EEE337/348 Solution 2014/15

1a.

i) Long minority carrier diffusion lengths are required so that photogenerated carriers in the neutral regions can diffuse to the depletion region without recombining. This is required to achieve high quantum efficiency.

$$L_e = \sqrt{D_e \tau_e} = \sqrt{20 \times 10^{-4} \times 10^{-7}} = 1.41 \times 10^{-5} m = 14.1 \mu m$$
$$L_h = \sqrt{D_h \tau_h} = \sqrt{12 \times 10^{-4} \times 10^{-8}} = 3.46 \times 10^{-6} m = 3.46 \mu m$$

ii) First we need to calculate the built in potential

$$V_{bi} = \frac{kT}{q} \ln\left(\frac{N_a N_d}{n_i^2}\right) = 0.026 \ln\left(\frac{1 \times 10^{16} \times 1 \times 10^{17}}{\left(1.5 \times 10^{10}\right)^2}\right) = 0.76V.$$

The depletion width is given by

$$W = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)V_{bi}} = \sqrt{\frac{2 \times 11.9 \times 8.85 \times 10^{-14}}{1.602 \times 10^{-19}}\left(\frac{1.1 \times 10^{17}}{1 \times 10^{33}}\right) \times 0.76} = 0.33\ \mu\text{m}.$$

1b.

i)

$$I_{ph} = qAG\left(L_e + W + L_h\right) = 1.6 \times 10^{-19} \times 0.1 \times 0.1 \times 10^{22} \times \left(14.1 + 0.33 + 3.46\right) \times 10^{-4} = 29mA$$

ii) From

$$V_{OC} = \frac{kT}{q} \ln\left(1 + \frac{I_{ph}}{I_s}\right) = 0.026 \ln\left(1 + \frac{29 \times 10^{-3}}{10 \times 10^{-15}}\right) = 0.746V$$

1c.

Each cell produces 0.6x0.9=0.54 V. To produce 10 V, we need to connect N cells in series so that N = 10/0.54 ~19 cells.

The power produced by this row of 19 cells is 10 x 0.9x0.03 = 0.27 W. To produce 10 W, we will need to have 10/0.27 = 37 rows. Therefore the total number of cells required is 37x19 =703 solar cells.

1d.

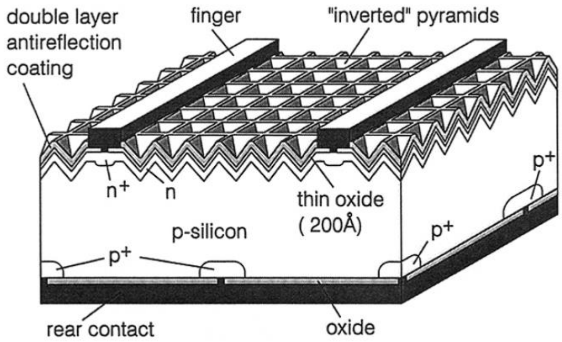


Figure 1.1: Schematic of a PERL cell (Zhao et. al., Solar Energy Materials and Solar Cells 41/42(1996) 87-89)

The key features are

a) Inverted pyramid: Sunlight incident on a side slope is partially transmitted into the cell and partially reflected to the other slope, increasing the probability of light being absorbed.
b) Oxide layer: Designed to minimise reflection of incident sunlight. It also passivates the surface to minimise surface recombination.
c) p-region: Should have long minority carrier diffusion length to ensure high output current. Minority carrier lifetime in ms is routinely achieved.
d) P+ regions: Minority carriers are collected and is highly doped to minimise series resistance. Metal-semiconductor area (defined by the small Boron diffused p+ region) is small to minimise surface recombination loss.
e) N+ regions: Highly doped to minimise series resistance
f) Si-Oxide-Aluminium: Act as mirror to reflect light (particularly at long wavelengths) back into the cell.

2a.

i) The wider bandgap InP is transparent to 1550 nm. Therefore no signal is absorbed near the surface, reducing loss of photogenerated carriers through recombination at the surface and in the p and n regions. The wider bandgap InP will also reduce diffusion current component, leading to lower dark current in the photodiode.

ii) $\eta = 1 - \exp(-\alpha W) = 1 - \exp(-8000 \times 1 \times 10^{-4}) = 0.55$. The quantum efficiency is 55%.

iii) Assuming it is RC limited.

$$f_{RC} = \frac{1}{2\pi RC}\text{, therefore } C = \frac{1}{2\pi f_{RC} R} = \frac{1}{2\pi \times 20 \times 10^{9} \times 50} = 0.16\, pF$$

$$A = \frac{Cd}{\varepsilon_s} = \frac{1.6 \times 10^{-13} \times 1 \times 10^{-4}}{13.9 \times 8.85 \times 10^{-14}} = 1.3 \times 10^{-5} cm^2$$

2b.

Consider the transit time limited bandwidth is given by

$$f_{3dB\_tr} = \frac{0.4}{t_r} = \frac{0.4 v_s}{W}\text{, for 75 GHz } W = \frac{0.4 \times 10^{5}}{75 \times 10^{9}} = 0.53 \mu m\,.$$

Consider the RC limited bandwidth for a 50Ω system

$$f_{RC} = \frac{1}{2\pi RC}, \; C = \frac{1}{2\pi f_{RC} R} = \frac{1}{2\pi \times 75 \times 10^9 \times 50} = 42.4\, fF$$

$$A = \frac{Cd}{\varepsilon_s} = \frac{4.24 \times 10^{-14} \times 0.53 \times 10^{-4}}{13.9 \times 8.85 \times 10^{-14}} = 1.83 \times 10^{-6}\, cm^2$$

To avoid diffusion limited bandwidth, the neutral p and n regions should consists of wide bandgap material such as InP that is transparent to 1550 nm.

The depletion region should be no thicker than 0.53 μm with the diode biased to achieve this full depletion.

Finally the diode capacitance should be no more than 42.4 fF. The area should be no larger than $1.83 \times 10^{-6} cm^2$.

2c.

i) At 10 V

$M = \dfrac{1}{1 - \left(\dfrac{10}{200}\right)^{1.6}} = 1.00$. The quantum efficiency is 0.9. Therefore the photocurrent produced is $I_{ph} = \dfrac{\eta \lambda P_{opt}}{1.24} = \dfrac{0.9 \times 0.633 \times 10^{-9}}{1.24} = 4.6 \times 10^{-10} A$. Clearly the photocurrent is lower than the dark current of 1nA and the gain is too low to amplify the signal.

ii) Minimum gain required to overcome the dark current is $\dfrac{1 \times 10^{-9}}{4.6 \times 10^{-10}} = 2.17$. To achieve a good signal to noise ratio, a gain higher than 2.17 is required.

$2.17 = \dfrac{1}{1 - \left(\dfrac{V}{200}\right)^{1.6}}$. V =136 V.

Therefore a suitable range will be between 136 to 195 V. For stability it is better to operate at a few volts below the breakdown voltage.

3a.

i)

The injection efficiency is given by (assuming no recombination due to traps, $J_{GR} = 0$)

$\gamma_{inj} = \dfrac{J_e}{J_e + J_h}$. Therefore we need to calculate J_e and J_h.

$J_e = \frac{qD_e n_p}{L_e} \exp\left(\frac{qV}{kT}\right)$ and $J_h = \frac{qD_h p_n}{L_h} \exp\left(\frac{qV}{kT}\right)$. Now we need to calculate n_p (minority electron concentration in p-layer) and p_n (minority hole concentration in n-layer).

Assuming and intrinsic concentration is $2\text{x}10^6$ cm^{-3},

$$n_p = \frac{n_i^2}{N_a} = \frac{(2\times10^6)^2}{5\times10^{16}} = 8\times10^{-5} cm^{-3} \text{ and } p_n = \frac{n_i^2}{N_d} = \frac{(2\times10^6)^2}{5\times10^{17}} = 8\times10^{-6} cm^{-3}$$

Next, we need to calculate the diffusion lengths

$$L_e = \sqrt{D_e \tau_e} = \sqrt{30\times10^{-7}} = 17.3\mu m \text{ and } L_h = \sqrt{D_h \tau_h} = \sqrt{15\times10^{-8}} = 3.87\mu m$$

Using the calculated minority carrier concentrations and diffusion lengths

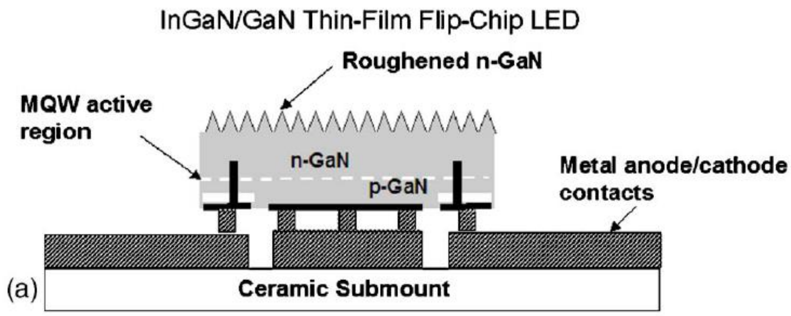
$$\gamma_{inj} = \frac{\frac{qD_e n_p}{L_e}}{\frac{qD_e n_p}{L_e} + \frac{qD_h p_n}{L_h}} = \frac{\frac{30\times8\times10^{-5}}{17.3\times10^{-4}}}{\left(\frac{30\times8\times10^{-5}}{17.3\times10^{-4}}\right) + \left(\frac{15\times8\times10^{-6}}{3.87\times10^{-4}}\right)} = 0.82 .$$

ii) The current density injected into the p-region is $J_e = \frac{qD_e n_p}{L_e} \exp\left(\frac{qV}{kT}\right)$

$$J_e = \frac{(1.6\times10^{-19} C)\times(30 cm^2/s)\times(8\times10^{-5} cm^{-3})}{17.3\times10^{-4} cm} \exp\left(\frac{1}{0.026}\right) = 11.2 mA/cm^2$$

The current is therefore $I_e = AJ_e = 10^{-2} cm^2 \times 11.2 mA/cm^2 = 0.11 mA$

3b.



Key features are

a) Roughened GaN disrupts lateral waveguiding action and caused internal reflections to increase vertically illuminated light.
b) Use of InGaN/GaN MQW increases the output power.
c) Mounted on high thermal conductivity submount.
d) Growth substrate is removed.
e) Only bottom contacts are used so that the top surface is transparent

4a.

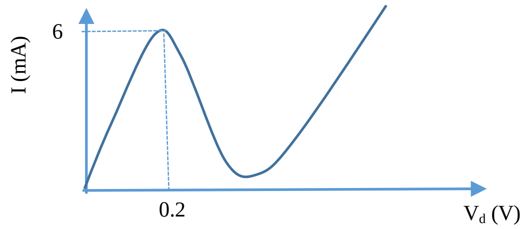
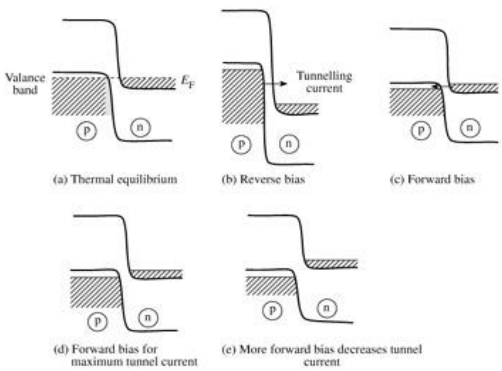


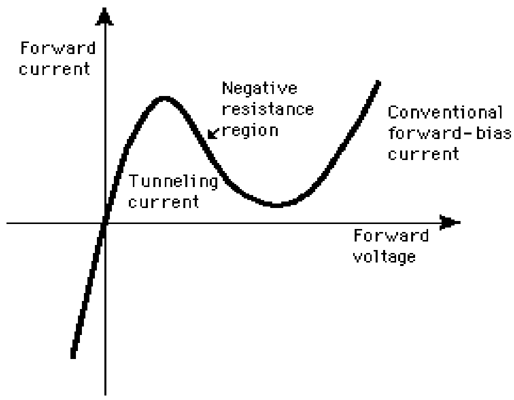
Figure 4.1

A typical current-voltage characteristics of a GaAs tunnel diode is shown in Figure 4.1. Using band diagrams, explain how the current changes with bias voltage.

Band to band tunnelling usually occurs when electrons tunnel through, from the p to the n-side under a large reverse bias across the pn diode (see figure (b)). To achieve tunnelling effect in the forward bias, we need to modify the pn diode so that electrons can tunnel through, in the reverse direction from n to p-side (see figure (c)). By increasing the doping on n-side we can raise the Fermi level into the conduction and ensure that there are sufficiently large concentration electrons in the conduction. Likewise increasing the doping on the p-side leads to a Fermi level in the valence band and we have a sufficiently large concentration of holes (unoccupied states).

The strength of the tunnelling effect depends on the “overlap” between the occupied and empty states. As the forward bias increases, tunnelling current increases with bias, then reaches a peak, drops to a minimum corresponding to the changes in the “overlap” as illustrated below. The drop in the current produces the negative resistance. At very large forward bias, the current mechanism is dominated by diffusion current and increases rapidly with voltage.





b. The impedance of a tunnel diode is given by

$$Z_{in} = \left[R_s + \frac{-R}{1+(\omega RC_j)^2} \right] + j\left[\omega L_s + \frac{-\omega C_j R^2}{1+(\omega RC_j)^2} \right].$$

Z_{in} changes with frequency, making it a very important component for high speed circuit applications. Consider a GaAs tunnel diode with the following parameters; a lead inductance of 0.1 nH, a series resistance of 4 Ω, a junction capacitance of 70 fF and a negative resistance of 20 Ω. Calculate the frequency when the real part of the impedance becomes zero.

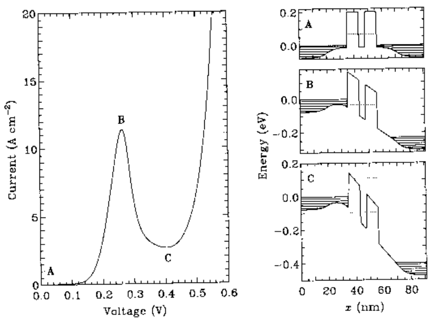
The real part becomes zero when

$R_s = \dfrac{R}{1+(\omega RC_j)^2}$. Rearranging this we have

$f_{r0} = \dfrac{1}{2\pi RC_j}\sqrt{\dfrac{R}{R_s} - 1}$. Substituting the component values we have

$$f_{r0} = \frac{1}{2\pi \times 20 \times 70 \times 10^{-15}}\sqrt{\frac{20}{4} - 1} = 2.27 \times 10^{11} Hz$$

c. With the aid of band diagrams, explain how a double barrier resonant tunnel diode works.



The energy band diagram of a double barrier RTD is shown above.

A) At 0V, the current is low as electrons are blocked by the barrier.

B) As the bias is increased, the band is tilted. Electrons from the left can tunnel to the state in the quantum well and then to the empty states on the right. Current increases.

C) At higher bias, the state in the quantum well is no longer aligned with the occupied states, so tunnelling reduces and the current drops.

d. Discuss the key advantages of resonant tunnelling diodes over conventional pn diode based tunnel diodes.

The key advantages of RTDs are

1) As the current-voltage is symmetrical, the leakage current in the reverse bias is lower than conventional tunnel diode.
2) The quantum well can be designed with different energy level spacing to control the oscillation peaks in the current-voltage characteristics (e.g: including equally spaced peaks using a parabolic quantum well).
3) Produce faster switching time than tunnel diodes allowing RTDs to operate above 1 THz.