A quick recap of the material covered in Week 11 lecture

Optical absorption

- When a light of energy ($h\nu$) is incident on a material of band gap E_g ($h\nu \geq E_g$), then photon absorption takes place. The intensity of the photon flux decreases exponentially with the absorption coefficient α and the distance/thickness of the material/slab 'd'.

$$\boxed{I = I_0 e^{-\alpha d}} \tag{1}$$

- When photons of certain wavelength λ incident on a semiconductor of thickness 'd', then photon absorption takes place and electron hole pairs are generated with generation rate 'g' per cm^3 per sec. The excess steady state carrier concentration 'Δn' is per cm^3 and 'τ' the excess minority carrier lifetime in sec.

$$\boxed{g = \frac{\alpha I_\nu(x)}{h\nu} = \frac{\delta n}{\tau}} \tag{2}$$

Solar cells

- When a solar cell (pn junction) is connected to a resistive load 'R' and light incident on it. Incident photons create elecron-hole pairs in the depletion region that swept the photocurrent I_L in the reverse biased condition and this produces a voltage 'V' across the load which forward biases the pn junction with forward current 'I_f' with reverse saturation current I_s.

$$\boxed{I = I_L - I_f = I_L - I_s[e^{\frac{qV}{kT}} - 1]} \tag{3}$$

- The reverse saturation current density J_s is given by

$$\boxed{J_s = \frac{I_s}{A} = qn_i^2(\frac{D_n}{L_n N_a} + \frac{D_p}{L_p N_d})} \tag{4}$$

  where D_n, D_p - diffusion coefficients, L_n, L_p - diffusion lengths, A - area of the device, N_a, N_d - doping concentrations, n_i - intrinsic concentration.

- The two limiting cases of the solar cell are the short circuit current 'I_{sc}' when $V = 0$ & $R = 0$ and open circuit voltage is 'V_{oc}' when $I_{tot} = 0$.

$$\boxed{I_{sc} = I_L} \quad \boxed{V_{oc} = \frac{kT}{q}\ln(1 + \frac{I_L}{I_s})} \tag{5}$$

- The load voltage V_m, that corresponds to the maximum power delivered to load $\boxed{\frac{dP}{dV} = 0}$.

$$\boxed{(1 + \frac{V_m}{V_t})e^{\frac{qV_m}{kT}} = 1 + \frac{I_L}{I_s} \simeq \frac{I_L}{I_s}} \quad (6)$$

- A solar cell of area 'A' produces a voltage 'V_m' at maximum current 'I_m' irradiates power density 'P' ($P_{in} = PA$), then the solar cell efficiency is'η' and the fill factor is given by 'FF'

$$\boxed{\eta = \frac{P_{out}}{P_{in}} = \frac{V_m I_m}{PA} = \frac{V_{oc} I_{sc}}{P_{in}} FF} \quad \boxed{FF = \frac{V_m I_m}{V_{oc} I_{sc}}} \quad (7)$$

- A photon of frequency 'f' is incident on a photodiode of area 'A' with a power density 'P'. The photon flux is given by :

$$\boxed{\phi = \frac{PA}{hf}} \quad (8)$$

Photodetectors

- Photodetectors are the devices which can convert light into electricity.

Photoconductor detectors

- When excess electrons and holes are generated in a semiconductor, there is an increase in the conductivity of the material. This change in conductivity results in photocurrent.

- When a light of certain energy '$h\nu$' incident on a long semiconductor of length 'L' and area 'A' with initial conductivity σ_0 and if the excess carriers are generated in the semiconductor thus the conductivity σ increases.

$$\boxed{\sigma_0 = q[\mu_n n_0 + \mu_p p_0]} \quad \boxed{\sigma = q[\mu_n(n_0 + \delta n) + \mu_p(p_0 + \delta p)]} \quad (9)$$

- The change in conductivity due to optical excitation is known as photoconductivity.

$$\boxed{\Delta\sigma = q(\delta n)(\mu_n + \mu_p) = qG_L \tau_p(\mu_n + \mu_p)} \quad (10)$$

- An electric field 'E' induced by the applied voltage, produces a current caused by the drift of carriers with a velocity $\boxed{v_d = \mu_n E}$ and electron transit time $\boxed{t_n = \frac{L}{\mu_n E}}$. The photocurrent is given by I_L.

$$\boxed{I_L = J_L.A = \Delta\sigma E.A = qG_L\tau_p(\mu_n + \mu_p)AE = qG_L\frac{\tau_p}{t_n}(1 + \frac{\mu_p}{\mu_n})AL} \quad (11)$$

- The photoconductor gain is the ratio of the rate at which charge is collected by the electrodes to the rate at which charge is generated within the photoconductor.

$$\boxed{\Gamma_{ph} = \frac{I_L}{qG_L AL} = \frac{\tau_p}{t_n}(1 + \frac{\mu_p}{\mu_n})} \tag{12}$$

Photovoltaic detectors

- If electrons and holes are generated within the space charge region of 'W' width in a pn junction, then they will be separated by the built-in electric field and thus photocurrent will be produced.
- The diffusion current density due to minority carrier holes is J_p and due to minority carrier electrons J_n and this is sum of steady-state photocurrent density and ideal reverse saturation current density.

$$\boxed{J_p = qG_L L_p + \frac{qD_p p_{n0}}{L_p}} \quad \boxed{J_n = qG_L L_n + \frac{qD_n n_{p0}}{L_n}} \tag{13}$$

- The total steady state photocurrent density for the long diode is $\boxed{J_L = q(L_n + L_p + W)G_L}$

PIN Photodiode

- Consider a PIN photodiode with an intrinsic width 'W'. The incident photon flux $\boxed{\Phi(x) = \Phi_0 e^{-\alpha x}}$ and photon absorption coefficient 'α'. Assume there is no ehp recombination within the space charge region.

$$\boxed{J_L = q\int_0^W G_L\,dx = q\int_0^W \Phi_0 e^{-\alpha x}\,dx = q\Phi_0(1 - e^{-\alpha W})} \tag{14}$$

Avalanche Photodiode

- Avalanche photodiode is similar to pn or pin photodiode except that the bias applied to the avalanche photodiode is suffi ciently large to cause impact ionization.The electron–hole pairs generated by photon absorption and by impact ionization are swept out of the space charge region very quickly.

Performance parameters (Figures of merit)

- Responsivity of a detector is the ratio of the generated photocurrent 'I_{ph}' to the optical power 'P_{in}' incident on the detector. $\boxed{R_\lambda = I_{ph}/P_{in}}$
- Quantum efficiency is number of electrons generated per number of incident photons. $\boxed{\eta = \frac{I/q}{P_{in}/h\nu}}$

$$\boxed{R_\lambda = I_{ph}/P_{in} = \frac{q\eta}{h\nu} = \frac{\eta}{hc/q\lambda} = \frac{\eta\lambda}{1.24}; \quad \lambda - in\ \mu m} \tag{15}$$

Solve the following questions. There are 12 questions, for a total of 25 marks.

1. (1 mark) Consider a slab of silicon 5 μm thick. Determine the percentage of photon energy that will pass through the slab if the photon wavelength is 0.8 μm. Assume absorption coefficient $\alpha = 10^3\ cm^{-1}$.

    A. 50

    B. 60

    C. 90

    D. 10

    E. 40

    F. 20

2. (2 marks) A photon flux with an intensity of $I_{\nu 0}$= 0.1 W/cm^2 and at a wavelength of 1 μm is incident on the surface of silicon. Assume absorption coefficient of silicon at 1 μm is 100 cm^{-1}.
    What is the steady state excess carrier concentration per cm^3 if the excess minority carrier lifetime is $10^{-7}s$?

    A. 2.5×10^{12}

    B. 2.5×10^{10}

    C. 2.5×10^{14}

    D. 5×10^{14}

    E. 5×10^{10}

    F. 5×10^{12}

    For (Q3 - Q4) Consider the following devices from (i-v)

    i. Solar cells

    ii. Charge - Coupled Device (CCD)

    iii. LEDs

    iv. Lasers

    v. Photodetectors

3. (2 marks) The devices which can convert light into electricity are ______.

    A. i,ii,iii

B. i,ii,iv

C. i,ii,v

D. i,iii,iv

E. iii,v

F. iii,iv

4. (1 mark) The devices which can convert electricity into light are ______.

A. i,ii,iii

B. i,ii,iv

C. i,ii,v

D. i,iii,iv

E. iii,v

F. iii,iv

5. (2 marks) A 1*cm* x 1*cm* silicon solar cell has a saturation current of $1\ pA$ and is illuminated with sunlight yielding a short-circuit photocurrent of 25 mA. The maximum output power is 12 mW. Assume power of the sun to be 100 mW/cm^2. What is the approximate fill factor? (Hint: Calculate open circuit voltage.)

A. 0.1

B. 0.2

C. 0.4

D. 0.9

E. 0.8

F. 1.0

6. (2 marks) A photo-diode has an area of 1 *cm* x 1 *cm* and is illuminated by monochromatic light with a wavelength of 780 nm and with a power density of 1000 W/m^2. At 300 K, the open circuit voltage is 0.683 V. What is the reverse saturation current (in pA)? (Assume 100% qunatum efficiency)

A. 22

B. 0.22

C. 220

D. 100

E. 200

F. 10

7. (3 marks) Consider a 1 cm^2, long Si p-n junction with a reverse bias of 1 V at T=300 K. The diode has the following parameters like, $N_a = 3 \times 10^{17}\ cm^{-3}$, $N_d = 1 \times 10^{17}\ cm^{-3}$, $D_n = 12\ cm^2/s$, $D_p = 8\ cm^2/s$, $\tau_{n0} = \tau_{p0} = 10^{-7}\ s$, optical absorption coefficient $\alpha = 10^3\ cm^{-1}$. A photon of energy $1.7\ eV$ is incident on it with a power density 10 W/cm^2. Calculate the approximate photocurrent in the diode (in A).

A. 2.5

B. 7.5

C. 25

D. 8

E. 5.8

F. 12

8. (3 marks) Consider a silicon pn diode at T=300 K with the following parameters: $N_a = N_d = 10^{16}\ cm^{-3}$, $D_n = 25\ cm^2/s$, $D_p = 10\ cm^2/s$, $\tau_{p0} = 10^{-7}\ s$, $\tau_{n0} = 5 \times 10^{-7}\ s$ and $G_L = 10^{21}\ cm^{-3}s^{-1}$.
Calculate the steady-state photocurrent density (in A/cm^2) in a reverse-biased voltage of 5V, long pn diode.

A. 0.25

B. 0.50

C. 1.50

D. 7.5

E. 0.75

F. 1.25

9. (1 mark) A photodiode has a responsivity of 0.5 A/W at 850 nm. Find the % efficiency of the detector.

A. 43

B. 100

C. 73

D. 82

E. 26

F. 56

Previous year GATE questions

10. (2 marks) **(EC-GATE 2016)** A solar cell illuminated uniformly with solar light of power 100 mW/cm^2. The solar cell has an area of 3 cm^2 and a fill factor of 0.7. The open circuit voltage is 0.5 V and the short-circuit current is 180 mA. The maximum efficiency of the device is ______ %.

Ans: 21

Range: 20-25

11. (3 marks) **(EC-GATE 2018)** A solar cell of area 1.0 cm^2 , operating at 1.0 sun intensity, has a short circuit current of 20 mA, and an open circuit voltage of 0.65 V. Assuming room temperature operation and thermal equivalent voltage of 26 mV, the open circuit voltage (in volts, correct to two decimal places) at 0.2 sun intensity is ______.
(Hint: Assume the reverse saturation current is constant in both the cases and the short circuit current is proportional to the intensity)

Ans: 0.608

Range: 0.58-0.65

12. (3 marks) **(EC-GATE 2020)** A pn junction solar cell of area 1.0 cm^2, illuminated uniformly with 100 $mWcm^{-2}$, has the following parameters: Efficiency = 15%, open circuit voltage = $0.7\ V$, fill factor $FF = 0.8$, and thickness = 200 μm. The charge of an electron is $1.610^{-19}\ C$. The average optical generation rate (in $cm^{-3}s^{-1}$) is

A. 0.84×10^{19}

B. 5.57×10^{19}

C. 1.04×10^{19}

D. 8.4×10^{19}

E. 0.4×10^{19}

F. 0.55×10^{19}