NE 205: Semiconductor Devices and IC Technology

Homework I
Name : Gaurav Somani
SR. No. -16082

1)

$$p = N_v \, e^{\left(\frac{-(E_F - E_V)}{KT}\right)}$$

$$\cancel{N_D^+ =} \qquad N_A^- = \frac{N_A}{1 + 4\, e^{\left(\frac{E_A - E_F}{KT}\right)}}$$

$$p = N_A^- \Rightarrow N_v \exp\left(-\frac{(E_F - E_v)}{KT}\right) = \frac{N_A}{1 + 4\exp\left(\frac{E_A - E_F}{KT}\right)}$$

$$\Rightarrow 4\exp\left(\frac{E_A + E_v - 2E_F}{KT}\right) + \exp\left(-\frac{(E_F - E_v)}{KT}\right) = \frac{N_A}{N_v}$$

$$\Rightarrow 4\exp\left(\frac{E_A - E_v}{KT} - 2\frac{(E_F - E_v)}{KT}\right) + \exp\left(-\frac{(E_F - E_v)}{KT}\right) = \frac{N_A}{N_v}$$

Let $x = \exp\left(-\frac{(E_F - E_v)}{KT}\right)$

$$\Rightarrow 4\exp\left(\frac{E_A - E_v}{KT}\right) x^2 + x - \frac{N_A}{N_v} = 0 \quad - (1)$$

Solving (1),

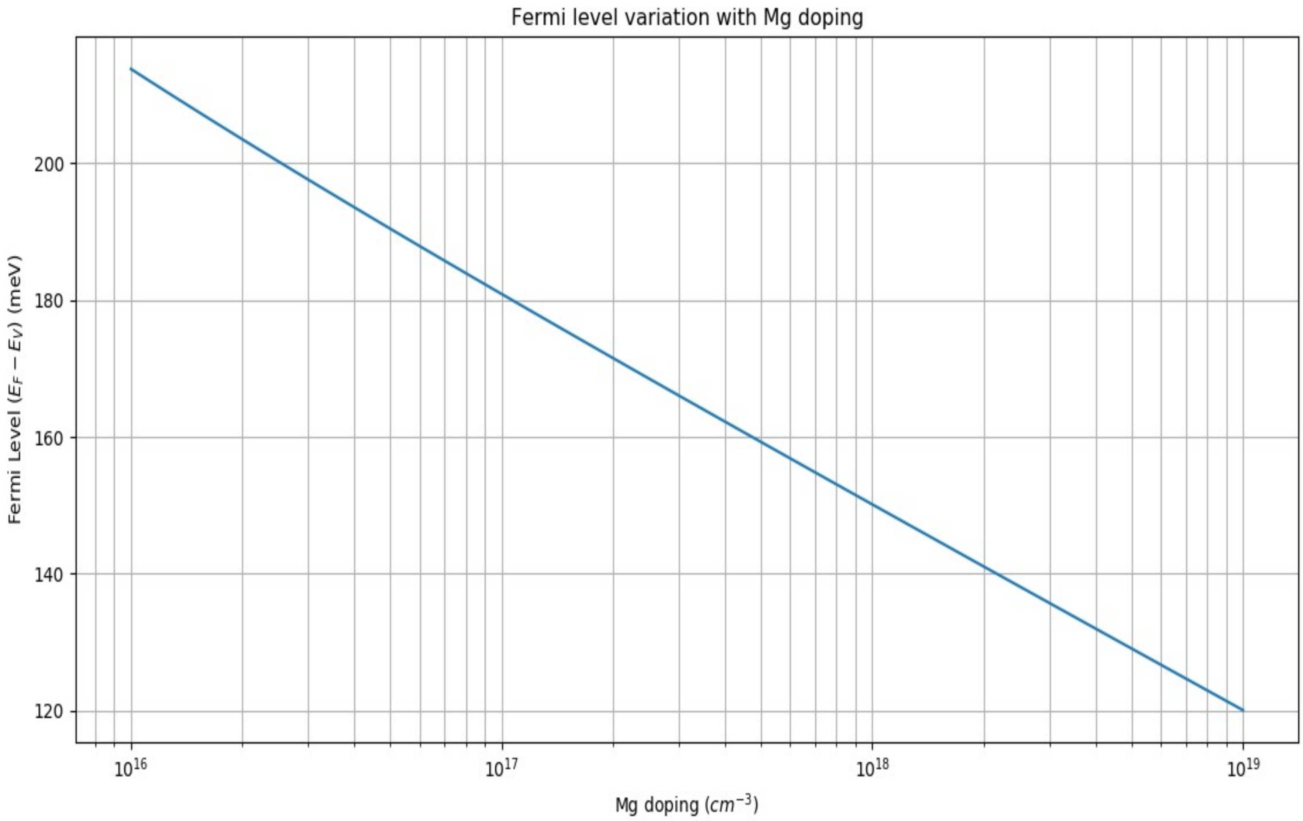
$$x = \frac{\sqrt{\frac{N_A}{N_v}\left(16\exp\left(\frac{E_A - E_v}{KT}\right)\right) + 1} - 1}{8\exp\left(\frac{E_A - E_v}{KT}\right)} \quad - (2)$$

$$\ln x = -\frac{(E_F - E_v)}{KT} \Rightarrow E_F - E_v = -KT \ln x$$

From (2), $$\boxed{E_F - E_v = -KT \ln\left(\frac{\sqrt{\frac{N_A}{N_v}\left(16\exp\left(\frac{E_A - E_v}{KT}\right)\right) + 1} - 1}{8\exp\left(\frac{E_A - E_v}{KT}\right)}\right)}$$

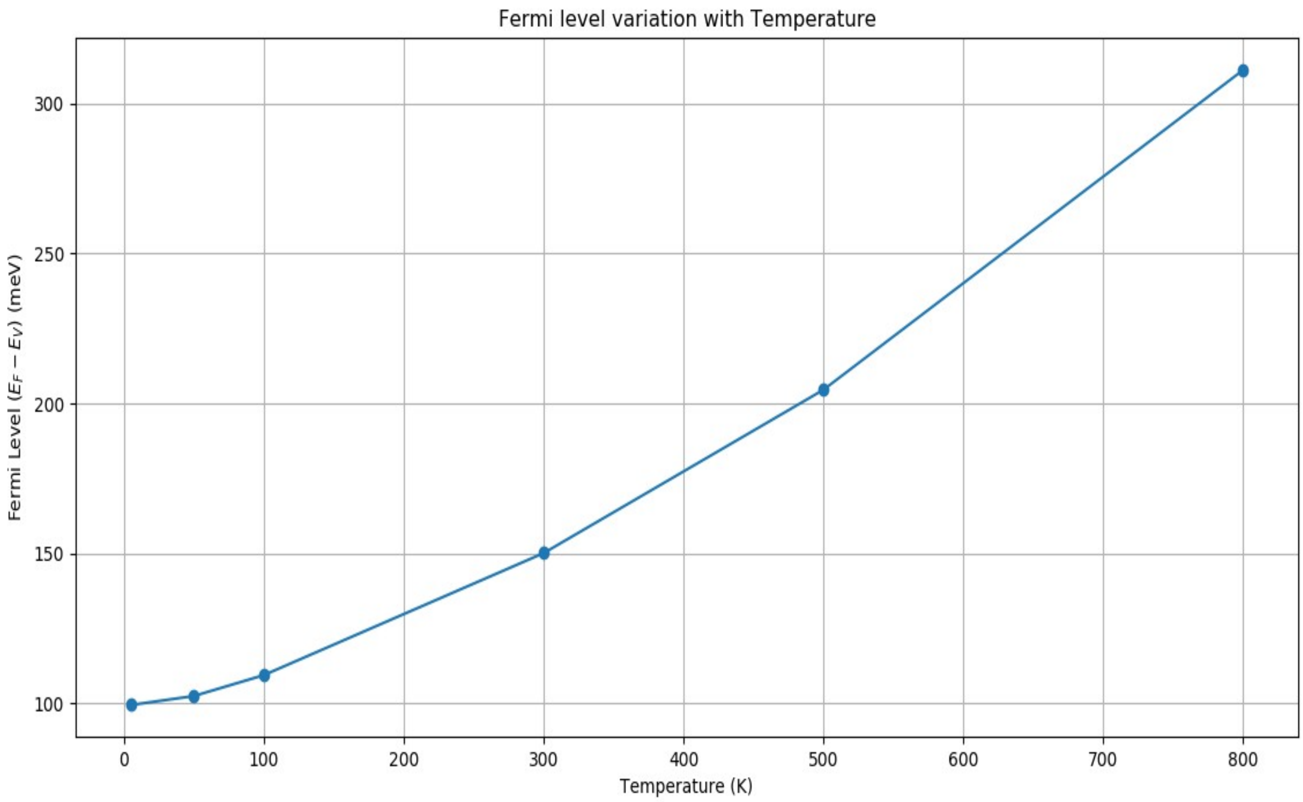
$$N_v = 2\left(\frac{2\pi m_h KT}{h^2}\right)^{3/2} ; \quad E_A - E_v = 200\ meV$$

Using T=300 K, $E_F - E_V$ is calculated.



2)
Using $N_D = 10^{18}$ cm^{-3}, $\mathbf{E_F - E_V}$ is calculated.

Temperature (K)	**Fermi Level ($E_F - E_V$) (meV)**
5 K	100 meV
50 K	102 meV
100 K	109 meV
300 K	150 meV
500 K	205 meV
800 K	311 meV



Fermi level variation with Temperature
Fermi Level ($E_F - E_V$) (meV)
Temperature (K)
100
150
200
250
300
0
100
200
300
400
500
600
700
800

3)

3 a)

$$n_i = \sqrt{N_V N_C}\, e^{\frac{-E_g}{2KT}}$$

$$N_V = 2\left(\frac{2\pi m_h KT}{h^2}\right)^{3/2}$$

$$N_C = 2\left(\frac{2\pi m_e KT}{h^2}\right)^{3/2}$$

b)

$$N_D^+ = \frac{N_D}{1+2\exp\left(\frac{E_F-E_D}{KT}\right)} \; ; \; n = N_c \exp\left(-\frac{(E_c-E_F)}{KT}\right)$$

$$n \approx N_D^+ \; ; \quad \text{Let } x = \exp\left(-\frac{(E_c-E_F)}{KT}\right)$$

$$\Rightarrow n = N_c x \; ; \quad N_D^+ = \frac{N_D}{1+2x\exp\left(\frac{E_c-E_D}{KT}\right)}$$

$$\Rightarrow N_c x = \frac{N_D}{1+2x\exp\left(\frac{E_c-E_D}{KT}\right)}$$

$$\Rightarrow 2\exp\left(\frac{E_c-E_D}{KT}\right)x^2 + x - \frac{N_D}{N_c} = 0$$

$$\Rightarrow x = \frac{\sqrt{1+8\frac{N_D}{N_c}\exp\left(\frac{E_c-E_D}{KT}\right)}-1}{4\exp\left(\frac{E_c-E_D}{KT}\right)}$$

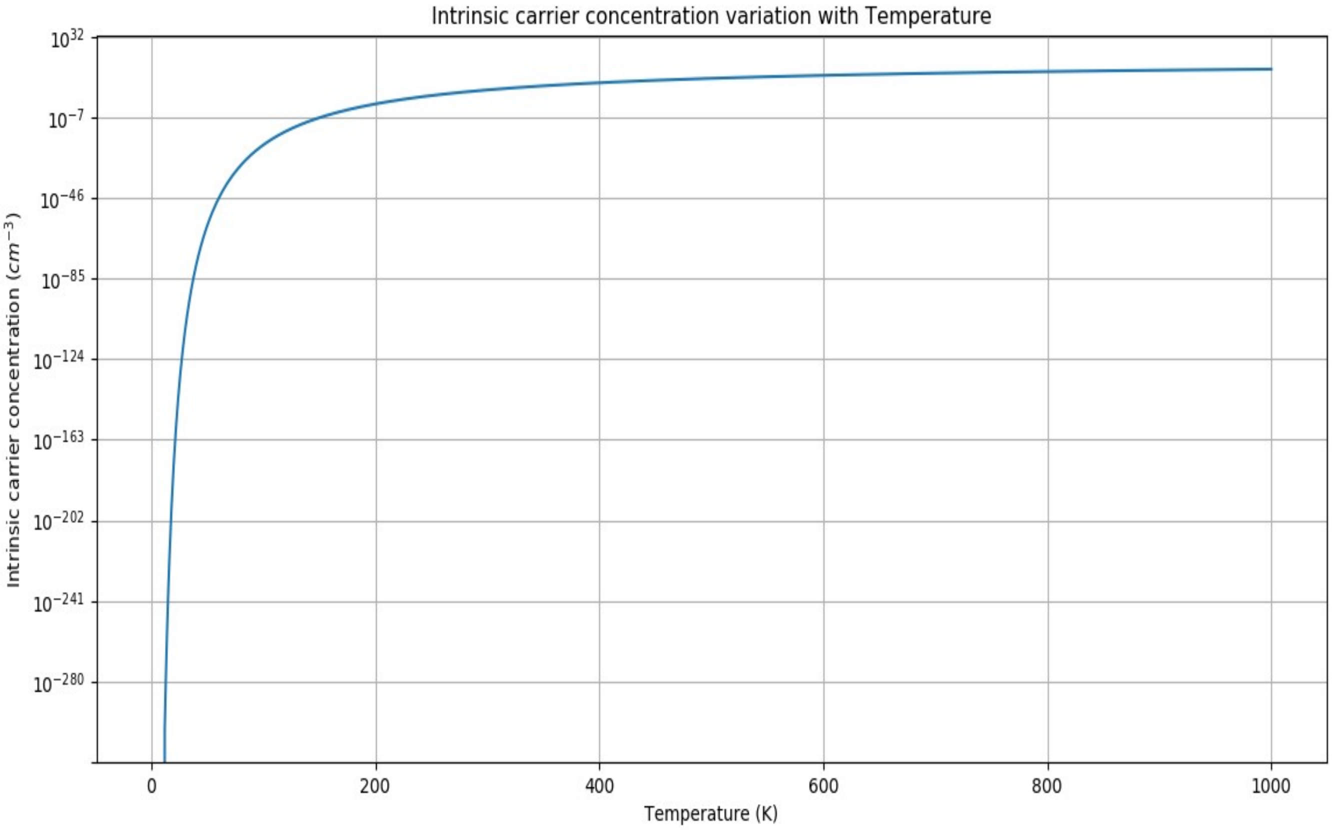
$$\Rightarrow n = N_c x \Rightarrow \boxed{n = \frac{N_c}{4\exp\left(\frac{E_c-E_D}{KT}\right)}\left(\sqrt{1+8\frac{N_D}{N_c}\exp\left(\frac{E_c-E_D}{KT}\right)}-1\right)}$$

a)

$m_h = 0.5\ m_0$; $m_e = 0.5\ m_0$ where m_0 is mass of electron in free space

$E_G(T) = 1.52 – 5.405 \times 10^{-4}\ T^2 /(T+ 204)$ (in eV, where T is in Kelvin)

Using these , n_i is calculated.



b)

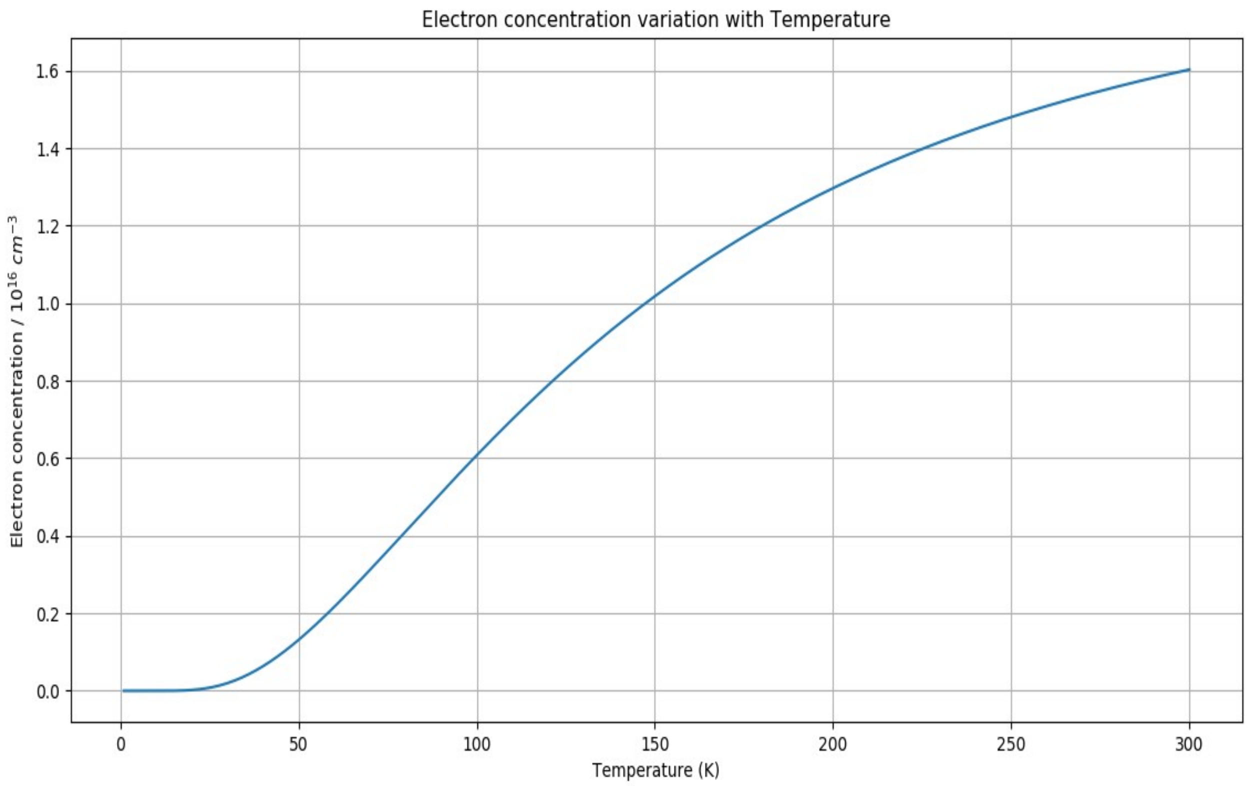
$E_C – E_D = 20$ meV ; $N_D = 2 \times 10^{16}$ cm -3

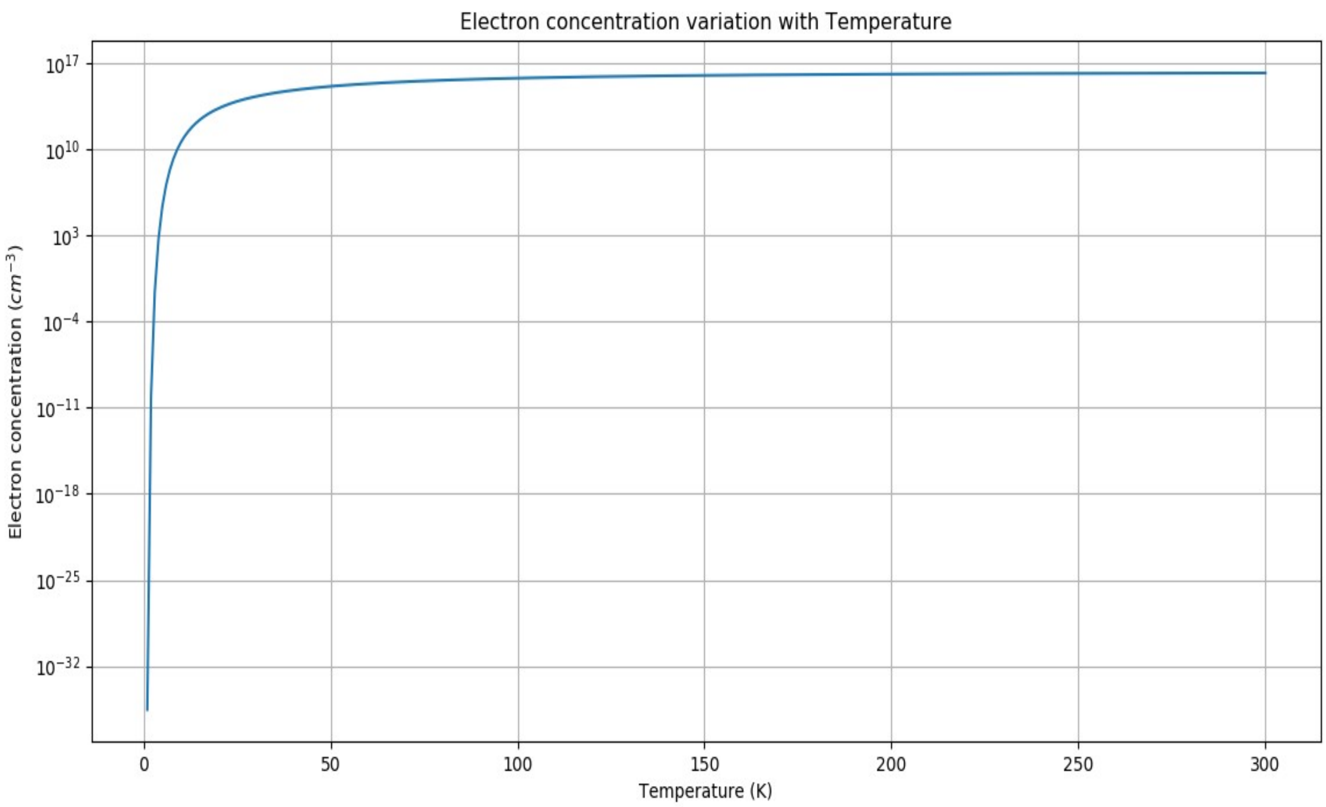
$m_h = 0.5\ m_0$; $m_e = 0.5\ m_0$ where m_0 is mass of electron in free space

Using these, free electron concentration is calculated.

Freeze-out starts at **53.6 K.**

Temperature (K)	**Electron concentration (cm^{-3})**
1 K	2.9×10^{-36}
5 K	2.0×10^{5}
10 K	3.8×10^{10}
20 K	2.1×10^{13}
30 K	2.0×10^{14}
40 K	6.3×10^{14}
50 K	1.3×10^{15}
300 K	1.6×10^{16}


Electron concentration variation with Temperature
Electron concentration / 10^{16} cm^{-3}
Temperature (K)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
0
50
100
150
200
250
300


Electron concentration variation with Temperature
Electron concentration (cm^{-3})
Temperature (K)
10^{17}
10^{10}
10^{3}
10^{-4}
10^{-11}
10^{-18}
10^{-25}
10^{-32}
0
50
100
150
200
250
300

4)

$a = 5\ A^0 = 5 \times 10^{-8}$ cm ; E = 1000 V/cm ; $q = 1.6 \times 10^{-19}$ C; $m_{eff} = 0.2\ m_0$

$m_0 = 9.1 \times 10^{-31}$ kg ; $h = 6.6 \times 10^{-34}$ J s

At Brillouin zone boundary, **$k = \pi / a$** .

Initially, k=0

$p = \hbar k$;

$dp / dt = F$; $F = q E$;

=> $\hbar\, dk/dt = q E$

=> $dk/dt = q E / \hbar$

=> **$k = q E t / \hbar$ { Since** $dk/dt = q E / \hbar$ is a constant }

At **$k = \pi / a$** ,

$\pi / a = q E t / \hbar$

=> $t = (\hbar \pi) / (a q E)$

=> **$t = 0.5\ h / (a q E)$**

=> $t = (0.5 \times 6.6 \times 10^{-34}) / (5 \times 10^{-8} \times 1.6 \times 10^{-19} \times 1000)$ s

=> **t = 41 ps (Time required to reach brillouin zone boundary)**

$v = p / m_{eff}$

=> $v = \hbar k / m_{eff}$

=> $v = \hbar \pi / (a\, m_{eff})$ { $k = \pi / a$ }

=> **$v = 0.5\ h / (a\, m_{eff})$**

=> **$v = 0.5\ h / (0.2 \times m_0 \times a)$**

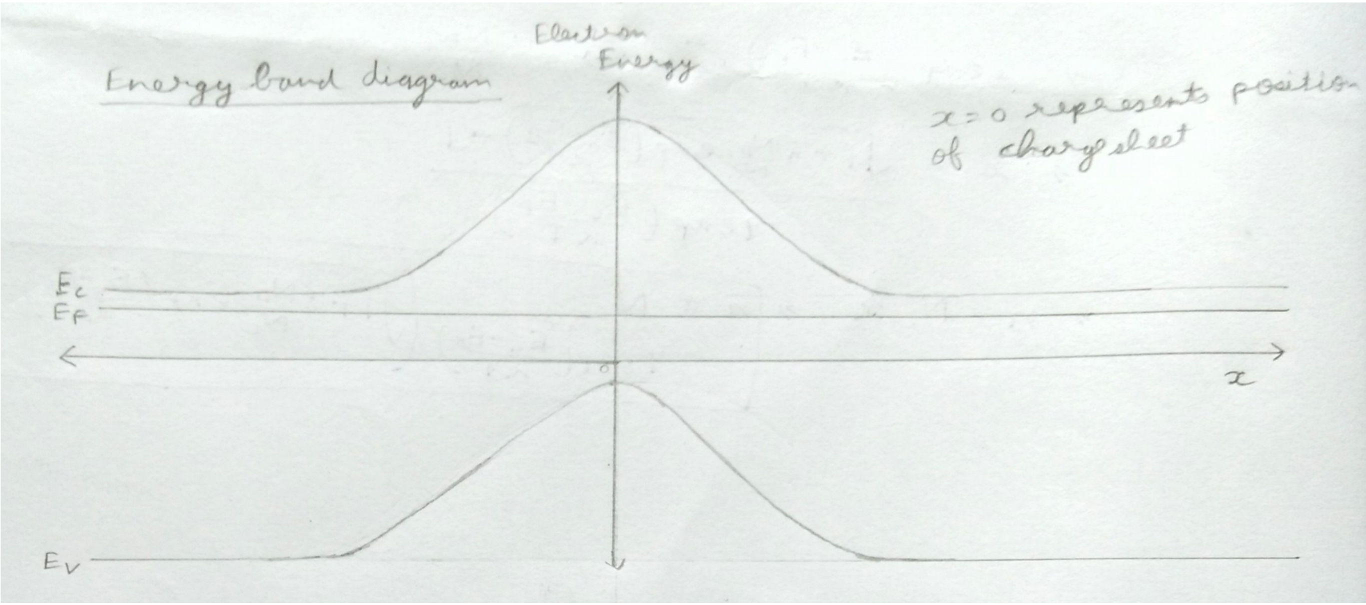
=> **$v = 2.5\ h / (m_0 a)$**

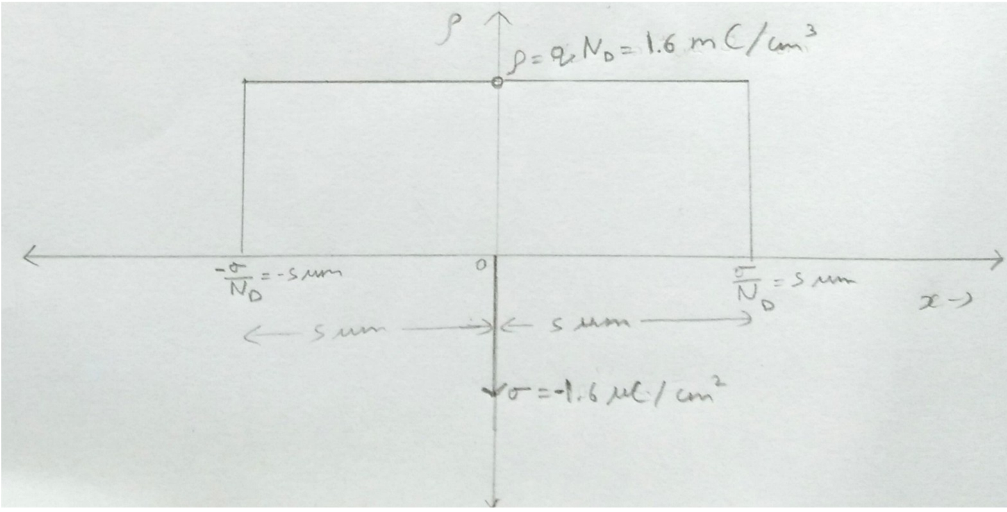
=> $v = (2.5 \times 6.6 \times 10^{-34}) / (5 \times 10^{-10} \times 9.1 \times 10^{-31})$

=> **$v = 3.6 \times 10^8$ cm / s (Velocity at brillouin zone boundary)**

5)

a)





b) Sheet of acceptor charge depletes the surrounding region because acceptor takes away the free electrons near it and gets ionised to form negative anions. So, the acceptor charge sheet becomes highly negatively charged sheet surrounded by positively charged depleted region formed due to free electrons taken acceptor atoms. It leaves only positively charged donor atoms in the surrounding. (This explains if semiconductor was already p-type doped , then no depletion would have occurred because of low number of electrons. Charge (Dopant sheet) introduced should be opposite to doping of bulk semiconductor for depletion to happen.)

Assuming full depletion (no charge carriers in depleted region) in nearby region,
by charge neutrality,

$q\, N_D\, w_{total} = q\, \sigma$

$\mathbf{w_{total} = (\sigma / N_D)}$

$\sigma = 10^{13}\ cm^{-2}$

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

$\mathbf{\Rightarrow w_{total} = 10^{-3}\ cm = 10\ um}$

Since material is infinitely long, it is symmetric on both sides of sheet, 5 um will be depleted on each side of acceptor sheet.

$\mathbf{W_{left} = W_{right} = 5\ um}$

c) Electric field due to charge sheet is given by

$|E| = \sigma_{charge} / (2\, \varepsilon_0\, \varepsilon_s)$

$\sigma_{charge} = q\, \sigma = 1.6 \times 10^{-19} \times 10^{13}\ C/cm^{-2} = 1.6 \times 10^{-6}\ cm^{-2} = 1.6 \times 10^{-2}\ m^{-2}$

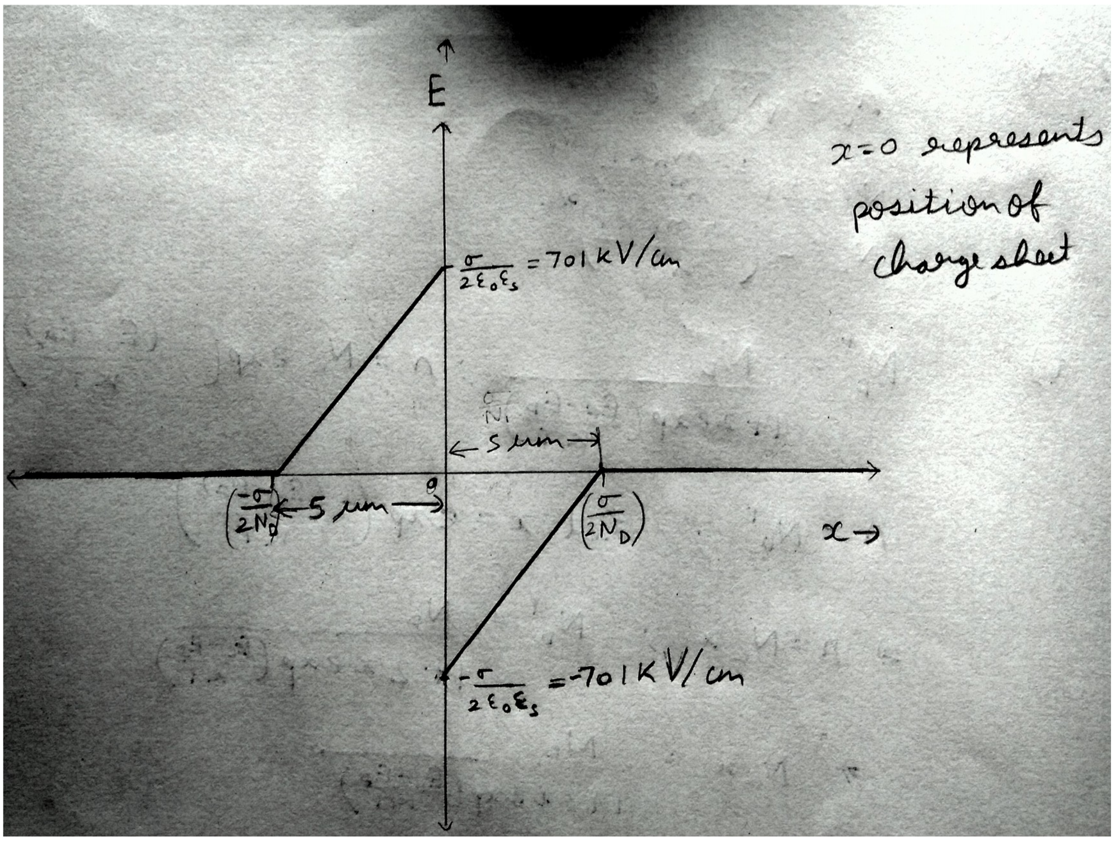
$\varepsilon_s = 12.9$

$\varepsilon_0 = 8.85 \times 10^{-12}\ C/(Vm)$

$|E| = 701\ kV/cm$

$\mathbf{E_{left} = |E|} = 701\ kV/cm$ **;** $\mathbf{E_{right} = -|E|} = -701\ kV/cm$

where positive electric field means it is pointing towards the right



E
$\frac{\sigma}{2\varepsilon_0\varepsilon_s} = 701$ kV/cm
x=0 represents position of charge sheet
5 µm
0
$\left(\frac{-\sigma}{2N_D}\right)$
5 µm
$\left(\frac{\sigma}{2N_D}\right)$
x →
$-\frac{\sigma}{2\varepsilon_0\varepsilon_s} = -701$ kV/cm