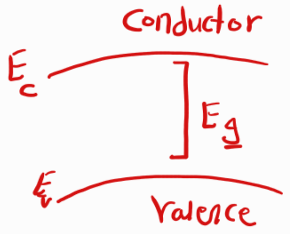
Fundamental of Electronics
Lecture 3-Tutorial-semiconductor
Part 1

EE1224
Fundamentals of Electronic Devices

Rules



1) Intrinsic Carrier Concentration n_i

$$n_i = BT^{3/2} e^{\frac{-E_g}{2KT}}$$

$K = 1.38 * 10^{-23}$ J/K

$B = 5.23 * 10^{15}$ cm → Si at 300k

2) Thermal equilibrium electron & hole

V غاى التكافؤ

Phos phorous

$n = N_d \Rightarrow$ المعطى

$p = \frac{n_i^2}{N_d} \Rightarrow$ لشبكة الموصل Si

III ثلاثي التكافؤ

Boron

$p = N_a =$ معطى

$n = \frac{n_i^2}{N_a}$ → لشبكة الموصل

n_i For Si at 300 k

$= 1.5 * 10^{10}\ cm^{-3}$

$\boxed{3}$ Drift current Density

$q = 1.68 * 10^{-19}$ C

$J = E\sigma$ or $J = E/\rho$

E: electric field

$$\sigma = q(p\mu_p + n\mu_n)$$

p: Thermal eq hole

μ_p: hole Mobility

n: Thermal eq electron

μ_n: electron Mobility

4 Diffusion Current

$$J_n = q\,D_n\,\frac{dn(x)}{dx}$$

D_n → electron Diffusion

$n(x)$ → electron concentration

dx → Distance

نفس الكلام لو هحسب ال J_p (ال hole)

$$\boxed{J_p = q\,D_p\,\frac{dp(x)}{dx}}$$

5 Find Current Flow in Silicon bar

$I = AJ$

$\because J = E\,q\,(p\,\mu_p + n\,\mu_n)$

حيث انه $J = I/A$

$$\boxed{\therefore I = A\,E\,q\,(p\,\mu_p + n\,\mu_n)}$$

$$\boxed{E = \frac{V}{L}}$$

Formula Sheet

$$n_i = BT^{3/2} e^{\frac{-E_g}{2kT}}, \quad V_T = \frac{kT}{q}, \quad V_T \text{ at } 300\ K = 26\ mV, \quad J = Eq(p\mu_p + n\mu_n), \quad |J| = qD\frac{dp(x)}{dx},$$

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = V_T$$

$$W = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)V_{bi}}, \; Q_J = AqW\left(\frac{N_a N_d}{N_a + N_d}\right), \; C_J = \frac{C_{J0}}{\sqrt{1+\frac{V_R}{V_{bi}}}}, \; C_d = \left(\frac{\tau_T}{V_T}\right) I_D$$

$$C_{J0} = A\sqrt{\frac{q\varepsilon_s}{2}\left(\frac{N_d N_a}{N_d + N_a}\right)\left(\frac{1}{V_{bi}}\right)}, \; i_D = I_s\left(e^{\left(\frac{v_D}{nV_T}\right)} - 1\right), \; I_s = Aqn_i^2\left(\frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A}\right)$$

$$k = 86 \times 10^{-6}\ eV/K = 1.38 \times 10^{-23}\ J/K, \; q = 1.68x10^{-19}\ C$$

For Si at temperature equals 300 K:

$$E_g = 1.1\ eV, B = 5.23 \times 10^{15}\ cm^{-3}K^{-3/2}, \varepsilon_s = 1.04 \times 10^{-12}\ {}^{F}/_{cm},$$

$$n_i = 1.5 \times 10^{10}\ cm^{-3}, \mu_n = 1350\ {}^{cm^2}/_{V.s}, \text{and } \mu_p = 480\ {}^{cm^2}/_{V.s}$$

Semiconductor Materials and Properties

Q1: Calculate the intrinsic carrier concentration in silicon at T = 300 K. $n_i = ??$

Q2: Calculate the intrinsic carrier concentration in gallium arsenide at T = 300 K. $n_i = ??$

Table 1.2 A portion of the periodic table

III	IV	V
5 **B** Boron	6 **C** Carbon	
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31 **Ga** Gallium	32 **Ge** Germanium	33 **As** Arsenic
49 **In** Indium		51 **Sb** Antimony

Table 1.3 Semiconductor constants

Material	E_g (eV)	B ($cm^{-3}K^{-3/2}$)
Silicon (Si)	1.1	5.23×10^{15}
Gallium arsenide (GaAs)	1.4	2.10×10^{14}
Germanium (Ge)	0.66	1.66×10^{15}

$$k = 86 \times 10^{-6}\ eV/K$$

Sol

Q1)   aT T = 300 k

$$n_i = B T^{3/2} e^{\frac{-E_g}{2kT}}$$

$$= (5.23 * 10^{15})(300)^{3/2} e^{\frac{-1.1}{2*(86*10^{-6})(300)}}$$

$$\boxed{n_{i\,\text{silicon}} = 1.5 * 10^{10} \, Cm^{-3}}$$

Q2)

$$n_i = B T^{3/2} e^{\frac{-E_g}{2kT}}$$

$$= (2.10 * 10^{14})(300)^{3/2} e^{\left(\frac{-1.4}{2*(86*10^{-6})(300)}\right)}$$

$$\boxed{n_i = 1.8 * 10^{6} \, Cm^{-3}}$$

Semiconductor Materials and Properties

Sol1:

T= 300 K

$$n_i = BT^{3/2}e^{\frac{-E_g}{2kT}}$$

$$n_i = (5.32 \times 10^{15})(300)^{3/2}e^{\left(\frac{-1.1}{2(86\times10^{-6})(300)}\right)}$$

$$n_i = 1.5 \times 10^{10} cm^{-3}$$

Sol2:

T=300 K

$$n_i = BT^{3/2}e^{\frac{-E_g}{2kT}}$$

$$n_i = (2.1 \times 10^{14})(300)^{3/2}e^{\left(\frac{-1.4}{2(86\times10^{-6})(300)}\right)}$$

$$n_i = 1.8 \times 10^{6} cm^{-3}$$

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Material	Eg (eV)	B ($cm^{-3} K^{-3/2}$)
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Germanium (Ge)	0.66	1.66×10^{15}

$$k = 86 \times 10^{-6}\ eV/K$$

Semiconductor Materials and Properties

Q3: Calculate the thermal equilibrium electron and hole concentrations.

N_d

V

(a) Consider silicon at T = 300 K doped with phosphorus at a concentration of $10^{16}\ cm^{-3}$.

III

(b) Consider silicon at T = 300 K doped with boron at a concentration of $5 \times 10^{16}\ cm^{-3}$.

N_a

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Silicon (Si)	1.1	5.23×10^{15}
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Germanium (Ge)	0.66	1.66×10^{15}

$k = 86 \times 10^{-6}\ eV/K$

a $T = 300\,K$ $N_d = 10^{16}\,cm^{-3}$

$$\therefore\ n \simeq N_d = 10^{16}\,cm^{-3}$$

حسبناها من المسئلة السابقة Q 1

$$p = \frac{n_i^2}{N_d} = \frac{(1.5 * 10^{10})^2}{10^{16}}$$

$$\boxed{p = 2.25 * 10^{4}\,cm^{-3}}$$

b $N_a = 5 * 10^{16}\,cm^{-3}$

$$p \simeq N_a = 5 * 10^{16}\,cm^{-3}$$

$$n = \frac{n_i^2}{N_a} = \frac{(1.5 * 10^{10})^2}{5 * 10^{16}} = 4.5 * 10^{3}\,cm^{-3}$$

Semiconductor Materials and Properties

Sol: (a) T= 300 K and $N_d = 10^{16}\ cm^{-3}$

$$n \approx N_d = 10^{16}\ cm^{-3}$$

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

(b) T= 300 K and $N_a = 5 \times 10^{16} cm^{-3}$

$$p \approx N_a = 5 \times 10^{16} cm^{-3}$$

$$n = \frac{n_i^2}{N_a} = \frac{(1.5 \times 10^{10})^2}{5 \times 10^{16}} = 4.5 \times 10^3 cm^{-3}$$

Semiconductor Materials and Properties

Q4: Calculate the drift current density for a silicon at T = 300 K doped with arsenic atoms at a concentration of $8 \times 10^{15}\ cm^{-3}$. Assume electron and hole mobility values are $1350\ {cm^2}/{V.s}$ and $480\ {cm^2}/{V.s}$. Assume the applied electric field is 100 V/cm.

N_d E μ_n μ_p

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$$J = E\sigma$$

$$\sigma = q(p\mu_p + n\mu_n)$$

$\because \quad n \simeq N_d = 8 * 10^{15}\, cm^{-3}$

$$P = \frac{n_i^2}{N_d} = \frac{(1.5 * 10^{10})^2}{8 * 10^{15}} = 2.81 * 10^{4}\, cm^{-3}$$

$$J = E\,\sigma$$

$$\sigma = q\,(p\,\mu_p + n\,\mu_n)$$

$$= 1.68 * 10^{-19}\left((2.81 * 10^{4}) * 480 + (8 * 10^{15})\, 1350\right)$$

$$\sigma = 1.81\,(\Omega \cdot cm)^{-1}$$

$$J = 100 * 1.81 = 181\, A/cm^2$$

Semiconductor Materials and Properties

Sol: T=300 K, $N_d = 8 \times 10^{15} cm^{-3}$

$\mu_n = 1350\ {}^{cm^2}/_{V.s}$, $\mu_p = 480\ {}^{cm^2}/_{V.s}$, and E= 100 V/cm

$$n \approx N_d = 8 \times 10^{15} cm^{-3}$$

$$p = \frac{n_i^2}{N_d} = \frac{(1.5 \times 10^{10})^2}{8 \times 10^{15}} = 2.81 \times 10^4 cm^{-3}$$

$J = E\sigma$ **OR** $J = {}^{E}/_{\rho}$

$$\sigma = q(p\mu_p + n\mu_n)$$

$$\sigma = 1.68 \times 10^{-19}\left((2.81 \times 10^4)480 + (8 \times 10^{15})1350\right)$$

$$= 1.68 \times 10^{-19}(13.488 \times 10^6 + 10.8 \times 10^{18})$$

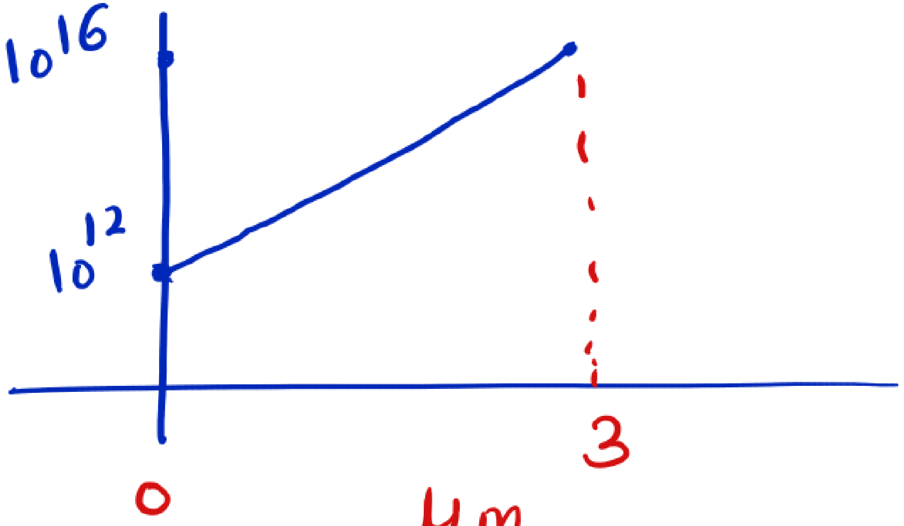
$$= 1.81(\Omega.cm)^{-1}$$

$$J = 100 \times 1.81 = 181\ {}^{A}/_{cm^2}$$

Semiconductor Materials and Properties

Q5: Calculate the diffusion current density for silicon at T = 300 K. Assume the electron concentration varies linearly from $10^{12}\ cm^{-3}$ to $10^{16}\ cm^{-3}$ over the distance from 0 to 3 μm. Assume electron diffusion constant is $35\ {cm^2}/{s}$.

D_n



μm

10^{-4}

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Diffusion

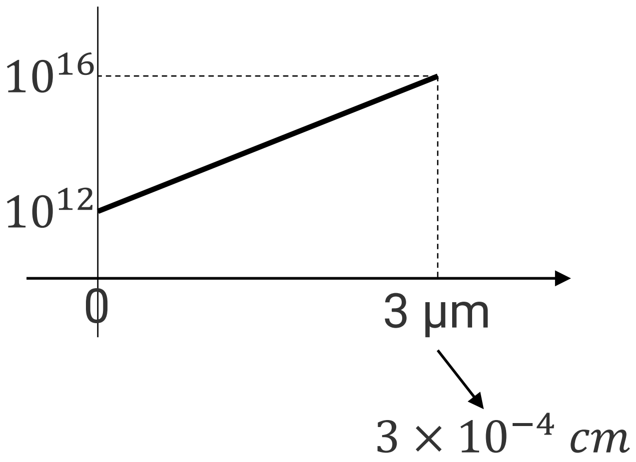
$$J_n = q D_n \frac{dn(x)}{dx}$$

$$J_n = (1.68 * 10^{-19}) \cdot 35 \cdot \frac{(10^{16} - 10^{12})}{(3 * 10^{-4} - 0)}$$

$$J_n = 196 \ A/cm^2$$

Semiconductor Materials and Properties

Sol:



T = 300 K and $D_n = 35\ {}^{cm^2}/_{s}$

$$J_n = qD_n \frac{dn(x)}{dx}$$

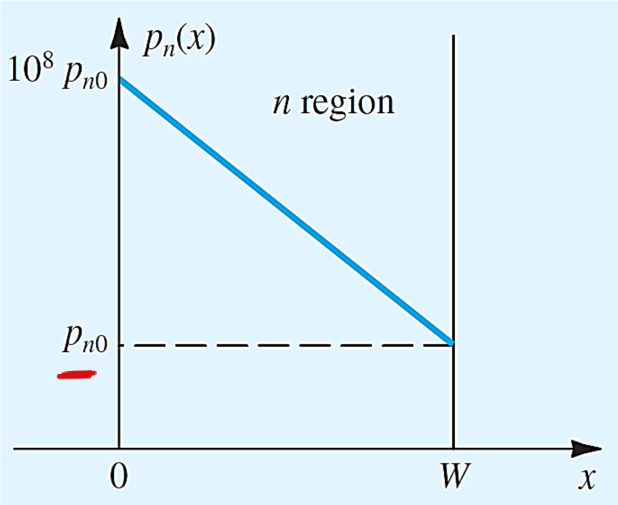
$$J_n = (1.68 \times 10^{-19})35 \frac{(10^{16} - 10^{12})}{(3 \times 10^{-4} - 0)}$$

$$J_n = 196\ {}^{A}/_{cm^2}$$

Semiconductor Materials and Properties

Q6: Holes are being steadily injected into a region of n-type silicon. $N_D = 10^{16}\ cm^{-3}$, $n_i = 1.5 \times 10^{10}\ cm^{-3}$, $D_p = 12\ {}^{cm^2}/_{s}$, and W = 50 nm find the density of the current that will flow in the x direction.

10^{-7} cm



$\because$ n-Type

$$n = N_d = 10^{16}\ cm^{-3}$$

$$\therefore p_{no} = \frac{n_i^2}{N_d} = \frac{(1.5*10^{10})^2}{10^{16}} = 2.25*10^4\ cm^{-3}$$

$$J_p = -q D_p \frac{dp(x)}{dx}$$

$$\therefore J_p = -(1.68*10^{-19}) . 12(-4.5*10^{17})$$

$$= 0.907 (A/cm^2)$$

$\because J_p$ positive

the Flow in the

X Direction

$$\frac{dp(x)}{dx} = \frac{\overset{p_{no}}{2.25*10^4} - \overset{10^8 p_{no}}{10^8 * 2.25*10^4}}{\underset{50*10^{-7}}{W} - 0}$$

$$= -4.5 * 10^{17}$$

Semiconductor Materials and Properties

Sol:
$N_D = 10^{16}\ cm^{-3}$, $n_i = 1.5 \times 10^{10}\ cm^{-3}$, $D_p = 12\ {}^{cm^2}/_{s}$, and W = 50 nm

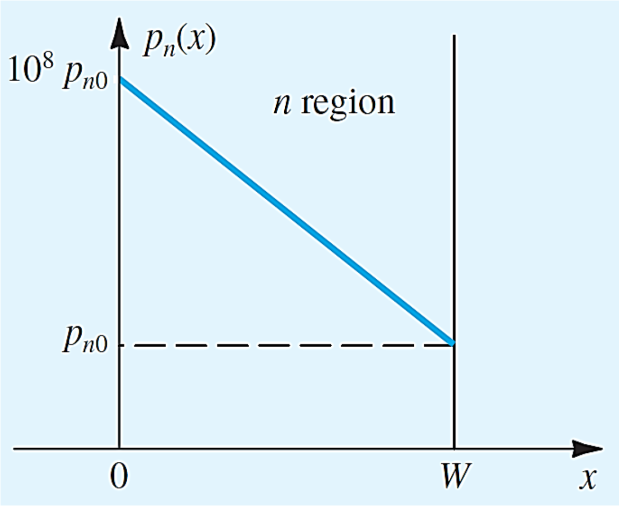
$$n \approx N_d = 10^{16}\ cm^{-3}$$

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

$$J_p = -qD_p \frac{dp(x)}{dx}$$

$$J_p = -(1.68 \times 10^{-19})12(-4.5 \times 10^{17})$$

$$J_p = 0.907\ \left({}^{A}/_{cm^2}\right)$$



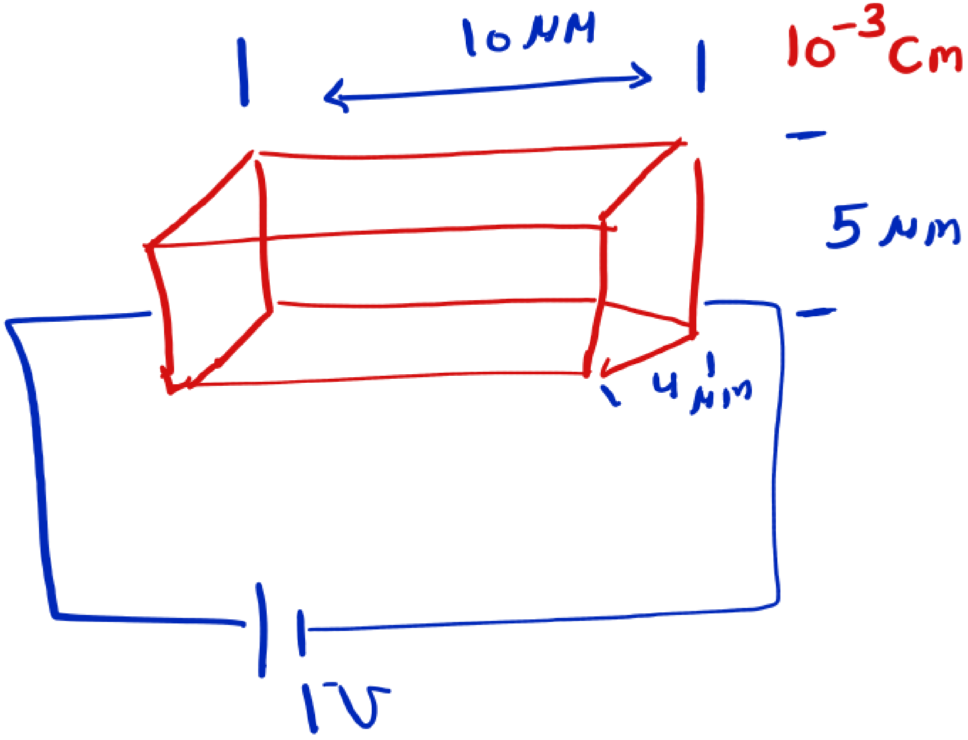
$$\frac{dp(x)}{dx} = \frac{(2.25 \times 10^4 - 10^8 \times 2.25 \times 10^4}{(50 \times 10^{-7} - 0)}$$

$$\frac{dp(x)}{dx} = -4.5 \times 10^{17}$$

Since J_p is positive, the current flows in the x direction

Semiconductor Materials and Properties

Q7: Find the current that flows in a silicon bar of 10 μm length having a 5 μm * 4 μm cross-section and having free-electron and hole densities of $10^4\ cm^{-3}$ and $10^{16}\ cm^{-3}$ respectively, when a 1 V is applied end-to-end. Use electron mobility value of $1350\ ^{cm^2}/_{V.s}$ and hole mobility value of $480\ ^{cm^2}/_{V.s}$.



$n = 10^4\ cm^{-3}$

$p = 10^{16}\ cm^{-3}$

$E = \frac{V}{L} = \frac{1}{1 \times 10^{-3}\ cm} = 1000$

$\mu_n = 1350$

$\mu_p = 480$

$\because \quad J = \dfrac{I}{A}$

$E = \dfrac{V}{L}$

$E = \dfrac{1}{1 * 10^{-3}}$

$E = 1000$

$I = A \cdot J$

$I = A \cdot Eq\,(p\,\mu_p + n\,\mu_n)$

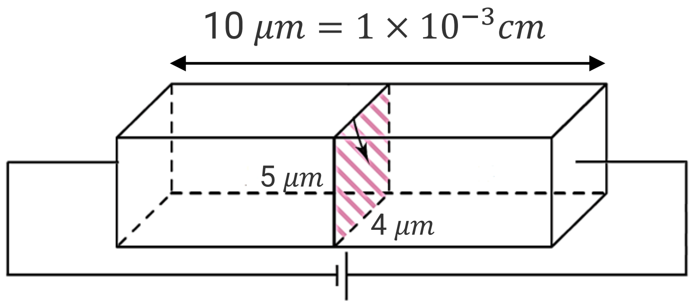
$I = (5 * 10^{-4} * 4 * 10^{-4}) \cdot (1000)\,(10^{16} * 480) + (10^{4} * 1350)$

$\boxed{I = 161\ \mu A}$

Semiconductor Materials and Properties

Sol:

$$J = Eq(p\mu_p + n\mu_n) \rightarrow I = AEq(p\mu_p + n\mu_n)$$



$$A = 5\ \mu m \times 4\ \mu m = 5 \times 10^{-4} \times 4 \times 10^{-4} = 2 \times 10^{-7} cm^2$$

$$E = \frac{V}{l} = \frac{1}{1 \times 10^{-3}} = 1000\ \text{V/cm}$$

$$I = (2 \times 10^{-7})(1000)(1.68 \times 10^{-19})\left((10^{16} \times 480) + (10^4 \times 1350)\right)$$

$$I = 161\ \mu A$$

Semiconductor Materials and Properties

N_d

Q8: In a phosphorus-doped silicon layer with impurity concentration of $10^{16}\ cm^{-3}$, find the hole and electron concentrations at 27°C

$T = 27^{\circ}C = 27 + 273 = 300\ K$

للتحويل من C° ل K° هنجمع على 273

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$$N_d = 10^{16}\ cm^{-3}$$

$$n = N_d = 10^{16}\ cm^{-3}$$

$$\therefore\ p = \frac{n_i^2}{N_d} = \frac{(1.5 * 10^{10})^2}{10^{16}}$$

$$p = 2.25 * 10^{4}\ cm^{-3}$$

Semiconductor Materials and Properties

Sol:

T= 27°C = 27+273= 300 K

$$N_d = 10^{16}\ cm^{-3}$$

$$n \approx\ N_d = 10^{16}\ cm^{-3}$$

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