CHAPTER

2.2

THE PN JUNCTION

In this chapter, N_d and N_a denotes the net donor and acceptor concentration in the individual n and p-region.

1. An abrupt silicon in thermal equilibrium at $T = 300$ K is doped such that $E_c - E_F = 0.21$ eV in the $n-$region and $E_F - E_v = 0.18$ eV in the $p-$region. The built-in potential barrier V_{bi} is

(A) 0.69 V (B) 0.83 V
(C) 0.61 V (D) 0.88 V

2. A silicon pn junction at $T = 300$ K has $N_d = 10^{14}$ cm^{-3} and $N_a = 10^{17}$ cm^{-3}. The built-in voltage is

(A) 0.63 V (B) 0.93 V
(C) 0.026 V (D) 0.038 V

3. In a uniformly doped GaAs junction at $T = 300$ K, at zero bias, only 20% of the total space charge region is to be in the p-region. The built in potential barrier is $V_{bi} = 1.20$ V. The majority carrier concentration in n-region is

(A) 1×10^{16} cm^{-3} (B) 4×10^{16} cm^{-3}
(C) 1×10^{22} cm^{-3} (D) 4×10^{22} cm^{-3}

Statement for Q.4–5:

An abrupt silicon pn junction at zero bias and $T = 300$ K has dopant concentration of $N_a = 10^{17}$ cm^{-3} and $N_d = 5 \times 10^{15}$ cm^{-3}.

4. The Fermi level on $n-$side is

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

5. The Fermi level on $p-$side is

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

Statement for Q.6–8:

A silicon pn junction at $T = 300$ K with zero applied bias has doping concentrations of $N_d = 5 \times 10^{16}$ cm^{-3} and $N_a = 5 \times 10^{15}$ cm^{-3}.

6. The width of depletion region extending into the n-region is

(A) 4×10^{-6} cm (B) 3×10^{-6} cm
(C) 4×10^{-5} cm (D) 3×10^{-5} cm

7. The space charge width is

(A) 3.2×10^{-5} cm (B) 4.5×10^{-5} cm
(C) 4.5×10^{-4} cm (D) 3.2×10^{-4} cm

8. In depletion region maximum electric field $|E_{max}|$ is

(A) 1×10^{4} V/cm (B) 2×10^{4} V/cm
(C) 3×10^{4} V/cm (D) 4×10^{4} V/cm

9. An $n - n$ isotype doping profile is shown in fig. P2.2.9. The built-in potential barrier is ($n_i = 1.5 \times 10^{10}$ cm^{-3})

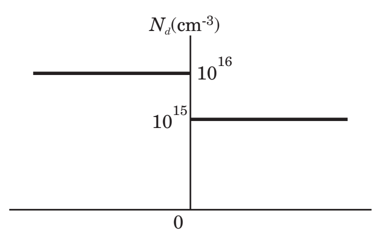

Fig. P2.2.9

(A) 0.66 V (B) 0.06 V
(C) 0.03 V (D) 0.33 V

Statement for Q.10–11:

A silicon abrupt junction has dopant concentration $N_a = 2 \times 10^{16}$ cm^{-3} and $N_d = 2 \times 10^{15}$ cm^{-3}. The applied reverse bias voltage is $V_R = 8$ V.

10. The maximum electric field $|E_{\max}|$ in depletion region is

(A) 15×10^4 V/cm (B) 7×10^4 V/cm

(C) 3.5×10^4 V/cm (D) 5×10^4 V/cm

11. The space charge region is

(A) 2.5 μm (B) 25 μm

(C) 50 μm (D) 100 μm

12. A uniformly doped silicon pn junction has $N_a = 5 \times 10^{17}$ cm^{-3} and $N_d = 10^{17}$ cm^{-3}. The junction has a cross-sectional area of 10^{-4} cm^{-3} and has an applied reverse-bias voltage of $V_R = 5$ V. The total junction capacitance is

(A) 10 pF (B) 5 pF

(C) 7 pF (D) 3.5 pF

Statement for Q.13–14:

An ideal one-sided silicon n^+p junction has uniform doping on both sides of the abrupt junction. The doping relation is $N_d = 50N_a$. The built-in potential barrier is $V_{bi} = 0.75$ V. The applied reverse bias voltage is $V_R = 10$.

13. The space charge width is

(A) 1.8 μm (B) 1.8 mm

(C) 1.8 cm (D) 1.8 m

14. The junction capacitance is

(A) 3.8×10^{-9} F/cm^2 (B) 9.8×10^{-9} F/cm^2

(C) 2.4×10^{-9} F/cm^2 (D) 5.7×10^{-9} F/cm^2

15. Two p^+n silicon junction is reverse biased at $V_R = 5$ V. The impurity doping concentration in junction A are $N_a = 10^{18}$ cm^{-3} and $N_d = 10^{-15}$ cm^{-3}, and those in junction B are $N_a = 10^{18}$ cm^{-3} and $N_d = 10^{16}$ cm^{-3}. The ratio of the space charge width is

(A) 4.36 (B) 9.8

(C) 19 (D) 3.13

16. The maximum electric field in reverse-biased silicon pn junction is $|E_{\max}| = 3 \times 10^5$ V/cm. The doping concentration are $N_d = 4 \times 10^{16}$ cm^{-3} and $N_a = 4 \times 10^{17}$ cm^{-3}. The magnitude of the reverse bias voltage is

(A) 3.6 V (B) 9.8 V

(C) 7.2 V (D) 12.3 V

17. An abrupt silicon pn junction has an applied reverse bias voltage of $V_R = 10$ V. it has dopant concentration of $N_a = 10^{18}$ cm^{-3} and $N_d = 10^{15}$ cm^{-3}. The pn junction area is 6×10^{-4} cm^2. An inductance of 2.2 mH is placed in parallel with the pn junction. The resonant frequency is

(A) 1.7 MHz (B) 2.6 MHz

(C) 3.6 MHz (D) 4.3 MHz

18. A uniformly doped silicon p^+n junction is to be designed such that at a reverse bais voltage of $V_R = 10$ V the maximum electric field is limited to $E_{max} = 10^6$ V/cm. The maximum doping concentration in the n-region is

(A) 3.2×10^{19} cm^{-3} (B) 3.2×10^{17} cm^{-3}

(C) 6.4×10^{17} cm^{-3} (D) 6.4×10^{19} cm^{-3}

19. A diode has reverse saturation current $I_s = 10^{-10}$ A and non ideality factor $\eta = 2$. If diode voltage is 0.9 V, then diode current is

(A) 11 mA (B) 35 mA

(C) 83 mA (D) 143 mA

20. A diode has reverse saturation current $I_s = 10^{-18}$ A and nonideality factor $\eta = 1.05$. If diode has current of 70 μA, then diode voltage is

(A) 0.63 V (B) 0.87 V

(C) 0.54 V (D) 0.93 V

21. An ideal pn junction diode is operating in the forward bais region. The change in diode voltage, that will cause a factor of 9 increase in current, is

(A) 83 mV (B) 59 mV

(C) 43 mV (D) 31 mV

22. An pn junction diode is operating in reverse bias region. The applied reverse voltage, at which the ideal reverse current reaches 90% of its reverse saturation current, is

(A) 59.6 mV (B) 2.7 mV

(C) 4.8 mV (D) 42.3 mV

23. For a silicon p^+n junction diode the doping concentrations are $N_a = 10^{18}$ cm^{-3} and $N_d = 10^{16}$ cm^{-3}. The minority carrier hole diffusion coefficient is $D_p = 12$ cm^2/s and the minority carrier hole life time is $\tau_{p0} = 10^{-7}$ s. The cross sectional area is $A = 10^{-4}$ cm^2. The reverse saturation current is

(A) 4×10^{-12} A (B) 4×10^{-15} A

(C) 4×10^{-11} A (D) 4×10^{-7} A

24. For an ideal silicon pn junction diode

$\tau_{no} = \tau_{po} = 10^{-7}$ s ,

$D_n = 25$ cm^2/s ,

$D_p = 10$ cm^2/s

The ratio of N_a/N_d , so that 95% of the current in the depletion region is carried by electrons, is

(A) 0.34 (B) 0.034

(C) 0.83 (D) 0.083

Statement for Q.25–26:

A ideal long silicon pn junction diode is shown in fig. P2.2.25–26. The n – region is doped with 10^{16} organic atoms per cm^3 and the p – region is doped with 5×10^{16} boron atoms per cm^3. The minority carrier lifetimes are $D_n = 23$ cm^2/s and $D_p = 8$ cm^2/s. The forward-bias voltage is $V_a = 0.61$ V.

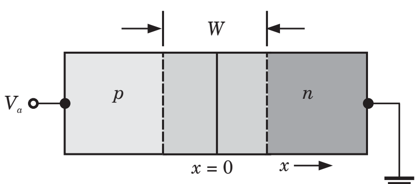

Fig. P.2.2.25-26

25. The excess hole concentration is

(A) $6.8 \times 10^{12} e^{-246x}$ cm^{-3}, $x \geq 0$

(B) $6.8 \times 10^{12} e^{-246x}$ cm^{-3}, $x \geq 0$

(C) $3.8 \times 10^{14} e^{-3534x}$ cm^{-3}, $x \geq 0$

(D) $3.8 \times 10^{14} e^{+3534x}$ cm^{-3}, $x \geq 0$

26. The hole diffusion current density at $x = 3$ μm is

(A) 0.6 A/cm^2 (B) 0.6×10^{-3} A/cm^2

(C) 0.4 A/cm^2 (D) 0.4×10^{-3} A/cm^2

27. The doping concentrations of a silicon pn junction are $N_d = 10^{16}$ cm^{-3} and $N_a = 8 \times 10^{15}$ cm^{-3}. The cross-sectional area is 10^{-3} cm^2. The minority carrier lifetimes are $\tau_{n0} = 1$ μs and $\tau_{p0} = 0.1$ μs. The minority carrier diffusion coefficients are $D_n = 35$ cm^2/s and $D_p = 10$ cm^2/s. The total number of excess electron in the p – region, if applied forward bias is $V_a = 0.5$ V, is

(A) 4×10^7 cm^{-3} (B) 6×10^{10} cm^{-3}

(C) 4×10^{10} cm^{-3} (D) 6×10^7 cm^{-3}

28. Two ideal pn junction have exactly the same electrical and physical parameters except for the band gap of the semiconductor materials. The first has a bandgap energy of 0.525 eV and a forward-bias current of 10 mA with $V_a = 0.255$ V. The second pn junction diode is to be designed such that the diode current $I = 10$ μA at a forward-bias voltage of $V_a = 0.32$ V. The bandgap energy of second diode would be

(A) 0.77 eV (B) 0.67 eV

(C) 0.57 eV (D) 0.47 eV

29. A pn junction biased at $V_a = 0.72$ V has DC bias current $I_{DQ} = 2$ mA. The minority carrier lifetime is 1 μs is both the n and p regions. The diffusion capacitance is in

(A) 49.3 nF (B) 38.7 nF

(C) 77.4 nF (D) 98.6 nF

30. A p^+n silicon diode is forward biased at a current of 1 mA. The hole life time in the n – region is 0.1 μs. Neglecting the depletion capacitance the diode impedance at 1 MHz is

(A) $38.7 + j12.1\,\Omega$ (B) $23.5 + j7.5\,\Omega$

(C) $38.7 - j12.1$ mΩ (D) $23.5 - j7.5\,\Omega$

31. The slope of the diffusion capacitance verses forward-bias current of a p^+n diode is 2.5×10^{-6} F/A. The hole lifetime is

(A) 1.3×10^{-7} s (B) 1.3×10^{-4} s

(C) 6.5×10^{-8} s (D) 6.5×10^{-4} s

32. A silicon pn junction with doping profile of $N_a = 10^{16}$ cm^{-3} and $N_d = 10^{15}$ cm^{-3} has a cross sectional area of 10^{-2} cm^2. The length of the p – region is 2 mm and length of the n – region is 1 mm. The approximately series resistance of the diode is

(A) 62 Ω (B) 43 Ω

(C) 72 Ω (D) 81 Ω

33. A gallium arsenide pn junction is operating in reverse-bias voltage $V_R = 5$ V. The doping profile are $N_a = N_d = 10^{16}$ cm^{-3}. The minority carrier life- time are $\tau_{p0} = \tau_{n0} = \tau_0 = 10^{-8}$ s. The reverse-biased generation current density is ($\varepsilon_r = 13.1$, $n_i = 1.8 \times 10^6$)

(A) 1.9×10^{-8} A/cm^2 (B) 1.9×10^{-9} A/cm^2

(C) 1.4×10^{-8} A/cm^2 (D) 1.4×10^{-9} A/cm^2

34. For silicon the critical electric field at breakdown is approximately $E_{crit} = 4 \times 10^5$ V/cm. For the breakdown voltage of 25 V, the maximum $n-$type doping concentration in an abrupt p^+n-junction is

(A) 2×10^{16} cm^{-3} (B) 4×10^{16} cm^{-3}

(C) 2×10^{18} cm^{-3} (D) 4×10^{18} cm^{-3}

35. A uniformly doped silicon pn junction has dopant profile of $N_a = N_d = 5 \times 10^{16}$ cm^{-3}. If the peak electric field in the junction at breakdown is $E = 4 \times 10^5$ V/cm, the breakdown voltage of this junction is

(A) 35 V (B) 30 V

(C) 25 V (D) 20 V

36. An abrupt silicon p^+n junction has an $n-$region doping concentration of $N_d = 5 \times 10^{15}$ cm^{-3}. The minimum $n-$region width, such that avalanche breakdown occurs before the depletion region reaches an ohmic contact, is ($V_B \approx 100$ V)

(A) 5.1 μm (B) 3.6 μm

(C) 7.3 μm (D) 6.4 μm

37. A silicon pn junction diode has doping profile $N_a = N_d = 5 \times 10^{19}$ cm^{-3}. The space charge width at a forward bias voltage of $V_a = 0.4$ V is

(A) 102 A° (B) 44 A°

(C) 153 A° (D) 62 A°

38. A GaAs pn^+ junction LED has following parameters

$D_n = 25$ cm^2/s, $D_p = 12$ cm^2/s

$N_d = 5 \times 10^{17}$ cm^{-3}, $N_a = 10^{16}$ cm^{-3}

$\tau_{n0} = 10$ ns , $\tau_{p0} = 10$ ns

The injection efficiency of the LED is

(A) 0.83 (B) 0.99

(C) 0.64 (D) 0.46

39. A GaAs laser has a threshold density of 500 A/cm^2. The laser has dimensions of $10\ \mu m \times 200\ \mu m$. The active region is $d_{Las} = 100$ A°. The electron-hole recombination time at threshold is 1.5 ns. The current density of $5J_{th}$ is injected into the laser. The optical power emitted, if emitted photons have an energy of 1.43 eV, is

(A) 143 mW (B) 71.5 mW

(C) 62.3 mW (D) 124.6 mW

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$= 3.01 \times 10^{-5}$ cm,

$$C_T = \frac{\varepsilon A}{W} = \frac{11.7 \times 8.85 \times 10^{-14} \times 10^{-4}}{3.01 \times 10^{-5}} = 3.5 \times 10^{-12} \text{ F}$$

13. (A) $V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right)$

$$0.751 = 0.0259 \ln\left(\frac{50 N_a^2}{2.25 \times 10^{20}}\right)$$

$N_a = 4.2 \times 10^{15}$ cm^{-3}, $N_d = 2.1 \times 10^{17}$ cm^{-3}

$$W = \left\{\frac{2\varepsilon_s(V_{bi} + V_R)}{e}\left[\frac{1}{N_a} + \frac{1}{N_a}\right]\right\}^{\frac{1}{2}},$$

$$N_d >> N_a \quad \Rightarrow \quad W \approx \left[\frac{2\,\varepsilon(V_{bi} + V_R)}{e}\left(\frac{1}{N_a}\right)\right]^{\frac{1}{2}}$$

$$= \left[\frac{2 \times (11.7 \times 8.85 \times 10^{-4})(10.752)}{1.6 \times 10^{-19} \times 4.2 \times 10^{15}}\right]^{\frac{1}{2}} = 1.8 \times 10^{-4} \text{ cm}$$

$= 1.8\ \mu$m

14. (D) $C' = \left[\frac{e\varepsilon\, N_a N_d}{2(V_{bi} + V_R)(N_a + N_d)}\right]^{\frac{1}{2}}$

For $N_d >> N_a$, $C' = \left[\frac{e\varepsilon\, N_a}{2(V_{bi} + V_R)}\right]^{\frac{1}{2}}$

$$= \left[\frac{1.6 \times 10^{-19} \times 11.7 \times 8.85 \times 10^{-4} \times 4.2 \times 10^{15}}{2\,(10 + 0.754)}\right]^{\frac{1}{2}}$$

$= 5.7 \times 10^{-9}$ F/cm^2

15. (D) $W = \left\{\frac{2\varepsilon_s(V_{bi} + V_R)}{e}\left[\frac{1}{N_a} + \frac{1}{N_a}\right]\right\}^{\frac{1}{2}}$

$$\frac{W_A}{W_B} = \left[\frac{(V_{bia} + V_R)}{(V_{bib} +_R)}\frac{(N_{aA} + N_{dA})}{(N_{aB} + N_{dB})}\frac{N_{aB}N_{dB}}{N_{aA}N_{dB}}\right]^{\frac{1}{2}}$$

$$V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

$$V_{biA} = 0.0259 \ln\left(\frac{10^{18} \times 10^{15}}{2.25 \times 10^{20}}\right) = 0.754 \text{ V}$$

$$V_{biB} = 0.0259 \ln\left(\frac{10^{18} \times 10^{16}}{2.25 \times 10^{20}}\right) = 0.814 \text{ V}$$

$$\frac{W_A}{W_B} = \left[\left(\frac{5.754}{5.814}\right)\left(\frac{10^{18} + 10^{15}}{10^{18} + 10^{16}}\right)\left(\frac{10^{16}}{10^{15}}\right)\right]^{\frac{1}{2}} = 3.13$$

16. (C) $V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right)$

$$= 0.0259 \ln\left(\frac{4 \times 10^{16} \times 4 \times 10^{17}}{2.25 \times 10^{20}}\right) = 0.826 \text{ V}$$

$$|E_{max}| = \left[\frac{2e(V_{bi} + V_R)}{\varepsilon}\;\frac{N_a N_d}{(N_a + N_d)}\right]^{\frac{1}{2}}$$

$$V_{bi} + V_R = \frac{\varepsilon E_{\max}^2}{2e}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)$$

$$= \frac{(11.7 \times 8.85 \times 10^{-14})(3 \times 10^5)^2}{2 \times 1.6 \times 10^{-19}}\left(\frac{1}{4 \times 10^{16}} + \frac{1}{4 \times 10^{17}}\right) \text{V}$$

$= 8.008$ V

$V_R = 8.008 - 0.826 = 7.18$ V

17. (B) $V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right)$

$$= 0.0259 \ln\left(\frac{10^{18} \times 10^{15}}{2.25 \times 10^{20}}\right) = 0.754 \text{ V}$$

$$C' = \left[\frac{e\varepsilon N_a N_d}{2\,(V_i + V_R)(N_a + N_d)}\right]^{\frac{1}{2}}$$

For $N_a >> N_d$, $C' = \left[\frac{e\varepsilon N_d}{2\,(V_{bi} + V_R)}\right]^{\frac{1}{2}}$

$$= \left[\frac{1.6 \times 10^{-19} \times 11.7 \times 8.85 \times 10^{-4} \times 10^{15}}{2\,(10 + 0.754)}\right]^{\frac{1}{2}}$$

$= 2.77 \times 10^{-9}$ F/cm^2

$C = AC' = 6 \times 10^{-4} \times 2.77 \times 10^{-9} = 1.66 \times 10^{-12}$ F

$$f_o = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{2.2 \times 10^{-3} \times 1.66 \times 10^{-12}}} = 2.6 \text{ MHz.}$$

18. (B) $|E_{\max}| = \frac{eN_a x_n}{\varepsilon}$

For a $p^+ n$ junction, $x_n \approx \left[\frac{2\varepsilon(V_{bi} + V_R)}{eN_d}\right]$

So that $|E_{max}| = \left[\frac{2\,eN_d}{\varepsilon_s}\;(V_{bi} + V_R)\right]^{\frac{1}{2}}$

Assuming $V_{bi} << V_R$,

$$N_d = \frac{\varepsilon E_{\max}^2}{2eV_R} = \frac{(11.7 \times 8.85 \times 10^{-14})(10^6)^2}{2(1.6 \times 10^{-14})(10)}$$

$= 3.24 \times 10^{17}$ cm^{-3}

19. (B) $I_D = I_s\left(e^{\frac{V_D}{\eta V_t}} - 1\right) = 10^{-10}\left(e^{\frac{0.9}{2 \times (0.0259)}} - 1\right) = 35$ mA

20. (B) $I_D = I_s\left(e^{\frac{V_D}{\eta V_t}} - 1\right) \quad \Rightarrow \quad V_D = \eta V_t \ln\left(1 + \frac{I_D}{I_s}\right)$

$$=(1.05)(0.0259)\ln\left(1+\frac{70\times10^{-6}}{10^{-18}}\right)=0.87\ \text{V}$$

21. (B) $I_d \approx I_s e^{\left(-\frac{V}{V_t}\right)}$, $\quad \dfrac{I_{d1}}{I_{d2}} = \dfrac{e^{-\frac{V_1}{V_t}}}{e^{-\frac{V_2}{V_t}}} = e^{-\frac{(V_1-V_2)}{V_t}}$

$$V_1 - V_2 = V_t \ln\left(\frac{I_{d2}}{I_{d1}}\right) = 0.0259\ln 10 = 59.6\ \text{mV}$$

22. (A) $I = I_s\left(e^{\frac{V}{V_t}} - 1\right) \Rightarrow V = V_t \ln\left(\dfrac{I}{I_s}+1\right)$

$\dfrac{I}{I_s} = -0.90$ (–ive due to reverse current)

$V = 0.0259\ln(1-0.9) = -59.6\ \text{mV}$

23. (B) $I_s = Aen_i^2 \dfrac{1}{N_d}\sqrt{\dfrac{D}{\tau_{po}}}$

$$=\frac{(10^{-4})(1.6\times10^{-19})(1.5\times10^{10})^2}{10^{16}}\sqrt{\frac{12}{10^{-7}}} = 3.94\times10^{-15}\ \text{A}$$

24. (D) $\dfrac{J_n}{J_n+J_p} = 0.95$,

$J_n = en_i^2 \dfrac{1}{N_a}\sqrt{\dfrac{D_n}{\tau_{no}}}$, $\quad J_p = en_i^2\dfrac{1}{N_d}\sqrt{\dfrac{D_p}{\tau_{po}}}$

$\dfrac{\sqrt{D_n}}{\sqrt{D_n}+\dfrac{N_a}{N_d}\sqrt{D_p}} = 0.95$, $\quad \dfrac{5}{5+\dfrac{N_a}{N_d}\sqrt{10}} = 0.95$

$\Rightarrow \dfrac{N_a}{N_d} = 0.083$

25. (C) $\delta p_n = p_n - p_{n0} = p_{n0}\left[e^{\left(\frac{eV_a}{kt}\right)} - 1\right]\left[e^{\left(-\frac{x}{L_p}\right)}\right]$

$p_{n0} = \dfrac{n_i^2}{N_d} = \dfrac{(1.5\times10^{10})^2}{10^{16}} = 2.25\times10^4\ \text{cm}^{-3}$

$L_p = \sqrt{D_p\tau_{p0}} = \sqrt{(8)(1\times10^{-8})} = 2.83\times10^{-4}\ \text{cm}$

$\delta p_n = 2.25\times10^4\left[e^{\left(\frac{0.61}{0.0259}\right)} - 1\right]\left[e^{\left(-\frac{x}{2.83\times10^{-4}}\right)}\right]$

$= 3.8\times10^{14}e^{-3534x}\ \ \text{cm}^{-3}$

26. (A) $J_p = -eD_p\dfrac{\partial(\delta p_n)}{\partial x} = eD_p(3.8\times10^{14})(3534)e^{-3534x}$

$x = 3\ \mu\text{m} = 3\times10^{-4}\ \text{cm}$

$J_p = (1.6\times10^{-19})(18)(3.8\times10^{14})(3534)e^{-(3534)(3\times10^{-4})}$

$= 0.6\ \text{A/cm}^2$

27. (A) $N_p = AL_n n_{p0}\left[e^{\left(\frac{eV_a}{kT}\right)} - 1\right]$

$n_{p0} = \dfrac{n_i^2}{N_a} = \dfrac{(1.5\times10^{10})^2}{8\times10^{15}} = 2.8\times10^4\ \text{cm}^{-3}$

$L_n = \sqrt{D_n\tau_{no}} = \sqrt{35\times10^{-6}} = 5.9\times10^{-3}$ Cm

$N_p = 10^{-3}\times5.9\times10^{-3}\times2.8\times10^4\left[e^{\left(\frac{0.5}{0.0259}\right)} - 1\right]$

$= 4\times10^7\ \text{cm}^{-3}$

28. (A) $I \propto n_i^2 e^{\left(\frac{V_a}{V_t}\right)} \propto e^{\left(\frac{-E_g}{V_t}\right)}e^{\left(\frac{V_a}{V_t}\right)}$

$\Rightarrow I \propto e^{\left(\frac{V_a-E_g}{V_t}\right)}$

$\dfrac{I_1}{I_2} = \dfrac{e^{\left(\frac{V_a-E_{g1}}{V_t}\right)}}{e^{\left(\frac{V_{a2}-E_{g2}}{V_t}\right)}} = e^{\frac{1}{V_t}(V_{a1}-V_{a2}-E_{g1}+E_{g2})}$

$\dfrac{10\times10^{-3}}{10\times10^{-6}} = e^{\frac{(0.255-0.32-0.525+E_{g2})}{(0.0259)}}$

$10^3 = e^{\left(\frac{E_{g2}-0.59}{0.0259}\right)}$

$E_{g2} = 0.59 + 0.0259\ln\ 10^3 = 0.769$ EV

29. (B) $C_d = \left(\dfrac{I_{p0}\tau_{p0}+I_{n0}\tau_{n0}}{2V_t}\right)$

$\tau_{n0} = \tau_{p0} = 10^{-6}$ s, $\qquad I_{p0}+I_{n0} = I_{dQ} = 2$ mA

$C_d = \dfrac{2\times10^{-3}\times10^{-6}}{2(0.0259)} = 3.86\times10^{-8}$ F

30. (D) $g_d = \dfrac{I_{dQ}}{V_t} = \dfrac{10^{-3}}{0.0259} = 3.86\times10^{-2}$ S

$C_d = \dfrac{I_{dQ}\tau_{p0}}{2V_t} = \dfrac{10^{-3}\times10^{-7}}{2\times(0.0259)} = 1.93\times10^{-9}$ F

$Z = \dfrac{1}{Y} = \dfrac{1}{g_d + j\omega C_d} = 23.5 - j7.5\ \Omega$

31. (A) For a p^+n diode $I_{p0} >> I_{n0}$

$C_d = \left(\dfrac{1}{2V_t}\right)(I_{po}\tau_{po})$, $\qquad \dfrac{\tau_{p0}}{2V_t} = 2.5\times10^{-6}$

$\Rightarrow \tau_{p0} = 2\times0.0259\times2.5\times10^{-6} = 1.3\times10^{-7}\ s$

32. (C) $R_P = \dfrac{\rho_p L}{A} = \dfrac{L}{A(e\mu_p N_a)}$

$$=\frac{0.2}{(10^{-2})(1.6\times10^{-19})(480)(10^{16})} = 26\ \Omega$$

$$R_n = \frac{\rho_n L}{A} = \frac{L}{Ae(\mu_n N_d)}$$

$$= \frac{0.10}{(10^{-3})(1.6 \times 10^{-19})(1350)(10^{15})} = 46.3\,\Omega$$

$$R = R_p + R_n = 72.3\,\Omega$$

33. (B) $V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right)$

$$= 2(0.0259)\ln\left(\frac{10^{16}}{1.8 \times 10^6}\right) = 1.16 \text{ V}$$

$$W = \left\{\frac{2\varepsilon_s(V_{bi} + V_R)}{e}\left[\frac{1}{N_a} + \frac{1}{N_a}\right]\right\}^{\frac{1}{2}}$$

$$= \left[\frac{2 \times (13.1 \times 8.85 \times 10^{-14})(6.16)}{1.6 \times 10^{-19}}\left(\frac{2}{10^{16}}\right)\right]^{\frac{1}{2}} = 1.34 \times 10^{-4} \text{ cm}$$

$$J_{gen} = \frac{en_i W}{2\tau_o}$$

$$= \frac{1.6 \times 10^{-19} \times 1.8 \times 10^6 \times 1.34 \times 10^{-4}}{2 \times 10^{-8}} = 1.93 \times 10^{-9} \text{ A/cm}^2$$

34. (A) $V_B = \frac{\varepsilon E_{crit}^2}{2eN_B}$

$$25 = \frac{(11.7 \times 8.85 \times 10^{-4})(4 \times 10^5)^2}{2 \times 1.6 \times 10^{-19} \times N_B}$$

$$N_B = N_d = 2 \times 10^{16} \text{ cm}^{-3}$$

35. (D) $E_{max} = \frac{eN_d x_n}{\varepsilon} \quad \Rightarrow \quad x_n = \frac{\varepsilon E_{max}}{eN_d}$

$$= \frac{(11.7 \times 8.85 \times 10^{-14})(4 \times 10^5)}{(1.6 \times 10^{-19})(5 \times 10^{16})} = 5.18 \times 10^{-5} \text{ cm}$$

$$V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right) = 2(0.0259)\ln\left(\frac{5 \times 10^6}{1.5 \times 10^{10}}\right) = 0.778 \text{ V}$$

$$x_n = \left\{\frac{2\varepsilon_s V_{bi}}{e}\left(\frac{N_a}{N_d}\right)\left(\frac{1}{N_a + N_d}\right)\right\}^{\frac{1}{2}}$$

$$(5.18 \times 10^{-5})^2 = \left[\frac{2(11.7 \times 8.85 \times 10^{-4})(V_{bi} + V_R)}{(1.6 \times 10^{-19})(2 \times 5 \times 10^6)}\right]$$

$$\Rightarrow \quad V_{bi} + V_R = 20.7, \quad V_R = 19.9 \text{ V}, \quad V_R = V_B$$

36. (A) For a p^+n diode, Neglecting V_i compared to V_B,

$$x_n \approx \left[\frac{2\varepsilon V_B}{eN_d}\right]^{\frac{1}{2}} = \left[\frac{2(11.7 \times 8.85 \times 10^{-14})(100)}{(1.6 \times 10^{-19})(5 \times 10^{15})}\right]^{\frac{1}{2}} = 5.1\ \mu\text{m}$$

37. (D) $V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right)$

$$= 2(0.0259)\ln\left(\frac{5 \times 10^{19}}{1.5 \times 10^{10}}\right) = 1.14 \text{ V}$$

$$W = \left\{\frac{2\varepsilon_s(V_{bi} + V_R)}{e}\left[\frac{1}{N_a} + \frac{1}{N_a}\right]\right\}^{\frac{1}{2}}$$

$$= \left[\frac{2 \times (11.7 \times 8.85 \times 10^{-14})(1.14 - 0.4)}{1.6 \times 10^{-14}}\left(\frac{2}{5 \times 10^{19}}\right)\right]^{\frac{1}{2}}$$

$$= 6.19 \times 10^{-7} \text{ cm} = 62 \text{ A°}$$

38. (B) $L_n = \sqrt{D_n \tau_{n0}}$, $L_p = \sqrt{D_p \tau_{p0}}$

$$\eta_{inj} = \frac{\frac{D_n n_{p0}}{L_n}}{\frac{D_n n_{p0}}{L_n} + \frac{D_p p_{n0}}{L_p}} = \frac{n_{p0}\sqrt{\frac{D_n}{\tau_{n0}}}}{n_{p0}\sqrt{\frac{D_n}{\tau_{n0}}} + p_{n0}\sqrt{\frac{D_p}{\tau_{p0}}}}$$

$$n_{p0} = \frac{n_i^2}{N_a} = \frac{(1.8 \times 10^6)^2}{10^{16}} = 3.24 \times 10^{-4} \text{ cm}^{-3}$$

$$p_{n0} = \frac{n_i^2}{N_d} = \frac{(1.8 \times 10^6)^2}{5 \times 10^{17}} = 6.48 \times 10^6 \text{ cm}^{-3}$$

$$\sqrt{\frac{D_n}{\tau_{n0}}} = \sqrt{\frac{25}{10 \times 10^{-9}}} = 5 \times 10^4,$$

$$\sqrt{\frac{D_p}{\tau_{p0}}} = \sqrt{\frac{12}{10 \times 10^{-9}}} = 3.5 \times 10^4$$

$$\eta_{inj} = \frac{(5 \times 10^4)(3.24 \times 10^{-4})}{(5 \times 10^4)(3.24 \times 10^{-4}) + (3.5 \times 10^4)(6.48 \times 10^{-6})}$$

$$= 0.986$$

39. (B) The areal density at threshold is

$$n_{2D} = \frac{J_{th}\tau_r}{e} = \frac{(500)(1.5 \times 10^{-9})}{1.6 \times 10^{-19}} = 4.69 \times 10^{12} \text{ cm}^{-3}$$

The carrier density is

$$n_{th} = \frac{n_{2D}}{d_{Las}} = \frac{4.69 \times 10^{12}}{10^{-6}} = 4.69 \times 10^{18} \text{ cm}^{-3}$$

Once the threshold is reached, the carrier density does not change. When $J > J_{th}$ the electron hole recombination is

$$\tau_r(J) = \frac{J_{th}}{J}\tau_r(J_{th}) = \frac{1.5 \times 10^{-9}}{5} = 3 \times 10^{-10} \text{ s}$$

The optical power produced is $p = \frac{JA}{e}h\omega$

$$= \frac{(5 \times 500)(2 \times 10^{-5})(1.43 \times 1.6 \times 10^{-19})}{1.6 \times 10^{-19}} = 71.5 \text{ MW}$$

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