Q 1.

(a) $f(\varepsilon) = \dfrac{1}{1 + e^{(\varepsilon - \varepsilon_f)/kT}}$ – at equilibrium

when $\varepsilon = \varepsilon_f$

$$f(\varepsilon) = \frac{1}{1 + e^{0}} = \frac{1}{2}$$

Probability for an electron to occupy a state located at fermi level is 50%.

b) $\varepsilon_f = \varepsilon_c$

$f(\varepsilon)$ at $\varepsilon_c + kT$

$$= \frac{1}{1 + e^{(\varepsilon_c + kT - \varepsilon_c)/kT}}$$

$$= \frac{1}{1 + e^{kT/kT}} = \frac{1}{1+e}$$

$$= 0.2689 \approx 27\%$$

c) ~~$\varepsilon(\varepsilon_f)$~~

$$f(\varepsilon_1) = 1 - f(\varepsilon_2)$$

$$\frac{1}{1+e^{(\varepsilon_c+kT-\varepsilon_f)kT}} = 1 - \frac{1}{1+e^{(\varepsilon_c+3kT-\varepsilon_f)}}$$

$$= \frac{1+e^{(\varepsilon_c+3kT-\varepsilon_f)/kT}}{1+e^{(\varepsilon_c+kT-\varepsilon_f)/kT}} = \frac{\cancel{1+}e^{(\varepsilon_c+3kT-\varepsilon_f)/kT}}{}$$

$$1 = e^{(\varepsilon_c+3kT-\varepsilon_f)/kT} + e^{(\varepsilon_c+3kT-\varepsilon_f)/kT} \cdot e^{(\varepsilon_c+kT-\varepsilon_f)/kT}$$

$$1 = e^{(\varepsilon_c+3kT-\varepsilon_f)/kT} + e^{(\varepsilon_c+4kT-2\varepsilon_f)/kT}$$

$$\boxed{\varepsilon_f = \varepsilon_c + 2kT}$$

Q2

a) $f(\varepsilon) = \dfrac{1}{1 + e^{(\varepsilon - \varepsilon_f)/kT}}$

if $\varepsilon = \varepsilon_f$

$= \dfrac{1}{1 + e^{(\varepsilon_f - \varepsilon_f)/kT}}$

$= \dfrac{1}{1+e^0} = \dfrac{1}{2}$

$\boxed{50\%}$

b) $f(\varepsilon_c) = \dfrac{1}{1 + e^{(\varepsilon_c - \varepsilon_f)/kT}}$

$\downarrow$

for finding an electron at ε_c

$$1 - f(\varepsilon_v) = 1 - \frac{1}{1+e^{(\varepsilon_v - \varepsilon_f)/kT}}$$

$$= \frac{e^{(\varepsilon_v - \varepsilon_f)/kT}}{1 + e^{(\varepsilon_v - \varepsilon_f)/kT}} \quad (i)$$

We know that

$$f(\varepsilon_c) = 1 - f(\varepsilon_v)$$

$$= \frac{1}{1 + e^{(\varepsilon_c - \varepsilon_f)/kT}} = \frac{e^{(\varepsilon_v - \varepsilon_f)/kT}}{1 + e^{(\varepsilon_v - \varepsilon_f)/kT}}$$

$$1 = e^{(\varepsilon_v - \varepsilon_f)/kT} \cdot \left[1 + e^{(\varepsilon_c - \varepsilon_f)/kT}\right]$$

$$1 = e^{(\varepsilon_v - \varepsilon_f)/kT} + e^{(\varepsilon_c + \varepsilon_v - 2\varepsilon_f)/kT}$$

using (i), can be written as.

$$\frac{1}{1 + e^{-(\varepsilon_v - \varepsilon_f)/kT}}$$

so it becomes.

$$\frac{1}{1 + e^{(\varepsilon_c - \varepsilon_f)/kT}} = \frac{1}{1 + e^{-(\varepsilon_v - \varepsilon_f)/kT)}}$$

$$\frac{\varepsilon_c - \varepsilon_f}{\cancel{kT}} = \frac{-(\varepsilon_v - \varepsilon_f)}{\cancel{kT}}$$

$$\boxed{\varepsilon_f = \frac{\varepsilon_c + \varepsilon_v}{2}}$$

Q3)

$$\varepsilon = \varepsilon_f + \Delta\varepsilon$$

$$f(\varepsilon) = \frac{1}{1 + e^{(\varepsilon_f + \Delta\varepsilon - \varepsilon_f)KT}}$$

$$= \frac{1}{1 + e^{\Delta\varepsilon/KT}} \quad i$$

$$1 - f(\varepsilon) = \frac{e^{(\varepsilon - \varepsilon_f)/KT}}{1 + e^{(\varepsilon - \varepsilon_f)/KT}}$$

$$\frac{e^{-\Delta\varepsilon/KT}}{1 + e^{-\Delta\varepsilon/KT}} \quad ii$$

multiplying ii by $e^{\Delta\varepsilon/KT}$
on numerator & denominator

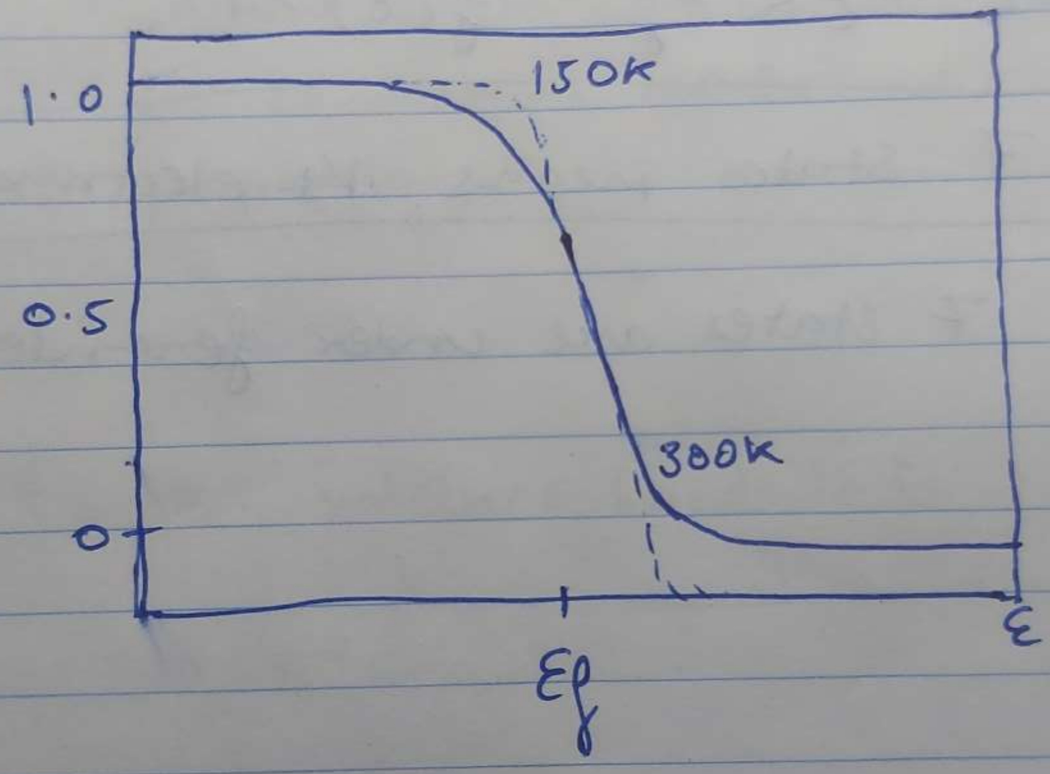
$$= \frac{1}{1 + e^{\Delta\varepsilon/KT}} \quad iii$$

from i & iii, we can say.

$$\boxed{f(E_f+\Delta\varepsilon) = 1 - f(\varepsilon_f - \Delta\varepsilon)}$$

Q4)

a)



b) At 0°K Temperature.

$f(\mathcal{E})$ = probability.

for $\mathcal{E} > \mathcal{E}_f$ $\quad f(\mathcal{E}) = 0$

for $\mathcal{E} < \mathcal{E}_f$ $\quad f(\mathcal{E}) = 1$

$\boxed{\text{7 states means 14 electrons}}$

Since 7 states are under fermi leve

Q5) $n(\mathcal{E}) = f\cdot(\mathcal{E}) \cdot D_c(\mathcal{E})$

for Conduction band.

= using boltzman approximation.

$f(\mathcal{E}) \approx e^{-(\mathcal{E}-\mathcal{E}_f)/kT}$

We know that carrier distribution for conduction band is directly proportional to

$\sqrt{\mathcal{E}-\mathcal{E}_c}$;

& for valence band it is

$\sqrt{\mathcal{E}_v-\mathcal{E}}$

& we know that carrier distribution is $\propto f(\mathcal{E}) \cdot \sqrt{\mathcal{E}-\mathcal{E}_c}$

using $D_c(\mathcal{E})$ & $D_v(\mathcal{E})$ derivations.

so we can say.

$$n(\varepsilon) = k \cdot \sqrt{\varepsilon - \varepsilon_c} \cdot e^{-(\varepsilon - \varepsilon_f)/kT}$$

(k is a constant)

so for it's maxima, we take derivative w.r.t ε.

$$\frac{d}{dE}\left(k \cdot \sqrt{\varepsilon - \varepsilon_c} \cdot e^{-(\varepsilon - \varepsilon_f)/kT}\right)$$

$$= k\left[\frac{1}{2\sqrt{\varepsilon - \varepsilon_c}} e^{-(\varepsilon - \varepsilon_F)/kT} - \frac{\sqrt{\varepsilon - \varepsilon_c}}{kT} \cdot e^{-(\varepsilon - \varepsilon_f)/kT}\right]$$

using product rule. & equating to zero.

$$\frac{1}{2\sqrt{\varepsilon - \varepsilon_c}} = \frac{\sqrt{\varepsilon - \varepsilon_c}}{kT}$$

$$\boxed{\varepsilon = \varepsilon_c + \frac{kT}{2}}$$

similarly for valence band.

$$p(\varepsilon) = D_v(\varepsilon) \cdot (1 - f(\varepsilon))$$

$$\frac{d}{dE} = x\left[\frac{-1}{2\sqrt{\varepsilon_v - \varepsilon}} e^{-(\varepsilon_f - \varepsilon)/kT} + \sqrt{\varepsilon_v - \varepsilon}\,\frac{1}{kT} e^{-(\varepsilon_f - \varepsilon)/kT}\right]$$

(x is a constant)

equating $\frac{d(p(\varepsilon))}{d\varepsilon} = 0$

we get,

$$\frac{-1}{2\sqrt{\varepsilon_v - \varepsilon}} + \frac{\sqrt{\varepsilon_v - \varepsilon}}{kT} = 0$$

we get

$$\boxed{\varepsilon = \varepsilon_v - \frac{kT}{2}}$$

4 b) a)

for a given T

$$n \cdot p = (n_i)^2$$

at 300 k

$$n_{i(Si)} = 1.5 \times 10^{10} \text{ cm}^{-3}$$

$$p = \frac{(1.5 \times 10^{10})^2}{10^5}$$

$$\boxed{p = 2.25 \times 10^{15} \text{ cm}^{-3}}$$

b) As $N_d - N_a >> n_i$

here

$$n \approx N_d - N_a$$

electron concentration is approx equal to $N_d - N_a$.

So, $p = \frac{(n_i)^2}{n} = \frac{n_i^2}{N_d - N_a}$

c)

$$\varepsilon_f - \varepsilon_i = 0.26 eV$$

Sample is n-type

~~assuming ε_i is located at midpoint~~

$$n = n_i e^{(\varepsilon_f - \varepsilon_i)/kT}$$

$$= \boxed{2.2 \times 10^{14} \text{ cm}^{-3}}$$

$$p = \frac{n_i^2}{n} = \boxed{4.55 \times 10^{5} \text{ cm}^{-3}}$$

d)

Calculate 'new' n_i for $T = 800K$

$$n_i = \sqrt{N_c(800K) N_v(800K) \cdot e^{-(E_g/2KT)}}$$

$$= \boxed{2.56 \times 10^{16} \text{ cm}^{-3}}$$

Here at such high temperature, the semiconductor becomes intrinsic.

So $= \boxed{n_i \approx n \approx p \approx 2.56 \times 10^{16} \text{ cm}^{-3}}$

As intrinsic semiconductor.

E_F is at middle of bandgap

so $= \boxed{E_F = \frac{E_c - E_v}{2}}$

Q7)

we know $\frac{n_i^2}{p} = n = 2p$

so

$$p = \frac{10^{13}}{\sqrt{2}} \approx 7.07 \times 10^{12}\ cm^{-3}$$

$$n = 2 \times p \approx 1.4 \times 10^{13}\ cm^{-3}$$

so at $N_a = 0$

$$\boxed{N_d \approx n \approx 1.4 \times 10^{13}\ cm^{-3}}$$

Q8)

a) Boron acts as an acceptor (gives holes)
So it's a P type Semiconductor.

~~XBD~~

b) At $T = 300K$

So Dopant Concentration > Intrinsic carrier density

$$p = N_a = 4 \times 10^{16}\ cm^{-3}$$
$$n = (n_i = 10^{10}\ cm^{-3})^2 / p$$
$$= 2.5 \times 10^{3}\ cm^{-3}.$$

At $T = 600K$

$$n_i = \sqrt{N_c(600)\, N_v(600)} \cdot e^{-(E_g)/KT}$$

$$= 1.16 \times 10^{15}\ cm^{-3}$$

Simplifying & substituting constants.

So now we have some intrinsic carrier concentration.

So,

$$p = N_a + n_i = (4 \times 10^{16} + 1.16 \times 10^{15})$$
$$= \boxed{4.12 \times 10^{16}\ cm^{-3}}$$

$$n = \frac{(n_i)^2}{p} = \boxed{3.27 \times 10^{13}\ cm^{-3}}$$

b) At $T = 300K$

So Dopant Concentration > Intrinsic carrier density

$$p = N_a = 4 \times 10^{16}\ cm^{-3}$$
$$n = (n_i = 10^{10}\ cm^{-3})^2 / p$$
$$= 2.5 \times 10^{3}\ cm^{-3}.$$

At $T = 600K$

$$n_i = \sqrt{N_c(600)\, N_v(600) \cdot e^{-(E_g)/kT}}$$

$$= 1.16 \times 10^{15}\ cm^{-3}$$

Simplifying & substituting constants.

So now we have some intrinsic carrier concentration.

So,

$$p = N_a + n_i = (4 \times 10^{16} + 1.16 \times 10^{15})$$
$$= \boxed{4.12 \times 10^{16}\ cm^{-3}}$$

$$n = \frac{(n_i)^2}{p} = \boxed{3.27 \times 10^{13}\ cm^{-3}}$$

c) At high temperatures, the number of intrinsic carriers increases due to more free electrons from silicon - silicon covalent bonds.

d) We have,

$$\mathcal{E}_f - \mathcal{E}_v = kT \ln\left[N_v(T)/P(T)\right]$$

$$= 0.34\,eV \quad \text{at } T = 600\,K$$

So, $\mathcal{E}_f$ is located at 0.34 from $\mathcal{E}_v$.

$$\mathcal{E}_f - \mathcal{E}_v = 0.34\ eV$$

Q9) we want,

a) $n_i = 10 N_d$

$$n_i = \sqrt{N_c(T) N_v(T)} \cdot e^{-(E_g)/2kT}$$

$$= 1.71 \times 10^{19} \left(\frac{T}{300K}\right)^{3/2} e^{-(E_g)/2kT}$$

Calculating N_c & N_v & iteratively solve for $n_i = 10 N_d$

for n-type we get $T \approx 778\ K$

for p-type, similarly

we get $T = 633\ K$

b) for n-type (arsenic)

$n \approx N_d = 10^{16}$

& $N_d >> n_i$ so = $p = \frac{n_i^2}{n}$

$= 2.1 \times 10^4\ cm^{-3}$

for p-type (boron)

$p \approx N_a$ $\quad n = \frac{n_i^2}{N_a} = 2.1 \times 10^5\ cm^{-3}$

b) $E_f - E_v = kT \ln \frac{N_v}{p} = \frac{1.04 \times 10^{19}}{2.1 \times 10^{4}}$

$$= \boxed{0.88\,eV}$$

for Boron (p-type)

$E_f - E_v = kT \ln \frac{N_v}{p} = \frac{1.04 \times 10^{19}}{10^{15}}$

$$= \boxed{0.24\,eV}$$

d) $n \approx N_d - N_a = 9 \times 10^{15}\,cm^{-3}$

$p = \frac{n_i^2}{n} = \frac{(10^{10})^2}{n} = 1.1 \times 10^{4}$

so $E_v - E_f = kT \ln \left(\frac{N_v}{p}\right)$

$= 0.026(eV) \ln \left(\frac{1.04 \times 10^{19}}{1.11 \times 10^{4}}\right) = 0.90\,eV$

Q10)

a) The mean free time betⁿ collisions is

$$\mu_n = \frac{q \tau_{mn}}{m_n}$$

$$\tau_{mn} = \frac{\mu_n m_n}{q} = 2.85 \times 10^{-13} \text{ sec}$$

b) drift velocity $V_d = \mu_n \mathcal{E} = 5 \times 10^4$ cm/sec

$$d = V_d \tau_{mn} = 0.14 \text{ nm.}$$

Q11) approx thermal velocity

$$V_{th} = \sqrt{\frac{3kT}{m}} = 2.29 \times 10^7 \text{ cm/sec}$$

$$V_d = \frac{V_{th}}{10} = 2.29 \times 10^6 \text{ cm/sec}$$

so 't' for distance of 1 µm

$$t = \frac{10^{-4} \text{ cm}}{2.29 \times 10^6 \text{ cm/sec}} = 4.37 \times 10^{-11} \text{ sec}$$

mean free time

$$\mu_n = \frac{q\tau_{mn}}{m_n} \longrightarrow \tau_{mn} = \frac{\mu_n m_n}{q}$$

$$\tau_{mn} = 2.1 \times 10^{-13} sec.$$

$$\frac{t}{\tau_{mn}} = 207.7 \text{ collision} \Longrightarrow \underline{\underline{207 \text{ collisions}}}$$

$$V_d = -\mu_n E \longrightarrow E = \frac{V_d}{\mu_n} = \frac{2.29 \times 10^6 \, cm/sec}{1400 \, cm^2/V sec}$$

$$E = 1635.71 \, Vcm^{-1}$$

so,

$$V = E \times \text{width} = 1635.71 \, Vcm^{-1} \times 10^{-4} cm$$

$$\boxed{V = 0.16V}$$

Q
12:) a) we know, σ for N-type doped with $1\times10^{16}\ cm^{-3}$ of phosphorous is $0.5\ \Omega$-cm.

b) $$\rho = \frac{1}{\sigma} = \frac{1}{qN_{net}\mu_p}$$

$$= \frac{1}{q\times 9\times10^{16}\,cm^{-3}\times 250\,cm^2/Vsec}$$

$$= 0.28\ \Omega\,cm$$

Here, acceptor density (Boron) is greater than doner density (phosphorous) so it's a '<u>p-type</u>' semiconductor.

c) $$\mathcal{E}_c - \mathcal{E}_f = KT\ln\left(\frac{N_c}{N_d}\right) =$$

$$0.026V\ln\left(\frac{2.8\times10^{19}\,cm^{-3}}{10^{16}\,cm^{-3}}\right) = 0.21eV$$

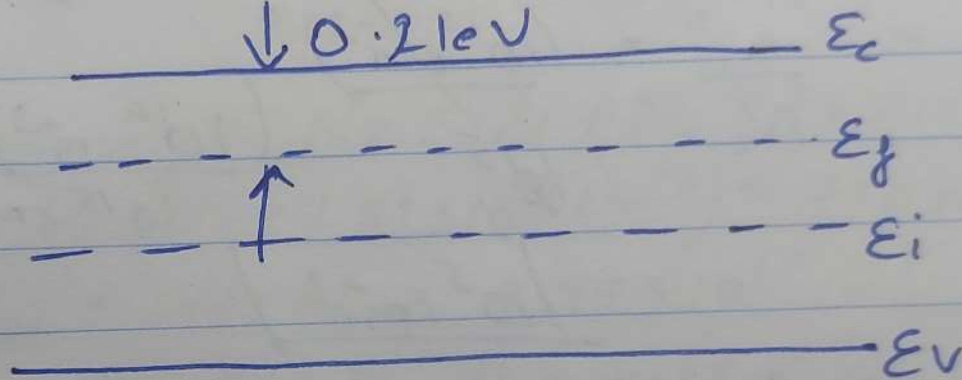
Ans for (a).

$$\mathcal{E}_f - \mathcal{E}_v = kT \ln\left(\frac{N_v}{N_{net}}\right)$$

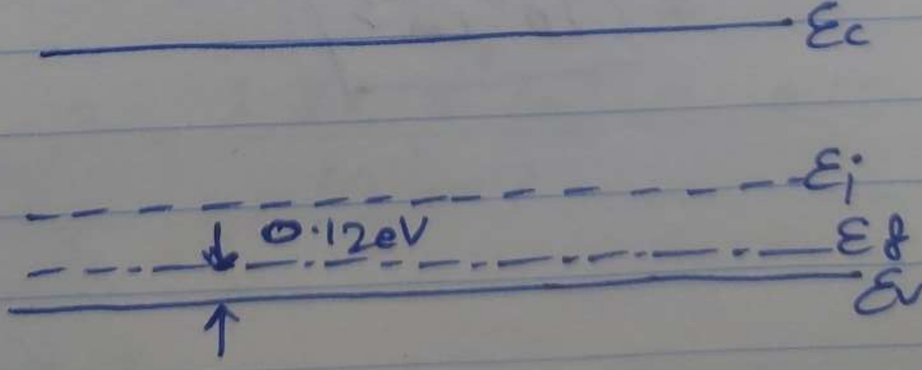
$$= 0.026V \ln\left(\frac{1.04\times 10^{19}\,cm^{-3}}{9\times 10^{16}\,cm^{-3}}\right)$$

$$= 0.12eV$$

(a)



(b)



(Sample 1)

Q 13) a) N-type, holes are minority carriers.

$$p = \frac{n_i^2}{N_d} = (10^{10}\,cm^{-3})^2 / 10^{17}\,cm^{-3}$$

$$= \boxed{10^2\,cm^{-3}}$$

Sample 2 – p-type, electrons are minority carriers.

$$n = \frac{n_i^2}{N_a} = \frac{(10^{10}\,\cancel{cm^{-3}})^2}{\cancel{10^{15}}} \quad \frac{(10^{10}\,cm^{-3})^2}{10^{15}\,cm^{-3}}$$

$$= \boxed{10^5\,cm^{-3}}$$

Sample 3, holes are minority carriers

$$p = \frac{n_i^2}{N_{net}} = (10^{10}\,cm^{-3})^2 / 9.9 \times 10^{7}\,cm^{-3})$$

$$= \boxed{10^2\,cm^{-3}}$$

b) Sample 1 = $N_d = 10^{17} cm^{-3}$

$$\mu_n(N_d = 10^{17} cm^{-3}) = 750\ cm^2/Vsec$$

$$\sigma = qN_d\mu_n = \boxed{12\ \Omega^{-1} cm^{-1}}$$

Sample 2 = $N_a = 10^{15} cm^{-3}$

$$\mu_p(N_a = 10^{15} cm^{-3}) = 480\ cm^2/Vsec$$

$$\sigma = qN_a\mu_p = \boxed{12\ \Omega^{-1} cm^{-1}}$$

Sample 3 = $N_T = N_d + N_a = 1.01 \times 10^{17} cm^{-3}$

$$\mu_n(N_T = 1.01 \times 10^{17} cm^{-3}) = 750\ cm^2/Vsec$$

$$N_{net} = N_d - N_a = 0.99 \times 10^{17} cm^{-3}$$

$$\sigma = qN_{net}\mu_n = 11.88\ \Omega^{-1} cm^{-1}$$

c) for sample 1

$$E_c - E_f = kT\ln\left(\frac{N_c}{N_d}\right) = 0.026V\ln\left(\frac{N_c}{N_d}\right)$$

$$= \frac{2.8 \times 10^{19} cm^{-3}}{10^{17} cm^{-3}} = 0.15\ eV$$

Sample 2.

$$E_f - E_v = kT\ln\left(\frac{N_v}{N_a}\right)$$

$$= 0.026V\ln\left(\frac{1.04 \times 10^{19} cm^{-3}}{10^{15} cm^{-3}}\right)$$

$$\boxed{0.24\,eV}$$

Sample 3 -

$$E_c - E_f = kT \ln\left(\frac{N_c}{N_{net}}\right)$$

$$N_{net} = N_d - N_a \quad ;$$

Substituting N_{net}

$$= 0.026\,V \ln\left(\frac{2.8\times10^{19}\,cm^{-3}}{9.9\times10^{16}\,cm^{-3}}\right)$$

$$= \underline{\underline{0.15\,eV}}$$

Q14) a) $J = qnv = qD\left(\frac{dn}{dx}\right)$

$$v = D\left(\frac{1}{n}\right)\left(\frac{dn}{dx}\right) = \boxed{\frac{-D}{\lambda}}$$

b) $J = q\mu_n n \mathcal{E} = qnv$ & $v = \mu_n \mathcal{E}$

So, $\mathcal{E} = \frac{-D}{\mu_n \lambda} = \boxed{-\left(\frac{kT}{q\lambda}\right)}$

c) $\mathcal{E} = -1000\,V/cm$

$\mathcal{E} = -0.026/\lambda$

So $\lambda = 0.25\,\mu m$

Q15)

$$\mathcal{E} = -\frac{dV}{dx} = \frac{1}{q}\frac{d\mathcal{E}_v}{dx}$$

$$= \frac{1}{q}\frac{\Delta}{L} = \frac{\Delta}{qL}$$

therefore the equation is

$$\mathcal{E} = \frac{\Delta}{qL}$$