

2.1

Semiconductor Physics

In the problems assume the parameter given in following table. Use the temperature $T = 300$ K unless otherwise stated.

Property	Si	GaAs	Ge
Bandgap Energy	1.12	1.42	0.66
Dielectric Constant	11.7	13.1	16.0
Effective density of states in conduction band N_c (cm^{-3})	2.8×10^{19}	4.7×10^{17}	1.04×10^{19}
Effective density of states in valence band N_v (cm^{-3})	1.04×10^{19}	7.0×10^{18}	6.0×10^{18}
Intrinsic carrier concentration n_i (cm^{-3})	1.5×10^{10}	1.8×10^6	2.4×10^8
Mobility			
Electron	1350	8500	3900
Hole	480	400	1900

1. In germanium semiconductor material at $T = 400$ K the intrinsic concentration is

- (A) $26.8 \times 10^{14} \text{ cm}^{-3}$ (B) $18.4 \times 10^{14} \text{ cm}^{-3}$
 (C) $8.5 \times 10^{14} \text{ cm}^{-3}$ (D) $3.6 \times 10^{14} \text{ cm}^{-3}$

2. The intrinsic carrier concentration in silicon is to be no greater than $n_i = 1 \times 10^{12} \text{ cm}^{-3}$. The maximum temperature allowed for the silicon is (Assume $E_g = 1.12 \text{ eV}$)

- (A) 300 K (B) 360 K
 (C) 382 K (D) 364 K

3. Two semiconductor material have exactly the same properties except that material A has a bandgap of 1.0

eV and material B has a bandgap energy of 1.2 eV. The ratio of intrinsic concentration of material A to that of material B is

- (A) 2016 (B) 47.5
 (C) 58.23 (D) 1048

4. In silicon at $T = 300$ K the thermal-equilibrium concentration of electron is $n_0 = 5 \times 10^4 \text{ cm}^{-3}$. The hole concentration is

- (A) $4.5 \times 10^5 \text{ cm}^{-3}$ (B) $4.5 \times 10^{15} \text{ m}^{-3}$
 (C) $2.3 \times 10^{-6} \text{ cm}^{-3}$ (D) $0.3 \times 10^{-6} \text{ m}^{-3}$

5. In silicon at $T = 300$ K if the Fermi energy is 0.22 eV above the valence band energy, the value of p_0 is

- (A) $2 \times 10^{15} \text{ cm}^{-3}$ (B) 10^{15} cm^{-3}
 (C) $3 \times 10^{15} \text{ cm}^{-3}$ (D) $4 \times 10^{15} \text{ cm}^{-3}$

6. The thermal-equilibrium concentration of hole p_0 in silicon at $T = 300$ K is 10^{15} cm^{-3} . The value of n_0 is

- (A) $3.8 \times 10^8 \text{ cm}^{-3}$ (B) $4.4 \times 10^4 \text{ cm}^{-3}$
 (C) $2.6 \times 10^4 \text{ cm}^{-3}$ (D) $4.3 \times 10^8 \text{ cm}^{-3}$

7. In germanium semiconductor at $T = 300$ K, the acceptor concentrations is $N_a = 10^{13} \text{ cm}^{-3}$ and donor concentration is $N_d = 0$. The thermal equilibrium concentration p_0 is

- (A) $2.97 \times 10^9 \text{ cm}^{-3}$ (B) $2.68 \times 10^{12} \text{ cm}^{-3}$
 (C) $2.95 \times 10^{13} \text{ cm}^{-3}$ (D) 2.4 cm^{-3}

Statement for Q.8-9:

In germanium semiconductor at $T = 300$ K, the impurity concentration are

$$N_d = 5 \times 10^{15} \text{ cm}^{-3} \text{ and } N_a = 0$$

8. The thermal equilibrium electron concentration n_0 is

- (A) $5 \times 10^{15} \text{ cm}^{-3}$ (B) $1.15 \times 10^{11} \text{ cm}^{-3}$
 (C) $1.15 \times 10^9 \text{ cm}^{-3}$ (D) $5 \times 10^6 \text{ cm}^{-3}$

9. The thermal equilibrium hole concentration p_0 is

- (A) 3.96×10^{13} (B) $1.95 \times 10^{13} \text{ cm}^{-3}$
 (C) $4.36 \times 10^{12} \text{ cm}^{-3}$ (D) $3.96 \times 10^{13} \text{ cm}^{-3}$

10. A sample of silicon at $T = 300 \text{ K}$ is doped with boron at a concentration of $2.5 \times 10^{13} \text{ cm}^{-3}$ and with arsenic at a concentration of $1 \times 10^{13} \text{ cm}^{-3}$. The material is

- (A) p -type with $p_0 = 1.5 \times 10^{13} \text{ cm}^{-3}$
 (B) p -type with $p_0 = 1.5 \times 10^7 \text{ cm}^{-3}$
 (C) n -type with $n_0 = 1.5 \times 10^{13} \text{ cm}^{-3}$
 (D) n -type with $n_0 = 1.5 \times 10^7 \text{ cm}^{-3}$

11. In a sample of gallium arsenide at $T = 200 \text{ K}$, $n_0 = 5p_0$ and $N_a = 0$. The value of n_0 is

- (A) $9.86 \times 10^9 \text{ cm}^{-3}$ (B) 7 cm^{-3}
 (C) $4.86 \times 10^3 \text{ cm}^{-3}$ (D) 3 cm^{-3}

12. Germanium at $T = 300 \text{ K}$ is uniformly doped with an acceptor concentration of $N_a = 10^{15} \text{ cm}^{-3}$ and a donor concentration of $N_d = 0$. The position of fermi energy with respect to intrinsic Fermi level is

- (A) 0.02 eV (B) 0.04 eV
 (C) 0.06 eV (D) 0.08 eV

13. In germanium at $T = 300 \text{ K}$, the donor concentration are $N_d = 10^{14} \text{ cm}^{-3}$ and $N_a = 0$. The Fermi energy level with respect to intrinsic Fermi level is

- (A) 0.04 eV (B) 0.08 eV
 (C) 0.42 eV (D) 0.86 eV

14. A GaAs device is doped with a donor concentration of $3 \times 10^{15} \text{ cm}^{-3}$. For the device to operate properly, the intrinsic carrier concentration must remain less than 5% of the total concentration. The maximum temperature on that the device may operate is

- (A) 763 K (B) 942 K
 (C) 486 K (D) 243 K

15. For a particular semiconductor at $T = 300 \text{ K}$ $E_g = 1.5 \text{ eV}$, $m_p^* = 10m_n^*$ and $n_i = 1 \times 10^{15} \text{ cm}^{-3}$. The

position of Fermi level with respect to the center of the bandgap is

- (A) +0.045 eV (B) -0.046 eV
 (C) +0.039 eV (D) -0.039 eV

16. A silicon sample contains acceptor atoms at a concentration of $N_a = 5 \times 10^{15} \text{ cm}^{-3}$. Donor atoms are added forming an n -type compensated semiconductor such that the Fermi level is 0.215 eV below the conduction band edge. The concentration of donors atoms added are

- (A) $1.2 \times 10^{16} \text{ cm}^{-3}$ (B) $4.6 \times 10^{16} \text{ cm}^{-3}$
 (C) $3.9 \times 10^{12} \text{ cm}^{-3}$ (D) $2.4 \times 10^{12} \text{ cm}^{-3}$

17. A silicon semiconductor sample at $T = 300 \text{ K}$ is doped with phosphorus atoms at a concentrations of 10^{15} cm^{-3} . The position of the Fermi level with respect to the intrinsic Fermi level is

- (A) 0.3 eV (B) 0.2 eV
 (C) 0.1 eV (D) 0.4 eV

18. A silicon crystal having a cross-sectional area of 0.001 cm^2 and a length of $20 \mu\text{m}$ is connected to its ends to a 20 V battery. At $T = 300 \text{ K}$, we want a current of 100 mA in crystal. The concentration of donor atoms to be added is

- (A) $2.4 \times 10^{13} \text{ cm}^{-3}$ (B) $4.6 \times 10^{13} \text{ cm}^{-3}$
 (C) $7.8 \times 10^{14} \text{ cm}^{-3}$ (D) $8.4 \times 10^{14} \text{ cm}^{-3}$

19. The cross sectional area of silicon bar is $100 \mu\text{m}^2$. The length of bar is 1 mm. The bar is doped with arsenic atoms. The resistance of bar is

- (A) 2.58 m Ω (B) 11.36 k Ω
 (C) 1.36 m Ω (D) 24.8 k Ω

20. A thin film resistor is to be made from a GaAs film doped n -type. The resistor is to have a value of 2 k Ω . The resistor length is to be $200 \mu\text{m}$ and area is to be 10^{-6} cm^2 . The doping efficiency is known to be 90%. The mobility of electrons is 8000 $\text{cm}^2/\text{V}\cdot\text{s}$. The doping needed is

- (A) $8.7 \times 10^{15} \text{ cm}^{-3}$ (B) $8.7 \times 10^{21} \text{ cm}^{-3}$
 (C) $4.6 \times 10^{15} \text{ cm}^{-3}$ (D) $4.6 \times 10^{21} \text{ cm}^{-3}$

21. A silicon sample doped n -type at 10^{18} cm^{-3} have a resistance of 10 Ω . The sample has an area of 10^{-6}

cm^2 and a length of $10 \mu\text{m}$. The doping efficiency of the sample is ($\mu_n = 800 \text{ cm}^2/\text{V-s}$)

- (A) 43.2% (B) 78.1%
(C) 96.3% (D) 54.3%

22. Six volts is applied across a 2 cm long semiconductor bar. The average drift velocity is 10^4 cm/s . The electron mobility is

- (A) $4396 \text{ cm}^2/\text{V-s}$ (B) $3 \times 10^4 \text{ cm}^2/\text{V-s}$
(C) $6 \times 10^4 \text{ cm}^2/\text{V-s}$ (D) $3333 \text{ cm}^2/\text{V-s}$

23. For a particular semiconductor material following parameters are observed:

$$\mu_n = 1000 \text{ cm}^2/\text{V-s},$$

$$\mu_p = 600 \text{ cm}^2/\text{V-s},$$

$$N_c = N_v = 10^{19} \text{ cm}^{-3}$$

These parameters are independent of temperature. The measured conductivity of the intrinsic material is $\sigma = 10^{-6} (\Omega\text{-cm})^{-1}$ at $T = 300 \text{ K}$. The conductivity at $T = 500 \text{ K}$ is

- (A) $2 \times 10^{-4} (\Omega\text{-cm})^{-1}$ (B) $4 \times 10^{-5} (\Omega\text{-cm})^{-1}$
(C) $2 \times 10^{-5} (\Omega\text{-cm})^{-1}$ (D) $6 \times 10^{-3} (\Omega\text{-cm})^{-1}$

24. An n -type silicon sample has a resistivity of $5 \Omega\text{-cm}$ at $T = 300 \text{ K}$. The mobility is $\mu_n = 1350 \text{ cm}^2/\text{V-s}$. The donor impurity concentration is

- (A) $2.86 \times 10^{-14} \text{ cm}^{-3}$ (B) $9.15 \times 10^{-14} \text{ cm}^{-3}$
(C) $11.46 \times 10^{-15} \text{ cm}^{-3}$ (D) $1 \times 10^{-15} \text{ cm}^{-3}$

25. In a silicon sample the electron concentration drops linearly from 10^{18} cm^{-3} to 10^{16} cm^{-3} over a length of $2.0 \mu\text{m}$. The current density due to the electron diffusion current is ($D_n = 35 \text{ cm}^2/\text{s}$).

- (A) $9.3 \times 10^4 \text{ A/cm}^2$ (B) $2.8 \times 10^4 \text{ A/cm}^2$
(C) $9.3 \times 10^9 \text{ A/cm}^2$ (D) $2.8 \times 10^9 \text{ A/cm}^2$

26. In a GaAs sample the electrons are moving under an electric field of 5 kV/cm and the carrier concentration is uniform at 10^{16} cm^{-3} . The electron velocity is the saturated velocity of 10^7 cm/s . The drift current density is

- (A) $1.6 \times 10^4 \text{ A/cm}^2$ (B) $2.4 \times 10^4 \text{ A/cm}^2$
(C) $1.6 \times 10^8 \text{ A/cm}^2$ (D) $2.4 \times 10^8 \text{ A/cm}^2$

27. For a sample of GaAs scattering time is $\tau_{sc} = 10^{-13} \text{ s}$ and electron's effective mass is $m_e^* = 0.067m_0$. If an electric field of 1 kV/cm is applied, the drift velocity produced is

- (A) $2.6 \times 10^6 \text{ cm/s}$ (B) 263 cm/s
(C) $14.8 \times 10^6 \text{ cm/s}$ (D) 482

28. A gallium arsenide semiconductor at $T = 300 \text{ K}$ is doped with impurity concentration $N_d = 10^{17} \text{ cm}^{-3}$. The mobility μ_n is $7500 \text{ cm}^2/\text{V-s}$. For an applied field of 10 V/cm the drift current density is

- (A) 120 A/cm^2 (B) 1200 A/cm^2
(C) $12 \times 10^4 \text{ A/cm}^2$ (D) $12 \times 10^4 \text{ A/cm}^2$

29. In a particular semiconductor the donor impurity concentration is $N_d = 10^{14} \text{ cm}^{-3}$. Assume the following parameters,

$$\mu_n = 1000 \text{ cm}^2/\text{V-s},$$

$$N_c = 2 \times 10^{19} \left(\frac{T}{300} \right)^{3/2} \text{ cm}^{-3},$$

$$N_v = 1 \times 10^{19} \left(\frac{T}{300} \right)^{3/2} \text{ cm}^{-3},$$

$$E_g = 1.1 \text{ eV}.$$

An electric field of $E = 10 \text{ V/cm}$ is applied. The electric current density at 300 K is

- (A) 2.3 A/cm^2 (B) 1.6 A/cm^2
(C) 9.6 A/cm^2 (D) 3.4 A/cm^2

Statement for Q.30-31:

A semiconductor has following parameter

$$\mu_n = 7500 \text{ cm}^2/\text{V-s},$$

$$\mu_p = 300 \text{ cm}^2/\text{V-s},$$

$$n_i = 3.6 \times 10^{12} \text{ cm}^{-3}$$

30. When conductivity is minimum, the hole concentration is

- (A) $7.2 \times 10^{11} \text{ cm}^{-3}$ (B) $1.8 \times 10^{13} \text{ cm}^{-3}$
(C) $1.44 \times 10^{11} \text{ cm}^{-3}$ (D) $9 \times 10^{13} \text{ cm}^{-3}$

31. The minimum conductivity is

- (A) $0.6 \times 10^{-3} (\Omega\text{-cm})^{-1}$ (B) $1.7 \times 10^{-3} (\Omega\text{-cm})^{-1}$
(C) $2.4 \times 10^{-3} (\Omega\text{-cm})^{-1}$ (D) $6.8 \times 10^{-3} (\Omega\text{-cm})^{-1}$

- 32.** A particular intrinsic semiconductor has a resistivity of $50 (\Omega - \text{cm})$ at $T = 300 \text{ K}$ and $5 (\Omega - \text{cm})$ at $T = 330 \text{ K}$. If change in mobility with temperature is neglected, the bandgap energy of the semiconductor is
 (A) 1.9 eV (B) 1.3 eV
 (C) 2.6 eV (D) 0.64 eV

- 33.** Three scattering mechanism exist in a semiconductor. If only the first mechanism were present, the mobility would be $500 \text{ cm}^2/\text{V} - \text{s}$. If only the second mechanism were present, the mobility would be $750 \text{ cm}^2/\text{V} - \text{s}$. If only third mechanism were present, the mobility would be $1500 \text{ cm}^2/\text{V} - \text{s}$. The net mobility is
 (A) $2750 \text{ cm}^2/\text{V} - \text{s}$ (B) $1114 \text{ cm}^2/\text{V} - \text{s}$
 (C) $818 \text{ cm}^2/\text{V} - \text{s}$ (D) $250 \text{ cm}^2/\text{V} - \text{s}$

- 34.** In a sample of silicon at $T = 300 \text{ K}$, the electron concentration varies linearly with distance, as shown in fig. P2.1.34. The diffusion current density is found to be $J_n = 0.19 \text{ A/cm}^2$. If the electron diffusion coefficient is $D_n = 25 \text{ cm}^2/\text{s}$, The electron concentration at is

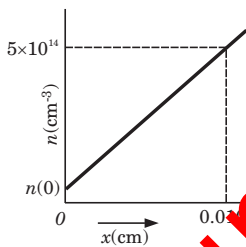


Fig. P2.1.34

- (A) $4.86 \times 10^8 \text{ cm}^{-3}$ (B) $2.5 \times 10^{13} \text{ cm}^{-3}$
 (C) $9.8 \times 10^{26} \text{ cm}^{-3}$ (D) $5.4 \times 10^{15} \text{ cm}^{-3}$
- 35.** The hole concentration in p -type GaAs is given by

$$p = 10^{16} \left(1 - \frac{x}{L} \right) \text{ cm}^{-3} \text{ for } 0 \leq x \leq L$$

- where $L = 10 \mu\text{m}$. The hole diffusion coefficient is $10 \text{ cm}^2/\text{s}$. The hole diffusion current density at $x = 5 \mu\text{m}$ is
 (A) 20 A/cm^2 (B) 16 A/cm^2
 (C) 24 A/cm^2 (D) 30 A/cm^2

- 36.** For a particular semiconductor sample consider following parameters:

- Hole concentration $p_0 = 10^{15} e^{\left(\frac{-x}{L_p}\right)} \text{ cm}^{-3}, x \geq 0$
 Electron concentration $n_0 = 5 \times 10^{14} e^{\left(\frac{-x}{L_n}\right)} \text{ cm}^{-3}, x \leq 0$
 Hole diffusion coefficient $D_p = 10 \text{ cm}^2/\text{s}$
 Electron diffusion coefficients $D_n = 25 \text{ cm}^2/\text{s}$
 Hole diffusion length $L_p = 5 \times 10^{-4} \text{ cm}$,
 Electron diffusion length $L_n = 10^{-3} \text{ cm}$
 The total current density at $x = 0$ is
 (A) 1.2 A/cm^2 (B) 5.2 A/cm^2
 (C) 3.8 A/cm^2 (D) 2 A/cm^2

- 37.** A germanium Hall device is doped with 5×10^{15} donor atoms per cm^3 at $T = 300 \text{ K}$. The device has the geometry $d = 5 \times 10^{-3} \text{ cm}$, $W = 2 \times 10^{-2} \text{ cm}$ and $L = 0.1 \text{ cm}$. The current is $I_x = 250 \mu\text{A}$, the applied voltage is $V_x = 100 \text{ mV}$ and the magnetic flux is $B_z = 5 \times 10^{-2}$ tesla. The Hall voltage is
 (A) -0.81 mV (B) 0.31 mV
 (C) 3.26 mV (D) -3.26 mV

Statement for Q.38-39:

A silicon Hall device at $T = 300 \text{ K}$ has the geometry $d = 10^{-3} \text{ cm}$, $W = 10^{-2} \text{ cm}$, $L = 10^{-1} \text{ cm}$. The following parameters are measured: $I_x = 0.75 \text{ mA}$, $V_x = 15 \text{ V}$, $V_H = +5.8 \text{ mV}$, tesla

- 38.** The majority carrier concentration is
 (A) $8 \times 10^{15} \text{ cm}^{-3}$, n -type
 (B) $8 \times 10^{15} \text{ cm}^{-3}$, p -type
 (C) $4 \times 10^{15} \text{ cm}^{-3}$, n -type
 (D) $4 \times 10^{15} \text{ cm}^{-3}$, p -type

- 39.** The majority carrier mobility is
 (A) $430 \text{ cm}^2/\text{V} - \text{s}$ (B) $215 \text{ cm}^2/\text{V} - \text{s}$
 (C) $390 \text{ cm}^2/\text{V} - \text{s}$ (D) $195 \text{ cm}^2/\text{V} - \text{s}$

- 40.** In a semiconductor $n_0 = 10^{15} \text{ cm}^{-3}$ and $n_i = 10^{10} \text{ cm}^{-3}$. The excess-carrier life time is 10^{-6} s . The excess hole concentration is $\delta p = 4 \times 10^{13} \text{ cm}^{-3}$. The electron-hole recombination rate is
 (A) $4 \times 10^{19} \text{ cm}^{-3}\text{s}^{-1}$ (B) $4 \times 10^{14} \text{ cm}^{-3}\text{s}^{-1}$
 (C) $4 \times 10^{24} \text{ cm}^{-3}\text{s}^{-1}$ (D) $4 \times 10^{11} \text{ cm}^{-3}\text{s}^{-1}$

41. A semiconductor in thermal equilibrium, has a hole concentration of $p_0 = 10^{16} \text{ cm}^{-3}$ and an intrinsic concentration of $n_i = 10^{10} \text{ cm}^{-3}$. The minority carrier life time is $4 \times 10^{-7} \text{ s}$. The thermal equilibrium recombination rate of electrons is

- (A) $2.5 \times 10^{22} \text{ cm}^{-3} \text{ s}^{-1}$ (B) $5 \times 10^{10} \text{ cm}^{-3} \text{ s}^{-1}$
 (C) $2.5 \times 10^{10} \text{ cm}^{-3} \text{ s}^{-1}$ (D) $5 \times 10^{22} \text{ cm}^{-3} \text{ s}^{-1}$

Statement for Q.42-43:

A n-type silicon sample contains a donor concentration of $N_d = 10^{16} \text{ cm}^{-3}$. The minority carrier hole lifetime is $\tau_{p0} = 10 \mu\text{s}$.

42. The thermal equilibrium generation rate of hole is

- (A) $5 \times 10^8 \text{ cm}^{-3} \text{ s}^{-1}$ (B) $10^4 \text{ cm}^{-3} \text{ s}^{-1}$
 (C) $2.25 \times 10^9 \text{ cm}^{-3} \text{ s}^{-1}$ (D) $10^3 \text{ cm}^{-3} \text{ s}^{-1}$

43. The thermal equilibrium generation rate for electron is

- (A) $1.125 \times 10^9 \text{ cm}^{-3} \text{ s}^{-1}$ (B) $2.25 \times 10^9 \text{ cm}^{-3} \text{ s}^{-1}$
 (C) $8.9 \times 10^{-10} \text{ cm}^{-3} \text{ s}^{-1}$ (D) $4 \times 10^9 \text{ cm}^{-3} \text{ s}^{-1}$

44. A n-type silicon sample contains a donor concentration of $N_d = 10^{16} \text{ cm}^{-3}$. The minority carrier hole lifetime is $\tau_{p0} = 20 \mu\text{s}$. The lifetime of the majority carrier is ($n_i = 1.5 \times 10^{10} \text{ cm}^{-3}$)

- (A) $8.9 \times 10^6 \text{ s}$ (B) $8.9 \times 10^{-6} \text{ s}$
 (C) $4.5 \times 10^{-17} \text{ s}$ (D) $1.13 \times 10^{-17} \text{ s}$

45. In a silicon semiconductor material the doping concentration are $N_a = 10^{16} \text{ cm}^{-3}$ and $N_d = 0$. The equilibrium recombination rate is $R_{p0} = 10^{11} \text{ cm}^{-3} \text{ s}^{-1}$. A uniform generation rate produces an excess- carrier concentration of $\delta n = \delta p = 10^{14} \text{ cm}^{-3}$. The factor, by which the total recombination rate increase is

- (A) 2.3×10^{13} (B) 4.4×10^{13}
 (C) 2.3×10^9 (D) 4.4×10^9

Solutions

1. (D) $n_i^2 = N_c N_v e^{-\left(\frac{E_g}{kT}\right)}$

$V_t = 0.0259 \left(\frac{400}{300}\right) = 0.0345$

For Ge at 300 K,

$N_c = 1.04 \times 10^{19}$, $N_v = 6.0 \times 10^{18}$, $E_g = 0.66 \text{ eV}$

$n_i^2 = 1.04 \times 10^{19} \times 6.0 \times 10^{18} \times \left(\frac{400}{300}\right)^3 \times e^{-\left(\frac{0.66}{0.0345}\right)}$

$\Rightarrow n_i = 8.5 \times 10^{14} \text{ cm}^{-3}$

2. (C) $n_i^2 = N_c N_v e^{-\left(\frac{E_g}{kT}\right)}$

$(10^{12})^2 = 2.8 \times 10^{19} \times 1.04 \times 10^{19} \left(\frac{T}{300}\right)^3 e^{-\left(\frac{1.12e}{kT}\right)}$

$T^3 e^{-\frac{13 \times 10^3}{T}} = 9.28 \times 10^{-8}$, By trial $T = 382 \text{ K}$

3. (B) $\frac{n_{iA}^2}{n_{iB}^2} = \frac{e^{-\frac{E_{gA}}{kT}}}{e^{-\frac{E_{gB}}{kT}}} = e^{-\left(\frac{E_{gA} - E_{gB}}{kT}\right)} = 2257.5 \Rightarrow \frac{n_{iA}}{n_{iB}} = 47.5$

4. (A) $p_0 = \frac{n_i^2}{n_0} = \frac{(1.5 \times 10^{10})^2}{5 \times 10^4} = 4.5 \times 10^{15} \text{ cm}^{-3}$

5. (A) $p_0 = N_v e^{-\frac{(E_F - E_v)}{kT}} = 1.04 \times 10^{19} e^{-\frac{0.22}{0.0259}} = 2 \times 10^{15} \text{ cm}^{-3}$

6. (B) $p_0 = N_v e^{-\frac{(E_F - E_v)}{kT}} \Rightarrow E_F - E_v = kT \ln \left(\frac{N_v}{p_0}\right)$

At 300 K, $N_v = 1.0 \times 10^{19} \text{ cm}^{-3}$

$E_F - E_v = 0.0259 \ln \left(\frac{1.04 \times 10^{19}}{10^{15}}\right) = 0.239 \text{ eV}$

$n_0 = N_c e^{-\frac{(E_c - E_F)}{kT}}$

At 300 K, $N_c = 2.8 \times 10^{19} \text{ cm}^{-3}$

$E_c - E_F = 1.12 - 0.239 = 0.881 \text{ eV}$

$n_0 = 4.4 \times 10^4 \text{ cm}^{-3}$

7. (C) $p_0 = \frac{N_a - N_d}{2} + \sqrt{\left(\frac{N_a - N_d}{2}\right)^2 + n_i^2}$

For Ge $n_i = 2.4 \times 10^3$

$p_0 = \frac{10^{13}}{2} + \sqrt{\left(\frac{10^{13}}{2}\right)^2 + (2.4 \times 10^3)^2} = 2.95 \times 10^{13} \text{ cm}^{-3}$

$$8. (A) n_0 = \frac{N_d - N_a}{2} + \sqrt{\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2}$$

$$= \frac{5 \times 10^{15}}{2} + \sqrt{\left(\frac{5 \times 10^{15}}{2}\right)^2 + (2.4 \times 10^{13})^2} = 5 \times 10^{15} \text{ cm}^{-3}$$

$$9. (B) p_0 = \frac{n_i^2}{p_0} = \frac{(2.4 \times 10^{13})^2}{2.95 \times 10^{13}} = 1.95 \times 10^{13} \text{ cm}^{-3}$$

10. (A) Since $N_a > N_d$, thus material is p-type ,
 $p_0 = N_a - N_d = 2.5 \times 10^3 - 1 \times 10^3 = 1.5 \times 10^{13} \text{ cm}^{-3}$

$$11. (D) kT = 0.0259 \left(\frac{200}{300}\right) = 0.0173 \text{ eV}$$

For GaAs at 300 K,

$$N_c = 4.7 \times 10^{17} \text{ cm}^{-3}, \quad N_v = 7.0 \times 10^{18}, \quad E_g = 1.42 \text{ eV}$$

$$n_i^2 = 4.7 \times 10^{17} \times 7.0 \times 10^{18} \left(\frac{200}{300}\right)^3 e^{-\left(\frac{1.42}{0.0173}\right)}$$

$$\Rightarrow n_i = 1.48 \text{ cm}^{-3}$$

$$n_i^2 = n_0 p_0 = 5 p_0^2 = \frac{n_0^2}{5}$$

$$n_0 = \sqrt{5} n_i = 3.3 \text{ cm}^{-3}$$

$$12. (A) kT = 0.0259 \left(\frac{400}{300}\right) = 0.0345 \text{ eV}$$

$$n_i^2 = N_c N_v e^{-\left(\frac{E_g}{kT}\right)}$$

For Ge at 300 K,

$$N_c = 1.04 \times 10^{19} \text{ cm}^{-3}, \quad N_v = 6 \times 10^{18} \text{ cm}^{-3}, \quad E_g = 0.66 \text{ eV}$$

$$n_i^2 = 1.04 \times 10^{19} \times 6 \times 10^{18} \left(\frac{400}{300}\right)^3 e^{-\left(\frac{0.66}{0.0345}\right)} = 7.274 \times 10^{29}$$

$$n_i = 8.528 \times 10^{14} \text{ cm}^{-3}$$

$$p_0 = \frac{N_a}{2} + \sqrt{\left(\frac{N_a}{2}\right)^2 + n_i^2}$$

$$= \frac{10^{15}}{2} + \sqrt{\left(\frac{10^{15}}{2}\right)^2 + 7.274 \times 10^{29}}$$

$$\Rightarrow p_0 = 1.489 \times 10^{15} \text{ cm}^{-3}$$

$$E_{Fi} - E_F = kT \ln \left(\frac{p_0}{n_0}\right) = 0.0345 \ln \left(\frac{1.489 \times 10^{15}}{8.528 \times 10^{14}}\right)$$

$$= 0.019 \text{ eV}$$

$$13. (A) n_0 = \frac{N_d}{2} + \sqrt{\left(\frac{N_d}{2}\right)^2 + n_i^2}$$

For Ge at $T = 300 \text{ K}$, $n_i = 2.4 \times 10^{13} \text{ cm}^{-3}$

$$n_0 = \frac{10^{14}}{2} + \sqrt{\left(\frac{10^{14}}{2}\right)^2 + (2.4 \times 10^{13})^2} = 1.055 \times 10^{14} \text{ cm}^{-3}$$

$$E_F - E_{Fi} = kT \ln \left(\frac{n_0}{n_i}\right) = 0.0259 \ln \left(\frac{1.055 \times 10^{14}}{2.4 \times 10^{13}}\right)$$

$$= 0.0383 \text{ eV}$$

$$14. (A) n_0 = \frac{N_d}{2} + \sqrt{\left(\frac{N_d}{2}\right)^2 + n_i^2}$$

$$n_i = 0.05 n_0$$

$$\Rightarrow n_0 = 1.5 \times 10^{15} + \sqrt{(1.5 \times 10^{15})^2 + (0.05 n_0)^2}$$

$$\Rightarrow n_0 = 3.0075 \times 10^{15} \text{ cm}^{-3}$$

$$n_i = 1.504 \times 10^{14} \text{ cm}^{-3}$$

$$n_i^2 = N_c N_v e^{-\left(\frac{E_g}{kT}\right)}$$

For GaAs at $T = 300 \text{ K}$,

$$N_c = 4.7 \times 10^{17}, \quad N_v = 7 \times 10^{18}, \quad E_g = 1.42 \text{ eV}$$

$$(1.504)^2 = 4.7 \times 10^{17} \times 7 \times 10^{18} \left(\frac{T}{300}\right)^3 e^{-\left(\frac{1.42 \times 300}{0.0259 T}\right)}$$

By trial and error $T = 763 \text{ K}$

$$15. (A) E_{Fi} - E_{midgap} = \frac{3}{4} kT \ln \left(\frac{m_p^*}{m_p}\right) = 0.0446 \text{ eV}$$

$$16. (A) n_0 = N_d - N_a = N_c e^{-\left(\frac{E_c - E_F}{kT}\right)}$$

For Si, $N_c = 2.8 \times 10^{19} \text{ cm}^{-3}$

$$N_d = 5 \times 10^{15} + 2.8 \times 10^{19} e^{-\left(\frac{0.215}{0.0259}\right)} = 1.19 \times 10^{16} \text{ cm}^{-3}$$

$$17. (A) E_F - E_{Fi} = kT \ln \left(\frac{N_d}{N_i}\right)$$

$$= 0.0259 \ln \left(\frac{10^{15}}{1.5 \times 10^{10}}\right) = 0.287 \text{ eV}$$

$$18. (D) R = \frac{V}{I} = \frac{20}{100\text{m}} = 200 \Omega$$

$$\sigma = \frac{L}{RA} = \frac{2 \times 10^{-3}}{(200)(0.001)} = 0.01 (\Omega \text{ - cm})^{-1}$$

$\sigma \approx e \mu_n n_0$, For Si, $\mu_n = 1350$.

$$\Rightarrow 0.01 = (1.6 \times 10^{-19})(1350)n_0$$

$$n_0 = 4.6 \times 10^{13} \text{ cm}^{-3},$$

$$n_0 \gg n_i \Rightarrow n_0 = N_d$$

19. (B) $N_d \gg n_i \Rightarrow n_0 = N_d$, $\sigma \approx e \mu_n n_0$,

$$R = \frac{L}{\sigma A} = \frac{L}{e \mu_n N_d A},$$

$$= \frac{0.1}{(1.6 \times 10^{-19})(1100)(5 \times 10^{16})(100 \times 10^{-8})} = 11.36 \text{ k}\Omega$$

20. (A) $R = \frac{L}{\sigma A}$, $\sigma \approx e\mu_n n_0$, $R = \frac{L}{e\mu_n n_0 A}$

$$\Rightarrow n_0 = \frac{L}{e\mu_n AR}$$

$$n_0 = 0.9N_d$$

$$= \frac{20 \times 10^{-4}}{(0.9)(1.6 \times 10^{-19})(8000)(10^{-6})(2 \times 10^3)} = 8.7 \times 10^{15} \text{ cm}^{-3}$$

21. (B) $\sigma \approx e\mu_n n_0$, $R = \frac{L}{\sigma A}$, $n_0 = \frac{L}{e\mu_n AR}$

$$= \frac{10 \times 10^{-4}}{(1.6 \times 10^{-19})(800)(10^{-6})(10)} = 7.81 \times 10^{17} \text{ cm}^{-3}$$

$$\text{Efficiency} = \frac{n_0}{N_d} \times 100 = \frac{7.8 \times 10^{17}}{10^{18}} \times 100 = 78.1 \%$$

22. (D) $E = \frac{V}{L} = \frac{6}{2} = 3 \text{ V/cm}$, $v_d = \mu_n E$,

$$\mu_n = \frac{v_d}{E} = \frac{10^4}{3} = 3333 \text{ cm}^2/\text{V-s}$$

23. (D) $\sigma_i = en_i(\mu_n + \mu_p)$

$$10^{-6} = (1.6 \times 10^{-19})(1000 + 600)n_i$$

$$\text{At } T = 300 \text{ K}, n_i = 3.91 \times 10^9 \text{ cm}^{-3}$$

$$n_i^2 = N_c N_v e^{-\left(\frac{E_g}{kT}\right)} \Rightarrow E_g = kT \ln \left(\frac{N_c N_v}{n_i^2} \right)$$

$$\Rightarrow E_g = 2(0.0259) \ln \left(\frac{10^{19}}{3.91 \times 10^9} \right) = 1.122 \text{ eV}$$

$$\text{At } T = 500 \text{ K}, kT = 0.0259 \left(\frac{500}{300} \right) = 0.0432 \text{ eV}$$

$$n_i^2 = (10^{19})^2 e^{-\left(\frac{1.122}{0.0432}\right)} \text{ cm}^{-6}$$

$$\Rightarrow n_i = 2.29 \times 10^{13} \text{ cm}^{-3}$$

$$= (1.6 \times 10^{-19})(2.29 \times 10^{13})(1000 + 600)$$

$$= 5.86 \times 10^{-3} (\Omega \text{-cm})^{-1}$$

24. (B) $\rho = \frac{1}{\sigma} = \frac{1}{e\mu_n N_d}$

$$N_d = \frac{1}{\rho e\mu_n} = \frac{1}{5(1.6 \times 10^{-19})(1350)} = 9.25 \times 10^{14} \text{ cm}^{-3}$$

25. (B) $J_n = eD_n \frac{dn}{dx}$

$$= (1.6 \times 10^{-19})(35) \left(\frac{10^{18} - 10^{16}}{2 \times 10^{-4}} \right) = 2.8 \times 10^4 \text{ A/cm}^2$$

26. (A) $J = evn = (1.6 \times 10^{-19})(10^7)(10^{16}) = 1.6 \text{ A/cm}^2$

27. (A) $v_d = \frac{e\tau_{sc} E}{m_e^*} = \frac{(1.6 \times 10^{-19})(10^{-13})(10^5)}{(0.067)(9.1 \times 10^{-31})}$

$$= 262 \times 10^3 \text{ m/s} = 2.6 \times 10^6 \text{ cm/s}$$

28. (A) $N_d \gg n_i \Rightarrow n_0 = N_d$

$$J = e\mu_n n_0 E = (1.6 \times 10^{-19})(7500)(10^{16})(10) = 120 \text{ A/cm}^2$$

29. (D) $n_i^2 = N_c N_v e^{-\left(\frac{E_g}{kT}\right)}$

$$= (2 \times 10^{19})(1 \times 10^{19}) e^{-\left(\frac{1.1}{0.0259}\right)} = 7.18 \times 10^9$$

$$\Rightarrow n_i = 8.47 \times 10^9 \text{ cm}^{-3}$$

$$N_d \gg n_i \Rightarrow N_d = n_0$$

$$J = \sigma E = e\mu_n n_0 E$$

$$= (1.6 \times 10^{-19})(1000)(10^{14})(100) = 1.6 \text{ A/cm}^2$$

30. (A) $\sigma = e\mu_n n_0 + e\mu_p p_0$ and $n_0 = \frac{n_i^2}{p_0}$

$$\Rightarrow \sigma = e\mu_n \frac{n_i^2}{p_0} + e\mu_p p_0$$

$$\frac{d\sigma}{dp_0} = 0 = \frac{(-1)e\mu_n n_i^2}{p_0^2} + e\mu_p$$

$$\Rightarrow p_0 = n_i \left(\frac{\mu_n}{\mu_p} \right)^{\frac{1}{2}} = 3.6 \times 10^{12} \left(\frac{7500}{300} \right)^{\frac{1}{2}}$$

$$= 7.2 \times 10^{11} \text{ cm}^{-3}$$

31. (B) $\sigma_{min} = \frac{2\sigma_i \sqrt{\mu_p \mu_n}}{\mu_p + \mu_n} = 2en_i \sqrt{\mu_p \mu_n}$

$$= 2 \times 1.6 \times 10^{-19} (3.6 \times 10^{12}) \sqrt{(7500)(300)}$$

$$= 1.7 \times 10^{-3} (\Omega \text{-cm})^{-1}$$

32. (B) $\sigma = \frac{1}{\rho} = e\mu n_i$,

$$\frac{1}{\rho_1} = \frac{n_{i1}}{n_{i2}} = \frac{e^{-\frac{E_g}{2kT_1}}}{e^{-\frac{E_g}{2kT_2}}}$$

$$\frac{1}{\rho_2} = \frac{e^{-\frac{E_g}{2kT_1} \left(\frac{1}{T_1} - \frac{1}{T_2} \right)}}{e^{-\frac{E_g}{2kT_2} \left(\frac{1}{T_1} - \frac{1}{T_2} \right)}}$$

$$0.1 = e^{-\frac{E_g}{2k} \left(\frac{1}{T_1} - \frac{1}{T_2} \right)}$$

$$\frac{E_g}{2k} \left(\frac{330 - 300}{330 \times 300} \right) = \ln 10$$

$$E_g = 22(k300) \ln 10 = 1.31 \text{ eV}$$

33. (D) $\frac{1}{\mu} = \frac{1}{\mu_1} + \frac{1}{\mu_2} + \frac{1}{\mu_3}$

$$\frac{1}{\mu} = \frac{1}{500} + \frac{1}{750} + \frac{1}{1500} \Rightarrow \mu = 250 \text{ cm}^2/\text{V-s}$$

$$34. \text{ (B) } J_n = eD_n \frac{dn}{dx}$$

$$0.19 = (1.6 \times 10^{-19})(25) \left(\frac{5 \times 10^{14} - n(0)}{0.010} \right)$$

$$n(0) = 2.5 \times 10^{13} \text{ cm}^{-3}$$

$$35. \text{ (B) } J = -eD_p \frac{dp}{dx} = -eD_p \frac{d}{dx} \left(10^{16} \left(1 - \frac{x}{L} \right) \right) = \frac{e10^{16}D_p}{L}$$

$$= \frac{(1.6 \times 10^{-19})(10^{16})(10)}{10 \times 10^{-4}}$$

$$J = 16 \text{ A/cm}^2$$

$$36. \text{ (B) } J_p = -eD_p \frac{dp_0}{dx} \Big|_{x=0} = \frac{10^{15}eD_p}{L_p}$$

$$J_n = eD_n \frac{dn_0}{dx} \Big|_{x=0} = \frac{5 \times 10^{14}eD_n}{L_n}$$

$$J = J_p + J_n = \frac{10^{15}eD_p}{L_p} + \frac{5 \times 10^{14}eD_n}{L_n}$$

$$= 1.6 \times 10^{-19} \left(\frac{10^{15}(10)}{15 \times 10^{-4}} + \frac{5 \times 10^{14}(25)}{10^{-3}} \right) = 5.2 \text{ A/cm}^2$$

$$37. \text{ (A) } V_H = \frac{-I_x B_z}{ned}$$

$$= \frac{(250 \times 10^{-6})(5 \times 10^{-2})}{(5 \times 10^{21})(1.6 \times 10^{-19})(5 \times 10^{-5})} = -0.313 \text{ mV}$$

38. (B) V_H is positive p-type

$$V_H = \frac{I_x B_z}{epd} \Rightarrow p = \frac{I_x B_z}{eV_H d}$$

$$p = \frac{(0.75 \times 10^{-3})(10^{-1})}{(1.6 \times 10^{-19})(5.8 \times 10^{-3})(10^{-5})}$$

$$= 8.08 \times 10^{21} \text{ m}^{-3} = 8.08 \times 10^{15} \text{ cm}^{-3}$$

$$39. \text{ (C) } \mu_p = \frac{eL}{epv_x Wd}$$

$$= \frac{(0.75 \times 10^{-3})(10^{-3})}{(1.6 \times 10^{-19})(8.08 \times 10^{21})(15)(10^{-4})(10^{-5})}$$

$$\mu_p = 3.9 \times 10^{-2} \text{ m}^2/\text{V-s} = 390 \text{ cm}^2/\text{V-s}$$

40. (A) n-type semiconductor

$$R = \frac{\delta p}{\tau_{p0}} = \frac{4 \times 10^{13}}{10^{-6}} = 4 \times 10^{19} \text{ cm}^{-3}\text{s}^{-1}$$

$$41. \text{ (C) } n_0 = \frac{n_i^2}{p_0} = \frac{(10^{10})^2}{10^{16}} = 10^4 \text{ cm}^{-3}$$

$$R_{n0} = \frac{n_0}{\tau_{n0}} = \frac{10^4}{4 \times 10^{-7}} = 2.5 \times 10^{10} \text{ cm}^{-3}\text{s}^{-1}$$

$$42. \text{ (C) } R_{n0} = \frac{p_0}{\tau_{p0}}, p_0 = \frac{n_i^2}{n_0}, n_0 = N_d = 10^6 \text{ cm}^{-3}$$

$$p_0 = \frac{(1.5 \times 10^{10})^2}{10^{16}} = 2.25 \times 10^4 \text{ cm}^{-3}$$

$$R_{n0} = \frac{2.25 \times 10^4}{10 \times 10^{-6}} = 2.25 \times 10^9 \text{ cm}^{-3}\text{s}^{-1}$$

43. (B) Recombination rate for minority and majority carrier are equal. The generation rate is equal to Recombination rate.

$$G = R_{n0} = R_{p0} = 2.25 \times 10^9 \text{ cm}^{-3}\text{s}^{-1}$$

44. (A) Recombination rates are equal $\frac{n_0}{\tau_{n0}} = \frac{p_0}{\tau_{p0}}$,

$$N_d \gg n_i$$

$$n_0 = N_d, p_0 = \frac{n_i^2}{n_0}$$

$$\frac{n_0}{\tau_{n0}} = \frac{n_0}{p_0} \tau_{p0} = \frac{n_0^2}{n_i^2} \tau_{p0}$$

$$= \left(\frac{10^{16}}{1.5 \times 10^{10}} \right)^2 \times 20 \times 10^{-6} = 8.9 \times 10^6 \text{ s}$$

45. (D) $N_d \gg n_i \Rightarrow n_0 = N_d$

$$p_0 = \frac{n_i^2}{n_0} = \frac{(1.5 \times 10^{10})^2}{10^{16}} = 2.25 \times 10^4 \text{ cm}^{-3}$$

$$R_{p0} = \frac{p_0}{\tau_{p0}} \Rightarrow \tau_{p0} = \frac{p_0}{R_{p0}} = \frac{2.25 \times 10^4}{10^{11}} = 2.25 \times 10^7 \text{ s}$$

$$R_p = \frac{\delta p}{\tau_{p0}} = \frac{10^{14}}{2.25 \times 10^{-7}} = 4.44 \times 10^{20} \text{ cm}^{-3}\text{s}^{-1}$$

$$\frac{R_p}{R_{p0}} = \frac{4.44 \times 10^{20}}{10^{11}} = 4.44 \times 10^9$$
