Data Provided: List of Formulae

The University Of Sheffield.

DEPARTMENT OF ELECTRONIC AND ELECTRICAL ENGINEERING

Spring Semester 2014-15 (2.0 hours)

EEE337 Semiconductor Electronics

Answer **THREE** questions. **No marks will be awarded for solutions to a fourth question.** Solutions will be considered in the order that they are presented in the answer book. Trial answers will be ignored if they are clearly crossed out. **The numbers given after each section of a question indicate the relative weighting of that section.**

1. **a.** Consider a Si pn junction with the following parameters.

Diode area, $A = 0.1$ cm × 0.1 cm
p-side doping, $N_a = 1\times10^{16}$ cm^{-3}
n-side doping, $N_d = 1\times10^{17}$ cm^{-3}
Electron diffusion coefficients, $D_e = 20$ cm^2/s
Hole diffusion coefficients, $D_h = 12$ cm^2/s
Electron minority carrier lifetime, $\tau_e = 100$ ns
Hole minority carrier lifetime, $\tau_h = 10$ ns
Intrinsic carrier concentration, $n_i = 1.5\times10^{10}$ cm^{-3}

i) Explain why it is important to have long minority carrier diffusion length in solar cell. Verify that the electron and hole minority carrier diffusion lengths are 14.1 and 3.46 μm, respectively. **(2)**

ii) In addition to long minority carrier diffusion length, it is also important to have a large depletion width. Verify that the depletion width is 0.33 μm at 0 V. **(4)**

b. i) When the solar cell in part (a) is exposed to direct sunlight the electron-hole pair generation rate is assumed to be constant and is given by 10^{22} cm^{-3}s^{-1}. Using parameters from part (a), verify that the photocurrent produced is 29 mA. **(2)**

ii) Calculate the open circuit voltage for this Si diode if the saturation leakage current is 10 fA. **(2)**

c. Consider a solar cell that produces a short circuit current $I_{SC} = 30$ mA and an open circuit voltage, $V_{OC} = 0.6$ V. Assuming that $V_m = 0.9V_{OC}$ and $I_m = 0.9I_{SC}$, describe how a cluster of solar cells can be connected to produce a total power of 10 W at an output voltage of 10 V. [V_m and I_m are the voltage and current that produces the maximum output power] **(4)**

d. Figure 1.1 shows an optimised solar cell known as Passivated Emitter & Rear Locally-diffused (PERL) cell.

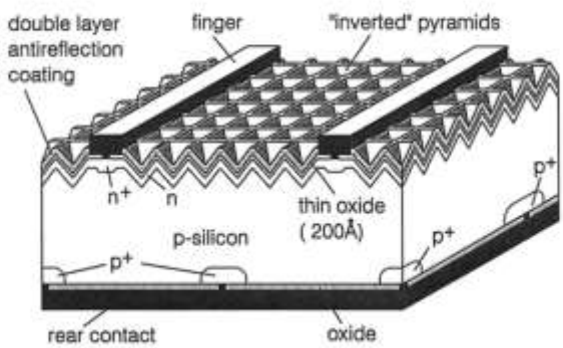

Figure 1.1: Schematic of a PERL cell (Zhao et. al., Solar Energy Materials and Solar Cells 41/42(1996) 87-89)

Explain the design features that enable PERL cell to achieve a high conversion efficiency. **(6)**

2. **a.** Consider an InGaAs pin photodiode designed to absorb signal at 1550 nm. This InGaAs pin diode has a depletion width of 1 μm and InP p and n layers. The dielectric constant is 13.9 and the saturation velocity is 10^5 cm/s.

i) Discuss the main advantages of using the wide bandgap InP for the p and n layers. **(3)**

ii) The absorption coefficient of InGaAs is 8000 cm^{-1} at the wavelength 1550 nm. Calculate the quantum efficiency of this photodiode assuming no surface reflection. **(2)**

iii) Determine the size of the photodiodes that should be fabricated in order to achieve an RC-limited bandwidth of 20 GHz. [Assume that the device series resistance is negligible and the metal transmission line is 50 Ω]. **(3)**

b. Current high speed optical networks operate up to 100 Gb/s with higher bit rate networks being evaluated. Recommend a photodiode design that will achieve a bandwidth of 75 GHz. Provide supporting statements for features included in your design (specify the choice of material, layer thicknesses and dimension of diode). **(6)**

c. Consider a Si avalanche photodiode (APD) with a breakdown voltage V_b = 200 V, a quantum efficiency of 0.9, series resistance of 1 Ω and n_m = 1.6. When biased at 90% of its breakdown voltage the dark current is 1 nA due to surface leakage.

i) The APD is used to detect a signal at 633 nm with an optical power of 1 nW. Verify whether this APD will be able to detect the signal when when operated at 10 V. **(3)**

ii) Suggest a suitable operating voltage range for this APD to generate gain that will raise the signal above the dark current. **(5)**

3. **a.** The parameters of a GaAs pn homojunction LED are given below

Electron diffusion coefficient, D_e = 30 cm^2/V-s
Hole diffusion coefficient, D_h = 15 cm^2/V-s
p-doping, $N_a = 5\times10^{16}$ cm^{-3}
n-doping, $N_d = 5\times10^{17}$ cm^{-3}
Electron minority carrier lifetime, $\tau_e = 10^{-7}$ s
Hole minority carrier lifetime, $\tau_h = 10^{-8}$ s
Intrinsic carrier concentration, $n_i = 2\times10^{6}$ cm^{-3}

i) Calculate the injection efficiency, $\gamma_{inj} = \dfrac{J_e}{J_e + J_h}$, assuming no recombination due to traps in this GaAs LED.

ii) The electrons are injected into the top p-layer, so that photons generated by radiative recombination can be emitted vertically. Calculate the injection current at a forward bias of 1 V. Assume the diode has an area of 1 mm^2 **(10)** **(4)**

b. Sketch and label the structure to produce high brightness GaN LED. Explain the features that improves the efficiency of the LED in your answer. **(6)**

4. **a.**

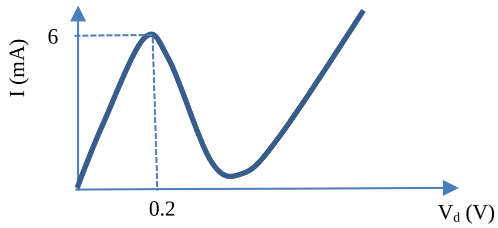

Figure 4.1

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. **(6)**

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. **(7)**

c. With the aid of band diagrams, explain how a resonant tunnel diode works. **(4)**

d. Discuss the key advantages of resonant tunnelling diodes over conventional tunnel diodes based on a pn junction. **(3)**

CHT/TWANG

List of formulae

$$f^{e}(E)=\frac{1}{\exp\left(\frac{E-E_{Fn}}{kT}\right)+1}$$

$$f^{h}(E)=\frac{1}{\exp\left(\frac{E_{Fp}-E}{kT}\right)+1}$$

$$I_d=I_s\left[\exp\left(\frac{qV}{kT}\right)-1\right]$$

$$I_s=qAN_cN_v\left[\frac{1}{N_A}\sqrt{\frac{D_e}{\tau_e}}+\frac{1}{N_D}\sqrt{\frac{D_h}{\tau_h}}\right]\exp\left(-\frac{E_g}{kT}\right)$$

$$J_e=\frac{qD_en_p}{L_e}\exp\left(\frac{qV}{kT}\right)$$

$$J_h=\frac{qD_hp_n}{L_h}\exp\left(\frac{qV}{kT}\right)$$

$$V_{bi}=\frac{kT}{q}\ln\left(\frac{N_aN_d}{n_i^{2}}\right)$$

$$W=\sqrt{\frac{2\varepsilon_s}{q}\left(\frac{N_a+N_d}{N_aN_d}\right)V_{bi}}$$

$$L_{e(h)}=\sqrt{D_{e(h)}\tau_{e(h)}}$$

$$D_{e(h)}=\frac{kT}{q}\mu_{e(h)}$$

$$V_{OC}=\frac{kT}{q}\ln\left(1+\frac{I_{ph}}{I_s}\right)$$

$$I_{tot}=I_s\left[1-\exp\left(\frac{q(V-I_{tot}R_s)}{kT}\right)\right]+I_{ph}$$

$$I_{ph}=qAG(L_e+W+L_h)$$

$$\eta=\left(\frac{I_{ph}}{q}\right)\left(\frac{P_{opt}}{h\nu}\right)^{-1}$$

$$\eta=(1-R)[1-\exp(-\alpha W)]$$

$$R_{res}=\frac{\eta q\lambda}{hc}$$

$$I_{ph}=\frac{\eta\lambda P_{opt}}{1.24}$$

$$t_{diff}=\frac{4x^2}{\pi^2D_p}$$

$$f_{3dB\_tr}=\frac{0.4}{t_r}=\frac{0.4v_s}{W}$$

$$f_{IMP}=\frac{v_{sat}}{2(w-x_a)}$$

$$f_{RC}=\frac{1}{2\pi RC}$$

$$M=\frac{1}{1-\left(\frac{V-IR}{V_b}\right)^{n_m}}$$

$$V_B=E_mx_a+\left(E_m-\frac{qQ_c}{\varepsilon_s}\right)(w-x_a)$$

$$SNR=\frac{I_{ph}^{2}}{<i_s^{2}>+<i_{th}^{2}>}=\frac{(q\eta P_{opt}/h\nu)^2}{2qI_TB+4kTB/R_{eq}}$$

$$g(h\nu)=G_{las}[f^{e}(E^{e})+f^{h}(E^{h})-1]\quad cm^{-1}\text{ where }G_{las}=5.6\times10^{4}\frac{(h\nu-E_g)^{1/2}}{h\nu}\text{ for GaAs}$$

$$J_{th}=\frac{qd_{las}n_{th}}{\tau_r(J_{th})}$$

PHYSICAL CONSTANTS

Quantity	Symbol	Value
Boltzmann constant	k	1.38066×10^{-23} J/K
Electron rest mass	m_o	9.1095×10^{-31} kg
Electronic charge	q	1.60218×10^{-19} C
Permeability in vacuum	μ_0	1.25663×10^{-8} H/cm
Permittivity in vacuum	ε_0	8.85418×10^{-14} F/cm
Planck constant	h	6.62617×10^{-34} Js
Speed of light in vacuum	c	2.99792×10^{10} cm/s
Thermal voltage at 300 K	kT/q	0.0259 V

Dielectric constant = 11.9 (Si), 12.4 (GaAs), 13.9 (InGaAs)