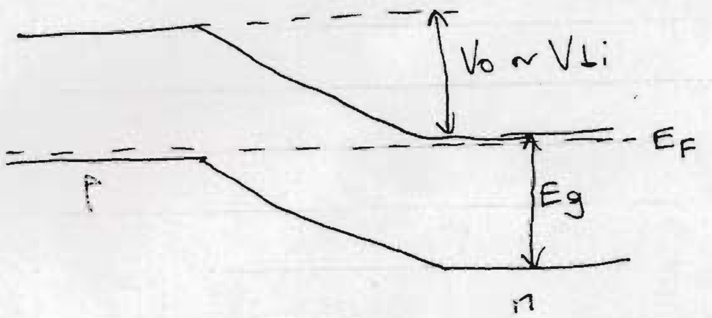
EEE 207 2008 - 2009 Worked Solutions

Q 1(a)



Equilibrium band diagram for p-n junction

[Most people got this]

(4)

(b) Charge neutrality: $n + N_a = p + N_d$

$$np = n_i^2$$

$$\frac{n_i^2}{p} + N_a = p + N_d$$

$$p^2 + p(N_d - N_a) - n_i^2 = 0$$

$$p = \left(\frac{N_a - N_d}{2}\right)\left(1 \pm \sqrt{1 + \left(\frac{2n_i}{N_a - N_d}\right)^2}\right)$$, similar expression for n

$n_i = 1.3\times10^{16}\ m^{-3}$ at RT

$N_a = 5\times10^{22}\ m^{-3}$ (A)

$N_d = 10^{21}\ m^{-3}$ (B)

In (B), $n_i \ll N_d$ so $n = N_d = \underline{10^{21}\ m^{-3}}$

$$p = \frac{n_i^2}{n} = \frac{(1.3\times10^{16})^2}{10^{21}} = \underline{1.7\times10^{11}\ m^{-3}}$$

In (A), $n_i \ll |N_a - N_d|$, so $p = N_a - N_d \approx N_a = \underline{5\times10^{22}\ m^{-3}}$

$$n = \frac{n_i^2}{p} = \frac{(1.3\times10^{16})^2}{5\times10^{22}} = \underline{3.38\times10^{9}\ m^{-3}}$$

(4)

[Very, very few gave me the majority and minority in Both sides of the p-n]

(c) At 500K, $n_i = 1.3\times10^{20}\ m^{-3}$, so cannot assume $n_i \ll |N_d - N_a|$,

so use full expression for region B.

$$n = \frac{10^{21}}{2}\left(1 \pm \sqrt{1 \pm \left(\frac{2.6\times10^{20}}{10^{21}}\right)^2}\right) = \frac{10^{21}}{2}(1 + 1.14)$$

$= 1.07\times10^{21}\ m^{-3}$ which is still $> n_i$ at 500K

[Several people started correctly but got the calculation wrong]

Since $|N_a - N_d|$ in region (A) is > region (B), we can assume that this will also give doping $> n_i$ at 500K.

The device will therefore still behave as a p-n junction photo diode.

(4)

[Only a few people got the final answer correct and could do the calculation correctly] out.

1(c) $n_i \propto T^{3/2} \cdot \exp(-E_g/2kT)$

at RT $n_i = C T^{3/2} \cdot \exp(-E_g/52\text{meV})$ where C = constant

p-n diode ceases to work when $n_i > n$ i.e. $10^{21}\ m^{-3}$.

(Assume that E_g does not change much with T)

[This bit is the key, and gets you some marks. Few only realised it]

From n_i at 500K,

$$C = \frac{1.3\times10^{20}}{500^{3/2}} \exp(1.1/0.086) = 3.82\times10^{21}$$

[Very few could get the constant correctly]

Use trial and error to find Temp when $n_i > n$

At 580K:

$$n_i = 3.82\times10^{21} \times 580^{3/2} \times \exp(-1.1/0.1) = 8.86\times10^{20}\ m^{-3}$$

At 600K

$$n_i = 3.82\times10^{21} \times 600^{3/2} \times \exp(-1.1/0.104) = 1.4\times10^{21}\ m^{-3}$$

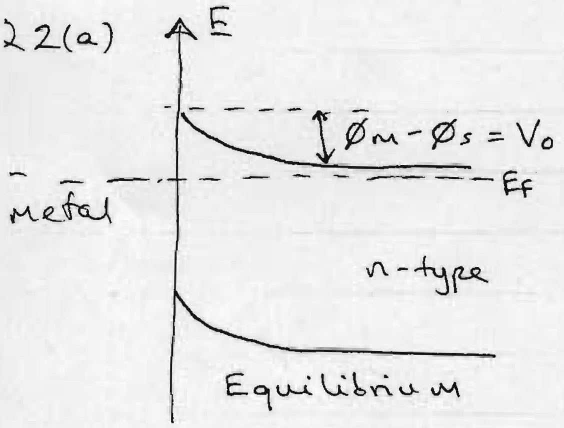
Photodiode will start to lose p-n junction characteristics at $\sim T > 580K$ (6)

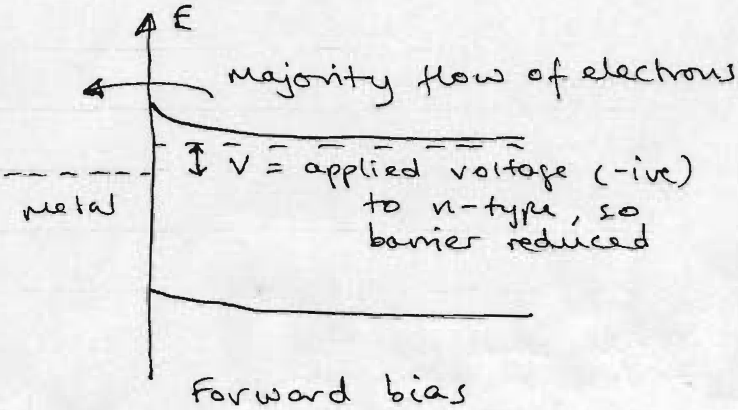
d) To ensure photodiode operation at high temperature, you need to ensure that the p-n junction is more heavily doped, so increase the doping level of the substrate/wafer and the acceptor diffusion. (2)

[Several people suggested increasing the doping of the acceptor only, so got half the marks]

[Only 1cii was 'new', so it should have been easy to get 14 marks for this question. The average mark was much lower due to carelessness]

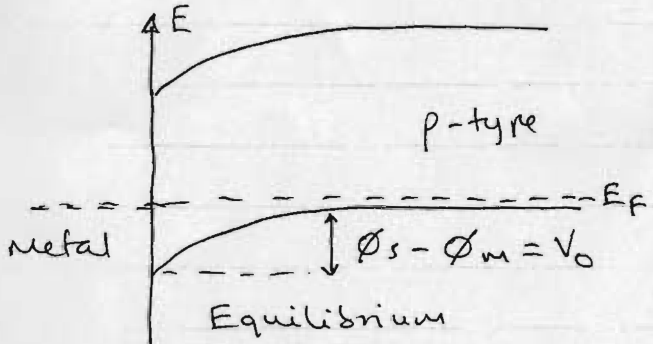
2 2(a)

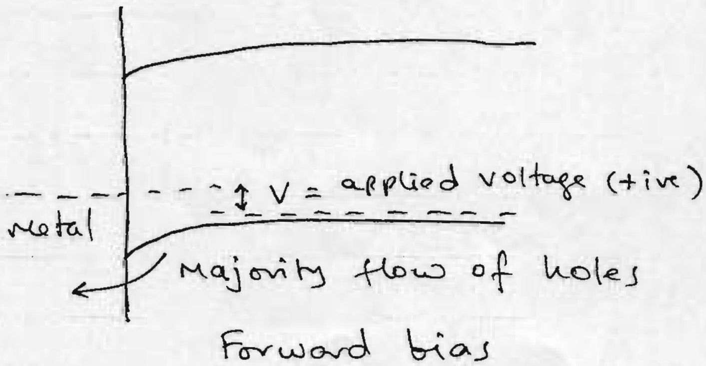




$\phi_m > \phi_s$ for schottky on n-type semiconductor

[Most got this bit correct] (4)

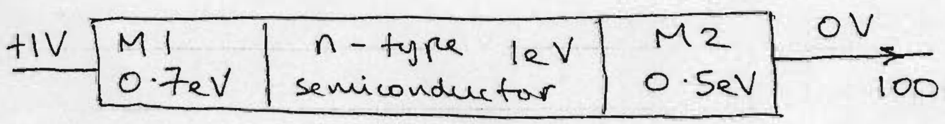




$\phi_m < \phi_s$ for schottky on p-type semiconductor

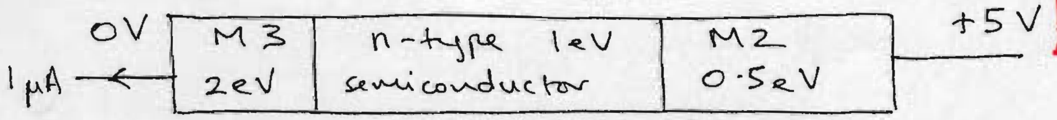
[Many did not get even $\phi_m < \phi_s$ correct] (4)

(b)



Since ϕ_m in M1 and M2 < ϕ semiconductor, these are ohmic contacts. Resistance of $1V/100mA = 10\,\Omega$ is therefore due to n-type semiconductor. (2)

[Few seemed to realise that this is just a resistor]



M2 is still ohmic but $\phi_{m3} > \phi_s$ so that is a schottky rectifying contact. With this polarity of bias, the device is reverse biased, so only I_0 of 1μA flows.

[This is now just a diode in series with a resistor - very few got this far]

Q2(b) out.

$$I = I_0\left[\exp\{e(V-IR)/kT\} - 1\right]$$

When M3 has +1V and M2 = 0,

$$I = 10^{-6}\left[\exp\{(1-10 I)/0.026\} - 1\right]$$ (3)

$$10^{6} I = \exp\left\{\frac{(1-10 I)}{0.026}\right\} - 1$$

Use a series of guesses of I to get LHS ≈ RHS

I	LHS		RHS
1mA	10^3	<	3.4×10^{16}
10mA	10^4	<	10^{15}
100mA	10^5	>	1
50 mA	5×10^4	<	5×10^8
60 mA	6×10^4	<	5×10^6
70 mA	7×10^4	<	10^5
71 mA	7.1×10^4	≈	7×10^4

[This is quite difficult and anyone who got this far got most of the marks]

So current that flows is ~ 71mA (5)

(c) Schottky diode vs. p-n diode
Advantages - faster as unipolar device
Disadvantage - smaller reverse bias breakdown voltage. (2)

[This was easy and most people got some of this correct. However there were still people who got no marks here]

3(a) An electron travelling in a vacuum has energy E,

$$E = \frac{1}{2} m v^2 = p^2/2m \quad \text{(since momentum } p = mv\text{)}$$

Differentiating this twice gives:

$$\frac{dE}{dp} = \frac{p}{m} \quad , \quad \frac{d^2E}{dp^2} = \frac{1}{m}$$

In a semiconductor replace m with 'effective' mass, m^* to account for lattice interactions

$$m^* = 1 \Big/ \left(\frac{d^2E}{dp^2}\right) \qquad (4)$$

[Most got this expression, but some started with Force = m.a and not an electron in a vacuum, so lost marks]

(b) E-K relationship is assumed parabolic, so:

$$E = A + Bk^2 \quad \text{where } A, B \text{ are constants} \qquad (2)$$

Bandgap at k = 0 for direct gap semiconductor, so A = 0.75eV

$$\frac{dE}{dk} = 2Bk \quad , \quad \frac{d^2E}{dk^2} = 2B \quad , \quad \text{so}$$

$$m_e^* = 0.04 \times 9.11 \times 10^{-31} = \frac{1}{2B} \times \hbar^2 \qquad (p = \hbar k)$$

$$B = \frac{\hbar^2}{2} \times \frac{1}{0.04 \times 9.11 \times 10^{-31}} = \left(\frac{6.626 \times 10^{-34}}{2\pi}\right)^2 \times \frac{1}{2} \times \frac{1}{0.04 \times 9.11 \times 10^{-31}}$$

$$= 1.53 \times 10^{-37} \text{ J m}^2 = 9.53 \times 10^{-19} \text{ eV} \qquad (2)$$

$$\therefore E = \cancel{xx} \; 0.75 + 9.53 \times 10^{-19} k^2 \text{ eV} \qquad (3)$$

[Quite a reasonable number got this correct. You can answer in Joules as well]

Q 3(c) (i) Electrode workfunction = 1eV

Energy of 850nm light = $\frac{1.24}{0.85}$ = 1.46eV

Electrons are emitted with $(1.46 - 1)$eV worth of energy, therefore a negative voltage of 0.46 V has to be applied to stop the electrons. [No problems] (1)

(ii) Since workfunction of electrode is 1eV $\equiv \frac{1.24}{1} = 1.24\,\mu m$ light is the longest wavelength that will result in the emission of electrons. [Easy] (1)

(iii) Doubling the intensity of the 850nm does not change the energy of the photons, so 0.46 V still required to stop the current [Many people doubled the wavelength!] (2)

(iv) For a given light power, halfing the wavelength is halfing the number of photons, as each photon has twice the energy. Electrons are therefore emitted with:

$$\left(\frac{1.24}{0.425} - 1\right)eV = (2.92 - 1)\,eV = 1.92\,eV$$

[No problems]

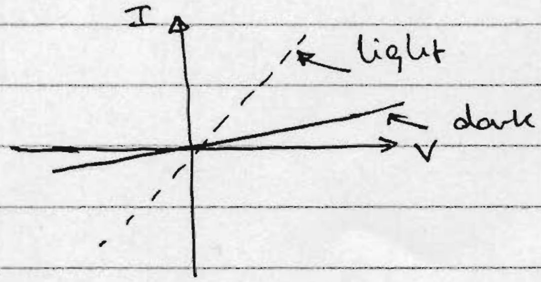
so stopping voltage is 1.92 V. (2)

(d) The de Broglie relationship relates the momentum, p, to the wavelength of photons according to:

$$p = \frac{E}{c} = \frac{hf}{f\lambda} = \frac{h}{\lambda}$$

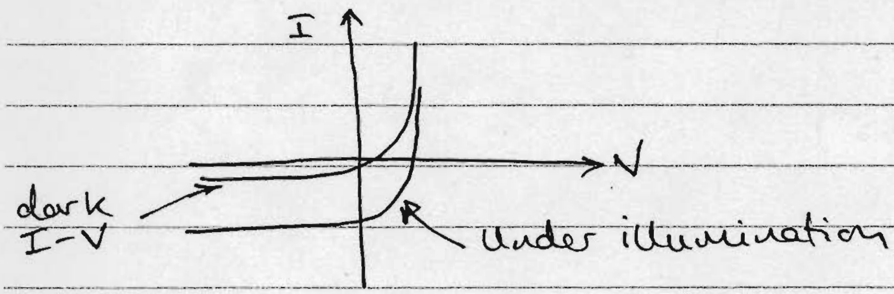
[Easy] (3)

4 (a) Photoconductors are basically resistors whose resistance changes when light creates e-h pairs and therefore changes the conductivity.



(3)

Photodiodes are usually reverse biased p-n or p-i-n diodes whose minority reverse leakage current is very small in the dark. Under illumination, the minority current increases as e-h are produced.



(3)

[Very few got both these correct]

(b) Assuming that all the photons are absorbed, and you get one e-h per photon, the minimum detectable power is the number of photons as carriers in 10 nA.

Current of 10 nA $= 10^{-8}/1.6\times10^{-19} = 6.25\times10^{10}$ electrons/sec. (2)

Energy of 633 nm photon $= 1.96\times1.6\times10^{-19}$ C

[Alternate way: $E = \frac{1.24}{\lambda}$, $P = \frac{E \times 10nA}{e}$]

4(b) out. So 6.25×10^{10} photons required, therefore power is

$$6.25\times10^{10} \times 1.96 \times 1.6\times10^{-19} = 1.96\times10^{-8}\,W = 19.6\,nW$$

(2)

Similarly 850nm photon $= 1.46\times1.6\times10^{-19}\,C$

Optical power required $= 6.25\times10^{10}\times1.46\times1.6\times10^{-19} = 14.6\,nW$

(2)

At 1300nm, photon energy = 0.95eV, which is < than E_g of GaAs, so no photocurrent will flow regardless of intensity. (2)

[A few got all sections correct but most had no idea how to proceed]

(c) With a 5nm thick GaAs layer with AlGaAs barriers, we need to take into consideration the effects of quantisation on the band-gap.

$$E_n = \frac{n^2 h^2}{8mL^2}$$

$n = 1$, $h = 6.63\times10^{-34}$, $M_e = 0.063M_0$, $M_h = 0.48M_0$, $L = 5\times10^{-9}m$

$$E_{1e} = \frac{(6.63\times10^{-34})^2}{8\times0.063\times9.11\times10^{-31}\times(5\times10^{-9})^2} = 239\,meV$$

$$E_{1h} = \frac{6.63\times10^{-34}}{8\times0.48\times9.11\times10^{-31}\times(5\times10^{-9})^2} = 31\,meV$$

(2)

[These seemed OK]

Total effective band-gap $= 1.42 + 0.239 + 0.031 = 1.69\,eV$

This corresponds to $\frac{1.24}{1.69} = 0.733\,\mu m$ as the maximum wavelength that can be absorbed. Consequently, only the 633nm wavelength can be detected. (2)

[Many people did "$2.2 + E_{1e} + E_{1h}$" so got it wrong]

4(d) If the 5 nm became very thick, it would be like bulk GaAs, so will detect up to $\frac{1.24}{1.42} = 0.873\ \mu m$

If the 5 nm became very thin, it would be limited by the absorption of the barriers with 2.2 eV, so the longest wavelength then would be $\frac{1.24}{2.2} = 0.563\ \mu m$. (2)

[Surprisingly few managed to get this correct]