$. (a) Find an expression for the built-in field $\mathscr{E}(x)$ at equilibrium over the range for which $N_D >> n_i$. (b) Evaluate $\mathscr{E}(x)$ when a = 1 μm^{-1}.

12. An n-type Si slice of a thickness L is inhomogeneously doped with phosphorus donor whose concentration profile is given by $N_D(x) = N_0 + (N_L - N_0)(x/L)$. What is the formula for the electric potential difference between the front and the back surfaces when the sample is at thermal and electric equilibria regardless of how the mobility and diffusivity varies with position? What is the formula for the equilibrium electric field at a plane x from the front surface for a constant diffusivity and mobility?

FOR SECTION 3.3 GENERATION AND RECOMBINATION PROCESS

13. Calculate the electron and hole concentration under steady-state illumination in an n-type silicon with $G_L = 10^{16}$ cm^{-3}s^{-1}, $N_D = 10^{15}$ cm^{-3}, and $\tau_n = \tau_p$ = 10 μs.

14. An n-type silicon sample has 2×10^{16} arsenic atoms/cm^3, 2×10^{15} bulk recombination centers/cm^3, and 10^{10} surface recombination centers/cm^2. (a) Find the bulk minority carrier lifetime, the diffusion length, and the surface recombination velocity under low-injection conditions. The values of σ_p and σ_s are 5×10^{-15} and 2×10^{-16} cm^2, respectively. (b) If the sample is illuminated with uniformly absorbed light that creates 10^{17} electron-hole pairs/cm^2-s, what is the hole concentration at the surface?

15. Assume that an n-type semiconductor is uniformly illuminated, producing a uniform excess generation rate G. Show that in steady state the change in the semiconductor conductivity is given by $\Delta\sigma = q(\mu_n + \mu_p)\tau_p G$.

FOR SECTION 3.4 CONTINUITY EQUATION

16. The total current in a semiconductor is constant and is composed of electron drift current and hole diffusion current. The electron concentration is constant and equal to 10^{16} cm^{-3}.

whe
ity is
diffu
elect

*17. Exce
W a
the r

18. In F
curr

*19. An n
time
zero
conc

FOR SEC

20. A m
with
trons

21. Cons
Show
trons
therm

whe

$\int_{-\infty}^{\infty} e$

FOR SEC

22. Cons
and a

23. Eval
poter
barri

FOR SEC

24. Use t
time
kV/c

25. Assu
relat
elect
small
valu

luctor is one that con-

ndependent of impurity
insic resistivity ρ_i and

sure the resistivity of a
eter is 200 mm and its
l voltage between the

vides the following
2.5 mA, and the mag-
nV is measured, find the
resistivity, and mobility

R_1. The same semicon-
$_{\iota} >> N_D$), yielding a

impurity atoms $N_D(x)$.
al equilibrium is given

it $N_D = N_0 \exp(-ax)$.
er the range for which

phosphorus donor
). What is the formula
surfaces when the
mobility and diffusivity
ric field at a plane x

ROCESS

lumination in an n-type

ulk recombination cen-
bulk minority carrier
ty under low-injection
respectively. (b) If the
^{17} electron-hole

ducing a uniform
he semiconductor

of electron drift current
and equal to 10^{16} cm^{-3}.

The hole concentration is given by

$$p(x) = 10^{15} \exp\left(\frac{-x}{L}\right) \text{ cm}^{-3} \qquad (x \geq 0),$$

where L = 12 μm. The hole diffusion coefficient is D_p = 12 cm²/s and the electron mobility is μ_n = 1000 cm²/V-s. The total current density is J = 4.8 A/cm². Calculate (a) the hole diffusion current density versus x, (b) the electron current density versus x, and (c) the electric field versus x.

*17. Excess carriers are injected on one surface of a thin slice of n-type silicon with thickness W and extracted at the opposite surface where $p_n(W) = p_{no}$. There is no electric field in the region $0 < x < W$. Derive the expression for current densities at the two surfaces.

18. In Prob. 17, if carrier lifetime is 50 μs and W = 0.1 mm, calculate the portion of injected current that reaches the opposite surface by diffusion (D = 50 cm²/s).

*19. An n-type semiconductor has excess carrier holes 10^{14} cm^{-3}, and a bulk minority carrier lifetime 10^{-6} s in the bulk material, and a minority carrier lifetime 10^{-7} s at the surface. Assume zero applied electric field and let D_p = 10 cm²/s. Determine the steady-state excess carrier concentration as a function of distance from the surface (x = 0) of the semiconductor.

FOR SECTION 3.5 THERMIONIC EMISSION PROCESS

20. A metal, with a work function ϕ_m = 4.2 V, is deposited on an n-type silicon semiconductor with affinity χ = 4.0 V and E_g = 1.12 eV. What is the potential barrier height seen by electrons in the metal moving into the semiconductor?

21. Consider a tungsten filament with metal work function ϕ_m inside a high vacuum chamber. Show that if a current is passed through the filament to heat it up sufficiently, the electrons with enough thermal energy will escape into the vacuum and the resulted thermionic current density is

$$J = A^* T^2 \exp\left(\frac{-q\phi_m}{kT}\right)$$

where A^* is $4\pi qmk^2 / h^3$ and m is free electron mass. The definite integral

$$\int_{-\infty}^{\infty} e^{-ax^2} dx = \left(\frac{\pi}{a}\right)^{1/2}.$$

FOR SECTION 3.6 TUNNELING PROCESS

22. Consider a electron with an energy of 2 eV impinging on a potential barrier with 20 eV and a width of 3 Å. What is the tunneling probability?

23. Evaluate the transmission coefficient for an electron of energy 2.2 eV impinging on a potential barrier of height 6.0 eV and thickness 10^{-10} meters. Repeat the calculation for a barrier thickness of 10^{-9} meters.

FOR SECTION 3.7 HIGH FIELD EFFECTS

24. Use the velocity-field relations for Si and GaAs shown in Fig. 22 to determine the transit time of electrons through a 1 μm distance in these materials for an electric field of (a) 1 kV/cm and (b) 50 kV/cm.

25. Assume that a conduction electron in Si (μ_n = 1350 cm²/V-s) has a thermal energy kT, related to its mean thermal velocity by $E_{th} = m_0 v_{th}^2/2$. This electron is placed in an electric field of 100 V/cm. Show that the drift velocity of the electron in this case is small compared to its thermal velocity. Repeat for a field of 10^4 V/cm, using the same value of μ_n. Comment on the actual mobility effects at this higher value of field.

3. R. H. Kingston, "Switching Time in Junction Diodes and Junction Transistors," *Proc. IRE*, 42, 829 (1954).
4. J. L. Moll, *Physics of Semiconductors*, McGraw-Hill, New York, 1964.
5. S. M. Sze and G. Gibbons, "Avalanche Breakdown Voltages of Abrupt and Linearly Graded p–n Junctions in Ge, Si, GaAs and GaP," *Appl. Phys. Lett.*, 8, 111 (1966).
6. S. K. Ghandhi, *Semiconductor Power Devices*, Wiley, New York, 1977.
7. S. M. Sze and G. Gibbons, "Effect of Junction Curvature on Breakdown Voltages in Semiconductors," *Solid State Electron.*, 9, 831 (1966).
8. H. Kroemer, " Critique of Two Recent Theories of Heterojunction Lineups," *IEEE Electron Device Lett.*, **EDL-4**, 259 (1983).

PROBLEMS (* DENOTES DIFFICULT PROBLEMS)

FOR SECTION 4.3 DEPLETION REGION

*1. A diffused silicon p–n junction has a linearly graded junction on the p-side with $a = 10^{19}$ cm^{-4}, and a uniform doping of 3×10^{14} cm^{-3} on the n-side. If the depletion layer width of the p-side is 0.8μm at zero bias, find the total depletion layer width, built-in potential, and maximum field at zero bias.

*2. Sketch the potential distribution in the Si p–n junction in Prob. 1.

3. For an ideal silicon p–n abrupt junction with $N_A = 10^{17}$ cm^{-3} and $N_D = 10^{15}$ cm^{-3}, (a) calculate V_{bi} at 250, 300, 350, 400, 450, and 500 K and plot V_{bi} versus T; (b) comment on your result in terms of energy band diagram; and (c) find the depletion layer width and the maximum field at zero bias for T = 300 K.

4. Determine the n-type doping concentration to meet the following specifications for a Si p–n junction:

$N_A = 10^{18}$ cm^{-3}, $\mathscr{E}_{max} = 4 \times 10^5$ V/cm at V_R = 30 V, T = 300 K.

FOR SECTION 4.4 DEPLETION CAPACITANCE

*5. An abrupt p–n junction has a doping concentration of 10^{15}, 10^{16}, or 10^{17} cm^{-3} on the lightly doped n-side and of 10^{19} cm^{-3} on the heavily doped p-side. Obtain series of curves of $1/C^2$ versus V, where V ranges from –4 V to 0 V in steps of 0.5 V. Comment on the slopes and the interceptions at the voltage axis of these curves.

6. For a silicon linearly graded junction with a impurity gradient of 10^{20} cm^{-4}, calculate the built-in potential and the junction capacitance at reverse bias of 4 V (T = 300 K).

7. A one-sided p^+–n Si junction at 300 K is doped with $N_A = 10^{19}$cm^{-3}. Design the junction so that C_j = 0.85 pF at V_R = 4.0 V.

FOR SECTION 4.5 CURRENT-VOLTAGE CHARACTERISTICS

8. Assume that the p–n junction considered in Prob. 3 contains 10^{15} cm^{-3} generation-recombination centers located 0.02 eV above the intrinsic Fermi level of silicon with $\sigma_n = \sigma_p = 10^{-15}$ cm^2. If $v_{th} \cong 10^7$ cm/s, calculate the generation and recombination current at –0.5 V.

9. Consider a Si p–n junction with n-type doping concentration of 10^{16} cm^{-3} and is forward biased with V = 0.8 V at 300 K. Calculate the minority-carrier hole concentration at the edge of the space charge region.

10. Calculate the applied reverse-bias voltage at which the ideal reverse current in a p–n junction diode at T = 300 K reaches 95% of its reverse saturation current value.

11. Design the Si p–n diode such that J_n = 25 A/cm^2 and J_p = 7 A/cm^2 at V_a = 0.7 V. The remaining parameters are given in Ex. 5.

12. An ideal silicon p–n junction has $N_D = 10^{18}$ cm^{-3}, $N_A = 10^{16}$ cm^{-3}, $\tau_p = \tau_n = 10^{-6}$ s, and a device area of 1.2×10^{-5} cm^2. (*a*) Calculate the theoretical saturation current at 300 K. (*b*) Calculate the forward and reverse currents at ±0.7 V.

13. In Prob. 12, assume the widths of the two sides of the junction are much greater than the respective minority-carrier diffusion length. Calculate the applied voltage at a forward current of 1 mA at 300 K.

14. A silicon p^+–n junction has the following parameters at 300 K: $\tau_p = \tau_g = 10^{-6}$ s, $N_D = 10^{15}$ cm^{-3}, $N_A = 10^{19}$ cm^{-3}. (*a*) Plot diffusion current density, J_{gen}, and total current density versus applied reverse voltage. (*b*) Repeat the above results for $N_D = 10^{17}$ cm^{-3}.

FOR SECTION 4.6 CHARGE STORAGE AND TRANSIENT BEHAVIOR

15. For an ideal abrupt silicon p^+–n junction with $N_D = 10^{16}$ cm^{-3}, find the stored minority carriers per unit area in the neutral n-region when a forward bias of 1 V is applied. The length of neutral region is 1 µm and the diffusion length of the holes is 5 µm.

FOR SECTION 4.7 JUNCTION BREAKDOWN

16. For a silicon p^+–n one-sided abrupt junction with $N_D = 10^{15}$ cm^{-3}, find the depletion layer width at breakdown. If the n-region is reduced to 5 µm, calculate the breakdown voltage and compare your result with Fig. 29.

17. Design an abrupt Si p^+–n junction diode that has a reverse breakdown voltage of 130 V and has a forward-bias current of 2.2 mA at V_a = 0.7 volt. Assume $\tau_{po}=10^{-7}$s.

18. In Fig. 20*b*, the avalanche breakdown voltage increases with increasing temperature. Give a qualitative argument for the result.

19. If $\alpha_n = \alpha_p = 10^4(\mathscr{E}/4 \times 10^5)^6$ cm^{-1} in gallium arsenide, where $\mathscr{E}$ is in V/cm, find the breakdown voltage of (*a*) a p-i-n diode with an intrinsic-layer width of 10µm and (*b*) p^+–n junction with a doping of 2×10^{16} cm^{-3} for the lightly doped side.

20. Consider that a Si p–n junction at 300 K with a linearly doping profile varies from $N_A = 10^{18}$ cm^{-3} to $N_D = 10^{18}$cm^{-3} over a distance of 2 µm. Calculate the breakdown voltage.

FOR SECTION 4.8 HETEROJUNCTION

21. For the ideal heterojunction in Ex. 10, find the electrostatic potential and depletion width in each material for applied voltage of 0.5 V and –5 V.

22. For an n-type GaAs/ p-type $Al_{0.3}Ga_{0.7}As$ heterojunction at room temperature, ΔE_C = 0.21 eV. Find the total depletion width at thermal equilibrium when both sides have impurity concentration of 5×10^{15} cm^{-3}. (Hint: the bandgap of $Al_xGa_{1-x}As$ is given by $E_g(x)$= 1.424 + 1.247x eV, and the dielectric constant is 12.4 – 3.12x. Assume N_C and N_V are the same for $Al_xGa_{1-x}As$ with $0 < x < 0.4$.

ing above 10,000 V. We have considered the basic characteristic of thyristor operation. In addition, we discussed the bidirectional thyristor (diac and triac) that has on-off states with either positive or negative terminal voltages, the asymmetric thyristor that has very short turn-on and turn-off times, the gate turn-off thyristor (GTO), and the light-activated thyristor. Thyristors can cover a wide range of applications from low-frequency high-current power supplies to high-frequency, low-power applications, including lighting controls, home appliances, and industrial equipment.

REFERENCES

1. (a) J. Bardeen and W. H. Brattain, "The Transistor, A Semiconductor Triode," *Phys. Rev.*, **74**, 230 (1948). (b) W. Shockley, "The Theory of *p–n* Junction in Semiconductors and *p–n* Junction Transistor," *Bell Syst. Tech. J.*, **28**, 435 (1949).
2. J. J. Ebers, "Four-Terminal *p-n-p-n* Transistor," *Proc. IEEE*, **40**, 1361 (1952).
3. S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed., Wiley, New York, 1981.
4. J. M. Early, "Effects of Space-Charge Layer Widening in Junction Transistors," *Proc. IRE*, **40**, 1401 (1952).
5. J. S. Yuan and J. J. Liou, "Circuit Modeling for Transient Emitter Crowding and Two-Dimensional Current and Charge Distribution Effects," *Solid-State Electron.*, **32**, 623 (1989).
6. J. J. Liou, "Modeling the Cutoff Frequency of Heterojunction Bipolar Transistors Subjected to High Collector-Layer Currents," *J. Appl. Phys.*, **67**, 7125 (1990).
7. B. Jalali and S. J. Pearton, Eds., *InP HBTs: Growth, Processing, and Application*, Artech House, Norwood, MA, 1995.
8. D. Mensa, et al., "Transferred-Substrate HBTs with 250 GHz Current-Gain Cutoff frequency," *Tech. Dig. IEEE Int. Electron Devices Meet.*, p. 657 (1998).
9. T. Ishibashi and Y. Yamauchi, "A Possible Near-Ballistic Collection in an AlGaAa/GaAs HBT with a Modified Collector Structure," *IEEE Trans. Electron Devices*, *ED-35*, 401 (1988).
10. P. D. Taylor, *Thyristor Design and Realization*, Wiley, New York, 1993.
11. H. P. Lips, "Technology Trends for HVDC Thyristor Valves," *1998 Int. Conf. Power Syst. Tech. Proc.*, **1**, 446 (1998).
12. E. I. Carroll, "Power Electronics for Very High Power Applications," *Seventh Int. Conf. Power Elect. Vari. Speed Drives*, p. 218 (1998).
13. B. K. Bose, "Evaluation of Modern Power Semiconductor Devices and Future Trends of Converters," *IEEE Trans. Ind. Appl.*, **28(2)**, 403 (1992).

PROBLEMS (* INDICATES DIFFICULT PROBLEMS)

FOR SECTION 5.2 STATIC CHARACTERISTICS OF BIPOLAR TRANSISTOR

1. An *n-p-n* transistor has a base transport factor α_T of 0.998, an emitter efficiency of 0.997, and an I_{Cp} of 10 nA. (a) Calculate α_0 and β_0 for the device. (b) If $I_B = 0$, what is the emitter current?
2. Given that an ideal transistor has an emitter efficiency of 0.999 and the collector-base leakage current is 10 μA, calculate the active region emitter current due to holes if $I_B = 0$.

4. For base time trat
5. Usi of tl rent cier
6. Ref as a line
*7. For of I
8. Der atec mat in F
9. Usi be a
10. Sho
11. If tl β_0 c
12. For β_0. regi (Hi
13. A si 10^{15} stan (kT
μ_n
*14. Usi regi 0.01 eacl
15. Basi tor,
*16. For by M imp trati

3. A silicon p-n-p transistor has impurity concentrations of 5×10^{18}, 2×10^{17}, and 10^{16} cm^{-3} in the emitter, base, and collector, respectively. The base width is 1.0 μm, and the device cross-sectional area is 0.2 mm^2. When the emitter-base junction is forward biased to 0.5 V and the base-collector junction is reverse biased to 5 V, calculate (a) the neutral base width and (b) the minority carrier concentration at the emitter-base junction.

4. For the transistor in Prob. 3, the diffusion constants of minority carriers in the emitter, base, and collector are 52, 40, and 115 cm^2/s, respectively; and the corresponding lifetimes are 10^{-8}, 10^{-7}, and 10^{-6} s. Find the current components I_{Ep}, I_{Cp}, I_{En}, I_{Cn}, and I_{BB} illustrated in Fig. 5.

5. Using the results obtained from Prob. 3 and 4, (a) find the terminal currents I_E, I_C, and I_B of the transistor; (b) calculate emitter efficiency, base transport factor, common-base current gain, and common-emitter current gain; and (c) comment on how the emitter efficiency and base transport factor can be improved.

6. Referring to the minority carrier concentration shown in Eq. 14, sketch $p_n(x)/p_n(0)$ curves as a function of x with different W/L_p. Show that the distribution will approach a straight line when W/L_p is small enough (say $W/L_p < 0.1$).

*7. For a transistor under the active mode of operation, use Eq. 14 to find the exact solutions of I_{Ep} and I_{Cp}.

8. Derive the expression for total excess minority-carrier charge Q_B, if the transistor is operated under the active mode and $p_n(0) >> p_{no}$. Explain how the charge can be approximated by the triangle area in the base shown in Fig. 6. In addition, using the parameters in Prob. 3, find Q_B.

9. Using Q_B derived from Prob. 8, show that the collector current expressed in Eq. 27 can be approximated by $I_C \cong (2D_p/W^2)Q_B$.

10. Show that the base transport factor α_T can be simplified to $1 - (W^2/2L_p{}^2)$.

11. If the emitter efficiency is very close to unity, show that the common-emitter current gain β_0 can be given by $2L_p^2/W^2$. (Hint: Use α_T in Prob. 10.)

12. For a p^+-n-p transistor with high emitter efficiency, find the common-emitter current gain β_0. If the base width is 2 μm and the diffusion constant of minority carrier in the base region is 100 cm^2/s, assume that the lifetime of the carrier in the base region is 3×10^{-7} s. (Hint: Refer to β_0 derived in Prob. 11.)

13. A silicon n-p-n bipolar transistor has impurity concentrations of 3×10^{18}, 2×10^{16}, and 5×10^{15} cm^{-3} in the emitter, base, and collector, respectively. Determine the diffusion constants of minority carrier in the three regions by using Einstein's relationship, $D = (kT/q)\mu$. Assume that he mobilities of electrons and holes, μ_n and μ_p, can be expressed as

$$\mu_n = 88 + \frac{1252}{\left(1 + 0.698 \times 10^{-17} N\right)} \text{ and } \mu_p = 54.3 + \frac{407}{\left(1 + 0.374 \times 10^{-17} N\right)} \text{ at } T = 300 \text{ K.}$$

*14. Using the results obtained from Prob. 13, determine the current components in each region with $V_{BE} = 0.6$V (operated under active mode). The device cross-sectional area is 0.01 mm^2 and the neutral-base width is 0.5 μm. Assume the minority-carrier lifetime in each region is the same and equals to 10^{-6} s.

15. Based on the results obtain from Prob. 14, find the emitter efficiency, base transport factor, common-base current gain, and common-emitter current gain.

16. For an ion implanted n-p-n transistor the net impurity doping in the neutral base is given by $N(x) = N_{AO}e^{-x/l}$, where $N_{AO} = 2 \times 10^{18}$ cm^{-3} and $l = 0.3$ μm. (a) Find the total number of impurities in the neutral-base region per unit area (b) Find the average impurity concentration in the neutral-base region for a neutral-base width of 0.8 μm.

17. Referring to Problem 16, if $L_E = 1\mu m$, $N_E = 10^{19}$ cm^{-3}, $D_E = 1$ cm^2/s, the average lifetime is 10^{-6} s in the base, and the average diffusion coefficient in the base corresponds to the impurity concentration in Prob. 16, find the common-emitter current gain.

18. Estimate the collector current level for the transistor in Probs. 16 and 17 that has an emitter area of 10^{-4} cm^2. The base resistance of the transistor can be expressed as $10^{-3}\,\overline{\rho}_B/W$, where W is the neutral-base width and $\overline{\rho}_B$ is the average base resistivity.

*19. Plot the common-emitter current gain as a function of the base current I_B from 0 to 25 μA at a fixed V_{EC} of 5 V for the transistor shown in Fig. 10*b*. Explain why the current gain is not a constant.

20. The general equations of the emitter and collector currents for the basic Ebers-Moll model [J. J. Ebers and J. L. Moll, "Large-Single Behavior of Junction Transistors," *Proc.IRE.*, 42,1761(1954)] are

$$I_E = I_{FO}\left(e^{qV_{EB}/kT} - 1\right) - \alpha_R I_{RO}\left(e^{qV_{CB}/kT} - 1\right),$$
$$I_C = \alpha_F I_{FO}\left(e^{qV_{EB}/kT} - 1\right) - I_{RO}\left(e^{qV_{CB}/kT} - 1\right),$$

where α_F and α_R are the *forward common-base current gain* and the *reverse common-base current gain*, respectively. I_{FO} and I_{RO} are the saturation currents of the normally forward- and reverse-biased diodes, respectively. Find α_F and α_R in terms of the constants in Eqs. 25, 26, 28, and 29.

*21. Referring to the transistor in Example 2, find α_F, α_R, I_{FO}, and I_{RO} by using the equations derived in Problem 20.

22. Derive Eq. 32*b* for the collector current starting with the field-free steady-state continuity equation. (Hint: Consider the minority carrier distribution in the collector region.)

FOR SECTION 5.3 FREQUENCY RESPONSE AND SWITCHING OF BIPOLAR TRANSISTOR

23. A Si transistor has D_p of 10 cm^2/s and W of 0.5 μm. Find the cutoff frequencies for the transistor with a common-base current gain α_0 of 0.998. Neglect the emitter and collector delays.

24. If we want to design a bipolar transistor with 5 GHz cutoff frequency f_T, what the neutral base width W will be? Assume D_p is 10 cm^2/s and neglect the emitter and collector delays.

FOR SECTION 5.4 THE HETEROJUNCTION BIPOLAR TRANSISTOR

25. Consider a $Si_{1-x}Ge_x$/Si HBT with $x = 10\%$ in the base region (and 0% in emitter and collector region). The bandgap of the base region is 9.8% smaller than that of Si. If the base current is due to emitter injection efficiency only, what is the expected change in the common-emitter current gain between 0° and 100°C?

26. For an $Al_xGa_{1-x}As$/GaAs HBT, the bandgap of the $Al_xGa_{1-x}As$ is a function of x and can be expressed as $1.424 + 1.247x$ eV (when $x \le 0.45$) and $1.9 + 0.125x + 0.143x^2$ eV (when $0.45 < x \le 1$). Plot $\beta_0(\mathrm{HBT})/\beta_0(\mathrm{BJT})$ as a function of x.

FOR SECTION 5.5 THE THYRISTOR AND RELATED POWER DEVICES

27. For the doping profile shown in Fig. 22, find the width W (> 10μm) of the $n1$-region so that the thyristor has a reverse blocking voltage of 120 V. If the current gain α_2 for the $n1$-$p2$-$n2$ transistor is 0.4 independent of current, and α_1 of the $p1$-$n1$-$p2$ transistor can be expressed as $0.5\sqrt{L_p/W}\,\ln(J/J_0)$, where L_p is 25 μm and J_0 is 5×10^{-6} A/cm^2, find the cross-sectional area of the thyristor that will switch at a current I_S of 1 mA.

28. For a GTO thryistor shown in Fig. 32, find the minimum gate current I_g to turn off the thyristor. Assume the current gains of the $p1$-$n1$-$p2$ and $n1$-$p2$-$n2$ transistors are α_1 and α_2, respectively.

10. density of 5×10^{11} cm^{-2} locating solely at $y = 5$ nm. The thickness of the oxide layer is 10 nm. Find the change in the flat-band voltage due to Q_{ot}.

11. Assume that the oxide trapped charge Q_{ot} in an oxide layer has a triangular distribution: $\rho_{ot}(y) = q \times (5 \times 10^{23} \times y)$ cm^{-3}. The thickness of oxide layer is 10 nm. Find the change in the flat-band voltage due to Q_{ot}.

12. Assume that initially there is a sheet of mobile ions at the metal-SiO_2 interface. After a long period of electrical stressing under a high positive gate voltage and raised temperature condition, the mobile ions completely drift to the SiO_2-Si interface. This leads to a change of 0.3 V in the flat-band voltage. The thickness of oxide layer is 10 nm. Find the area density of Q_m.

FOR SECTION 6.2 MOSFET FUNDAMENTALS

13. Derive Eq. 34 from Eq. 33 in the text assuming $V_D << (V_G - V_T)$.

*14. Derive the I-V characteristics of a MOSFET with the drain and gate connected together and the source and substrate grounded. Can one obtain the threshold voltage from these characteristics?

15. Consider a long-channel MOSFET with $L = 1$ μm, $Z = 10$ μm, $N_A = 5 \times 10^{16}$ cm^{-3}, $\mu_n = 800$ cm^2/ V-s, $C_o = 3.45 \times 10^{-7}$ F/cm^2, and $V_T = 0.7$ V. Find V_{Dsat} and I_{Dsat} for $V_G = 5$ V.

16. Consider a submicron MOSFET with $L = 0.25$ μm, $Z = 5$ μm, $N_A = 10^{17}$ cm^{-3}, $\mu_n = 500$ cm^2/ V-s, $C_o = 3.45 \times 10^{-7}$ F/cm^2, and $V_T = 0.5$ V. Find the channel conductance for $V_G = 1$ V and $V_D = 0.1$ V.

17. For the device stated in Prob. 16, find the transconductance.

18. An n-channel, n^+-polysilicon-SiO_2-Si MOSFET has $N_A = 10^{17}$ cm^{-3}, $Q_f/q = 5 \times 10^{10}$ cm^{-2}, and $d = 10$ nm. Calculate the threshold voltage.

19. For the device stated in Prob. 18, boron ions are implanted to increase the threshold voltage to +0.7 V. Find the implant dose, assume that the implanted ions form a sheet of negative charges at the Si-SiO_2 interface.

20. A p-channel, n^+-polysilicon-SiO_2-Si MOSFET has $N_D = 10^{17}$ cm^{-3}, $Q_f/q = 5 \times 10^{10}$ cm^{-2}, and d =10 nm. Calculate the threshold voltage.

21. For the device stated in Prob. 20, boron ions are implanted to decrease the value of threshold voltage to −0.7 V. Find the implant dose, assuming that the implanted ions form a sheet of negative charges at the Si-SiO_2 interface.

22. For the device stated in Prob. 20, if the n^+ poly-Si gate is replaced by p^+ poly-Si gate, what will the threshold voltage be?

23. A field transistor with a structure similar to Fig. 21 in the text has $N_A = 10^{17}$ cm^{-3}, $Q_f/q = 10^{11}$ cm^{-2}, and an n^+ polysilicon local interconnect as the gate electrode. If the requirement for sufficient isolation between device and well is $V_T > 20$ V, calculate the minimum field oxide thickness.

24. A MOSFET has a threshold voltage of $V_T = 0.5$ V, a subthreshold swing of 100 mV/decade, and a drain current of 0.1 μA at V_T. What is the subthreshold leakage current at $V_G = 0$?

25. For the device stated in Prob. 24, calculate the reverse substrate-source voltage required to reduce the leakage current by one order of magnitude. ($N_A = 5 \times 10^{17}$ cm^{-3}, $d = 5$ nm).

give

FOR SE

28. De

FOR SE

29. For ma

30. For 4 n all

31. For vari

FOR SEC

32. Wh thic that

33. A D each age dyn

34. A fl regi the volt

FOR SEC

35. A p oxid

36. For 5 ×

.orm volume charge
.ation of the charge to
n. Find the change in

arge sheet with an area
of the oxide layer is

riangular distribution:
nm. Find the change in

iO_2 interface. After a
;e and raised tempera-
erface. This leads to a
yer is 10 nm. Find the

ate connected together
old voltage from these

$= 5 \times 10^{16}$ cm^{-3}, μ_n =
nd I_{Dsat} for V_G = 5 V.

$= 10^{17}$ cm^{-3}, μ_n = 500
l conductance for V_G =

$Q_f/q = 5 \times 10^{10}$ cm^{-2},

rease the threshold volt-
ons form a sheet of neg-

$Q_f/q = 5 \times 10^{10}$ cm^{-2},

rease the value of
the implanted ions form

by p^+ poly-Si gate,

$N_A = 10^{17}$ cm^{-3}, Q_f/q =
rode. If the require-
calculate the minimum

wing of 100
reshold leakage cur-

FOR SECTION 6.3 MOSFET SCALING

26. When the linear dimensions of MOSFET are scaled down by a factor of 10 based on the constant field scaling, what is the scaling factor for the corresponding switching energy?

*27. Based on the charge-sharing model, Fig. 24, show that the threshold voltage roll-off is given by Eq. 47.

FOR SECTION 6.4 CMOS AND BiCMOS

28. Describe the pros and cons of BiCMOS.

FOR SECTION 6.5 MOSFET ON INSULATOR

29. For an n-channel FD-SOI device having $N_A = 5 \times 10^{17}$ cm^{-3} and d = 4 nm, calculate the maximum allowable thickness for Si channel layer (d_{Si}).

30. For an n-channel SOI device with n^+-polysilicon gate having $N_A = 5 \times 10^{17}$ cm^{-3}, d = 4 nm, and d_{Si} = 30 nm, calculate the threshold voltage. Assume that Q_f, Q_{ot}, and Q_m are all zero.

31. For the device stated in Prob. 29, calculate the range of V_T distribution if the thickness variation of d_{Si} across the wafer is ±5 nm.

FOR SECTION 6.6 MOS MEMORY STRUCTURES

32. What is the capacitance of a DRAM capacitor if it is planar, 1 µm × 1 µm, with an oxide thickness of 10 nm? Calculate the capacitance if the same surface area is used for a trench that is 7 µm deep and with the same oxide thickness.

33. A DRAM must operate with a minimum refresh time of 4 ms. The storage capacitor in each cell has a capacitance of 50 fF and is fully charged to 5 V. Find the worst-case leakage current (i.e., during the refresh cycle 50% of the stored charge is lost) that the dynamic node can tolerate.

34. A floating-gate nonvolatile memory has an initial threshold voltage of –2 V, and a linear-region drain conductance of 10 µmhos at a gate voltage of –5 V. After a write operating, the drain conductance increases to 40 µmhos at the same gate voltage. Find the threshold voltage shift.

FOR SECTION 6.7 THE POWER MOSFET

35. A power MOSFET has an n^+-polysilicon gate and a p-base with $N_A = 10^{17}$ cm^{-3}. Gate oxide thickness d = 100 nm. Calculate the threshold voltage.

36. For the device stated in Prob. 35, calculate the effect of a positive fixed charge density of 5×10^{11} cm^{-3} on the threshold voltage.

3. G. Myburg, et al., "Summary of Schottky Barrier Height Data on Epitaxially Grown n- and p-GaAs," *Thin Solid Films*, **325**, 181 (1998).
4. C. R. Crowell, J. C. Sarace, and S. M. Sze, "Tungsten-Semiconductor Schottky-Barrier Diodes," *Trans. Met. Soc. AIME*, **23**, 478 (1965).
5. V. L. Rideout, "A Review of the Theory, Technology and Applications of Metal-Semiconductor Rectifiers," *Thin Solid Films*, **48**, 261 (1978).
6. S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed., Wiley, New York, 1981.
7. C. A. Mead, "Schottky Barrier Gate Field-Effect Transistor," *Proc. IEEE*, **54**, 307 (1966).
8. S. M. Sze, Ed., *High Speed Semiconductor Device*, Wiley, New York, 1992.
9. K. K. Ng, *Complete Guide to Semiconductor Devices*, McGraw Hill, New York, 1995.
10. S. Luryi, J. Xu, and A. Zaslavsky, Eds., *Future Trends in Microelectronics*, Wiley, New York, 1999.

PROBLEMS (* DENOTES DIFFICULT PROBLEMS)

FOR SECTION 7.1 METAL-SEMICONDUCTOR CONTACTS

1. Calculate the theoretical barrier height and built-in potential in a metal-semiconductor diode for zero applied bias. Assume the metal work function is 4.55 eV, the electron affinity is 4.01 eV, and $N_D = 2 \times 10^{16}$ cm^{-3} at 300 K.

2. (a) Find the donor concentration and barrier height of the W-GaAs Schottky barrier diode shown in Fig. 6. (b) Compare the barrier height with that obtained from the saturation current density of 5×10^{-7} A/cm^2 shown in Fig. 8. (c) For a reverse bias of –1 V, calculate the depletion-layer width W, the maximum field, and the capacitance.

3. Copper is deposited on a carefully prepared n-type silicon substrate to form an ideal Schottky diode. $\phi_m = 4.65$ eV, the electron affinity is 4.01 eV, $N_D = 3 \times 10^{16}$ /cm^3, and T = 300 K. Calculate the barrier height, the built-in potential, the depletion-layer width, and the maximum field at a zero bias.

*4. The capacitance of a Au-n-type GaAs Schottky barrier diode is given by the relation $1/C^2 = 1.57 \times 10^5 - 2.12 \times 10^5\ V_a$, where C is expressed in μF and V_a is in volts. Taking the diode area to be 10^{-1} cm^2, calculate the built-in potential, the barrier height, the dopant concentration, and the work function.

5. Calculate the value of V_{bi} and ϕ_m in an ideal metal-Si Schottky barrier contact. Assume the barrier height is 0.8 eV, $N_D = 1.5 \times 10^{16}$ cm^{-3}, and $q\chi = 4.01$ eV.

6. In a metal-Si Schottky barrier contact, the barrier height is 0.75 eV and $A^* = 110$ A/cm^2–K^2. Calculate the ratio of the injected hole current to the electron current at 300 K, assuming $D_p = 12$ cm^2 s^{-1}, $L_p = 1 \times 10^{-3}$ cm, and $N_D = 1.5 \times 10^{16}$ cm^{-3}.

FOR SECTION 7.2 MESFET

7. Given $\phi_{Bn} = 0.9$ eV and $N_D = 10^{17}$ cm^{-3}, find the minimum value of the thickness of the epitaxial layer for a GaAs MESFET to be a depletion mode device (i.e., $V_T < 0$).

8. Assume the doping in a GaAs MESFET is $N_D = 7 \times 10^{16}$ cm^{-3} and the dimensions are a = 0.3 µm, L = 1.5 µm, Z = 5 µm, μ_n = 4500 cm^2/V-s, and ϕ_{Bn} = 0.89 V. Calculate the ideal value of g_m for V_G = 0, and V_D = 1 V.

9. The n-channel GaAs MESFET shown in Fig. 10 has a barrier height ϕ_{Bn} = 0.9 V, N_D = 10^{17} cm^{-3}, a = 0.2 µm, L = 1 µm, and Z = 10 µm. (a) Is this an enhancement or depletion-

11. The
0.85
N_D =
the t

FOR SEC

12. For
cm^{-3}
tinui
thres

*13. Find
tron
bias.
the S
is 12

14. Cons
space
chan
rier l

15. The
space
and t
Find

16. Cons
dope
0.89
and (

43 (1938).
iiconductor System," *J.*
Grown n- and p-GaAs,"
/-Barrier Diodes," *Trans.*
l-Semiconductor
307 (1966).
<, 1995.
ey, New York, 1999.
etal-semiconductor
eV, the electron affin-
Schottky barrier diode
from the saturation
bias of −1 V, calculate
:e.
to form an ideal
× 10^{16} /cm^3, and T =
tion-layer width, and
ı by the relation $1/C^2$
ı volts. Taking the
r height, the dopant
er contact. Assume the
and A^* = 110 A/cm^2 –
urrent at 300 K,
he thickness of the
i.e., $V_T < 0$).
ıe dimensions are a =

mode device? (b) Find the threshold voltage (the enhancement mode indicates $V_T > 0$; the depletion mode indicates $V_T < 0$).

10. An n-channel GaAs MESFET has a channel doping $N_D = 2 \times 10^{15}$ cm^{-3}, $\phi_{Bn} = 0.8$ V, $a = 0.5$ μm, $L = 1$ μm, $\mu_n = 4500$ cm^2/V-s, and $Z = 50$ μm. Find the pinch-off potential, threshold voltage, and the saturation current at $V_G = 0$.

11. The barrier height ϕ_{Bn} of two GaAs n-channel MESFETs are the same and equal to 0.85 V. The channel doping in device 1 is $N_D = 4.7 \times 10^{16}$ cm^{-3}, and that in device 2 is $N_D = 4.7 \times 10^{17}$ cm^{-3}. Determine the channel thickness required in each device such that the threshold voltage is zero for each device.

FOR SECTION 7.3 MODFET

12. For an abrupt AlGaAs/GaAs heterojunction with the n-AlGaAs layer doped to 3×10^{18} cm^{-3}, the Schottky barrier is 0.89 V and the heterojunction conduction-band edge discontinuity ΔE_C is 0.23 eV. Calculate the thickness of the doped AlGaAs layer d_1 so that the threshold voltage is −0.5 V. Assume the permittivity of the AlGaAs is 12.3.

*13. Find the thickness of the undoped spacer layer d_0, such that the two-dimensional electron gas concentration of an AlGaAs/GaAs heterojunction is 1.25×10^{12} cm^{-2} at zero gate bias. Assume that the n-AlGaAs is doped to 1×10^{18}cm^{-3} and has a thickness d_1 of 50 nm, the Schottky barrier height is 0.89 V, and $\Delta E_C/q = 0.23$ V. The permittivity of the AlGaAs is 12.3.

14. Consider a AlGaAs/GaAs HFET with a 50 nm n-AlGaAs and a 10 nm undoped AlGaAs spacer. Assume the threshold voltage is −1.3 V, N_D is 5×10^{17}cm^{-3}, $\Delta E_C = 0.25$ eV, the channel width is 8 nm, and the permittivity of AlGaAs is 12.3. Calculate the Schottky barrier height and the two-dimensional electron gas concentration at $V_G = 0$.

15. The AlGaAs/GaAs has a two-dimensional electron gas concentration of 1×10^{12}cm^{-2}, the spacer is 5 nm, the channel width is 8 nm, the pinch-off voltage is 1.5 V, $\Delta E_C/q = 0.23$ V, and the doping concentration of AlGaAs is 10^{18} cm^{-3}. The Schottky barrier height is 0.8 V. Find the thickness of the doped AlGaAs and the threshold voltage.

16. Consider an n-AlGaAs–intrinsic GaAs abrupt heterojunction. Assume that the AlGaAs is doped to $N_D = 3 \times 10^{18}$cm^{-3} and has a thickness of 35 nm (there is no spacer). Let ϕ_{Bn} = 0.89 V, and assume that $\Delta E_C = 0.24$ eV and the dielectric constant is 12.3. Calculate (a) V_P and (b) n_s for $V_G = 0$.

15. [illegible] Prepared by Molecular Beam Epitaxy," *Appl. Phys. Lett.*, 54, 2333 (1989).

16. K. Hess, et al., "Negative Differential Resistance Through Real-Space-Electron Transfer," *Appl. Phys. Lett.*, 35, 469 (1979).

17. S. Luryi, "Hot Electron Transistors," in S. M. Sze, Ed., *High Speed Semiconductor Devices*, Wiley, New York, 1990.

18. S. Luryi and A. Zaslavsky, "Quantum-Effect and Hot-Electron Devices," in S. M. Sze, Ed., *Modern Semiconductor Device Physics*, Wiley, New York, 1998.

19. P. M. Mensz, et al, "High Transconductance and Large Peak-to-Valley Ratio of Negative Differentional Conductance in Three Terminal InGaAs/InAlAs Real-Space-Transfer Devices," *Appl. Phys. Lett.*, 57, 2558 (1990).

20. M. Mastrapasqua, et al., "Charge Injection Transistor and Logic Elements in Si/SiGe Heterostructures," in S. Luryi, J. Xu, and A. Zaslavsky, Eds., *Future Trends in Microelectrons*, Kluwer, Dordrecht, 1996.

PROBLEMS (* DENOTES DIFFICULT PROBLEMS)

FOR SECTION 8.1 BASIC MICROWAVE TECHNOLOGY

1. For a nearly lossless transmission line (R is very small) with a 75 Ω characteristic impedance, if this transmission line has a unit length capacitance of 2 pF, what is the unit length inductance of this transmission line?

2. For a cavity of the dimensions a = 10 cm (0.1 m), b = 5 cm (0.05 m), and d = 25 cm (0.25 m), find the resonant frequency in the dominant TE_{101} mode.

FOR SECTION 8.2 TUNNEL DIODE

3. Find the depletion-layer capacitance and depletion-layer width at 0.25 V forward bias for a GaAs tunnel diode doped to 10^{19} cm^{-3} on both sides, using the abrupt junction approximation and assuming $V_n = V_p = 0.03$ V.

4. The current-voltage characteristic of a GaSb tunnel diode can be expressed by the empirical form of Eq. 5. with I_p = 10 mA, V_p = 0.1 V, and I_0 = 0.1 nA. Find the largest negative differential resistance and the corresponding voltage.

FOR SECTION 8.3 IMPATT DIODE

5. The variation of electric field in the depletion region due to avalanche-generated space charge gives rise to an incremental resistance for abrupt p^+-n diode. The incremental resistance is called the space-charge resistance, R_{SC}, and is given by $(1/I)\int_0^W \Delta\mathscr{E}dx$, where $\Delta\mathscr{E}$ is given by

$$\Delta\mathscr{E}(W) = \frac{\int_0^W \rho_S dx}{\varepsilon_S} = \frac{IW}{A\varepsilon_S v_S}.$$

(a) Find R_{SC} for a p^+-n Si IMPATT diode with $N_D=10^{15}$ cm^{-3}, W = 12 μm, and A = 5×10^{-4} cm^2. (b) Find the total applied dc voltage for a current density of 10^3 A/cm^2.

6. A GaAs IMPATT diode is operated at 10 GHz with a dc bias of 100 V and an average biasing current ($I_0/2$) of 100 mA. (a) If the power-generating efficiency is 25% and the thermal resistance of the diode is 10° C/W, find the junction temperature rise above the

-Opt. Inst. Eng.

sistor," Jpn. J. Appl.

cture Bipolar Transistor

Transfer," Appl. Phys.

tor Devices, Wiley,

I. Sze, Ed., Modern

Negative Differential
Appl. Phys. Lett., 57,

/SiGe Heterostruc-
ns, Kluwer, Dordrecht,

haracteristic
pF, what is the unit

and d = 25 cm

5 V forward bias for
pt junction approxi-

ressed by the empiri-
the largest negative

e-generated space
The incremental
$1/I)\int_0^W \Delta \mathscr{E} dx$, where

μm, and A =

room temperature. (b) If the breakdown voltage increases with temperature at a rate of 60 mV/°C, find the breakdown voltage of the diode at room temperature.

7. Consider a GaAs single drift lo-hi-lo IMPATT diode shown in Fig. 6c with an avalanche region width (where the electric field is constant) of 0.4 μm and a total depletion width of 3 μm. The n^+ clump has a charge Q of $1.5 \times 10^{12}/\text{cm}^2$. (a) Find the breakdown voltage of the diode and the maximum field at breakdown. (b) Is the field in the drift region high enough to maintain the velocity saturation of electrons? (c) Find the operating frequency.

*8. A silicon p^+-p-π-p^+ IMPATT diode has a p-layer 3 μm thick and a π-layer (low-doping p-layer) 9 μm thick. The biasing voltage must be high enough to cause avalanche breakdown in the p-region and velocity saturation in the π region. (a) Find the minimum required biasing voltage and the doping concentration of the p-region. (b) Estimate the transit time of the device.

FOR SECTION 8.4 TRANSFERRED-ELECTRON DEVICES

9. An InP TED is 1 μm long with a cross-section area of 10^{-4} cm^2 and is operated in the transit-time mode. (a) Find the minimum electron density n_0 required for transit-time mode. (b) Find the time between current pulses. (c) Calculate the power dissipated in the device if it is biased at one-half the threshold.

*10. (a) Find the effective density of states in the upper valley N_{CU} of the GaAs conduction band. The upper-valley effective mass is 1.2 m_0. (b) The ratio of electron concentrations between the upper and lower valleys is given by $(N_{CU}/N_{CL})\exp(-\Delta E/kT_e)$, where N_{CL} is the effective density of states in the lower valley, ΔE = 0.31 eV is the energy difference, and T_e is the effective electron temperature. Find the ratio at T_e = 300 K. (c) When electrons gain kinetic energies from the electric field, T_e increases. Find the concentration ratio for T_e = 1500 K.

FOR SECTION 8.5 QUANTUM-EFFECT DEVICES

11. Modecular beam epitaxy interfaces are typically abrupt to within one or two monolayers (one monolayer = 0.28 nm in GaInAs) because of terrace formation in the growth plane. Estimate the energy level broadening for the ground and first excited-electron states of a 15 nm GaInAs quantum well bound by thick AlInAs barriers. (Hint: assume the case of two-monolayer thickness fluctuation and an infinity deep quantum well. The electron effective mass in GaInAs is 0.0427 m_0.)

12. Find the first excited level and the corresponding width of the peak ΔE_2 for a RTD with AlAs (2 nm)/GaAs (6.78 nm)/AlAs (2 nm). If we want to maintain the same energy level but increase the width ΔE_2 by a factor of 10, what should be the thicknesses of AlAs and GaAs?