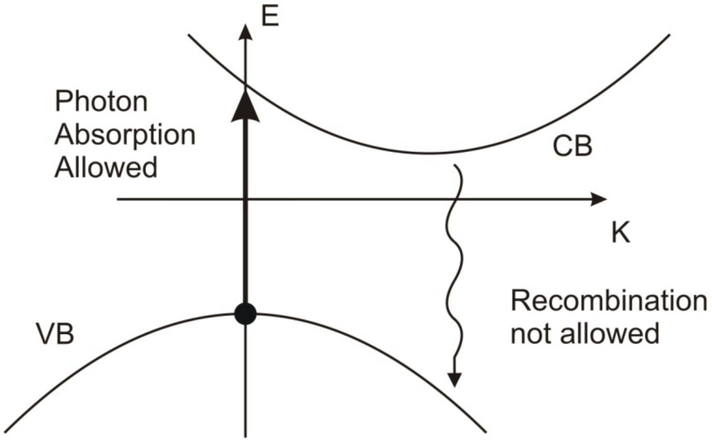
Phys 4061 – Lecture Thirteen – Photodetectors

Recall properties of indirect band gap materials that are used as photodetectors



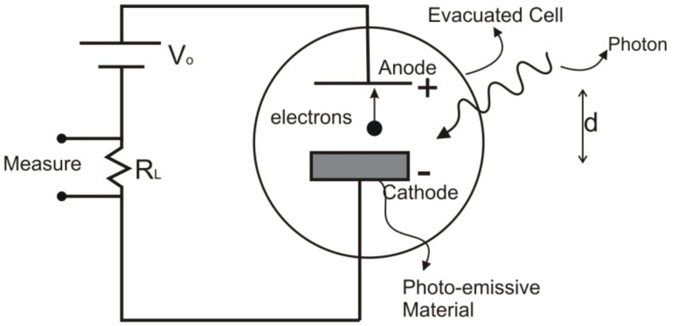
Photoelectric Effect in Semiconductors

$$h\nu > E_g + \chi$$

χ is the electron affinity which is the energy required to eject electrons into conduction band.
The efficiency of escape large for injected electrons since there are few collisions with other electrons and lattice.
These electrons can be swept into an external circuit.
Here, the kinetic energy of photoelectrons depends on frequency ν and the number of electrons depends on the intensity of light

Vacuum Photodiode [a simple photodetector]

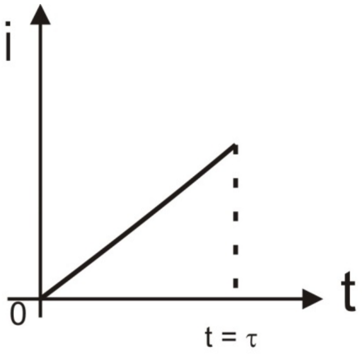
- electrons swept into external circuit produce a current through R_L. The signal is the voltage across R_L.



$$i = \left(\frac{P}{h\nu}\right) q\eta$$

- P is the power
- q is the electron charge
- V_o is the battery voltage
- η is the efficiency for conversion of photons to electrons

The responsivity, $R = i/P = q\eta/h\nu$ (units of Amps/W)



Work done on electrons $\Delta W = F\Delta x$

$$\Delta W/\Delta t = qEv(t)$$

This represents increase in kinetic energy. Here v is the electron speed through free space between electrodes and E is the electric field.

External power supplied by battery is $V_o i$

$$i = (qE/V_o)\, v(t)$$

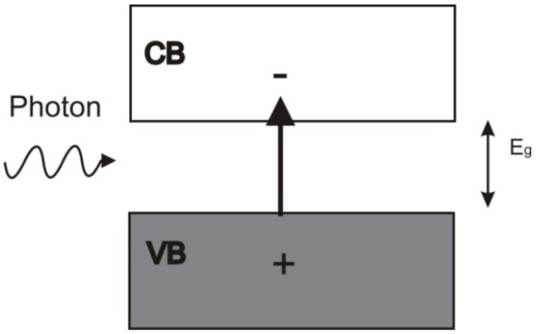
- current depends on v(t)
- electrons reaches anode in time τ
- current not zero even when electrons transverses gap

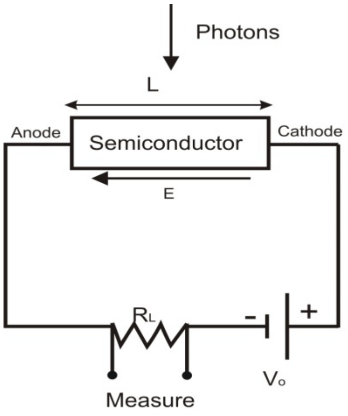
Show that Response Time of detector

$$\tau = \sqrt{\left(\frac{2md}{qE}\right)} = d\sqrt{\frac{2m}{qVo}}$$

- τ smaller for large V_o and small d
- vacuum photodiodes requires higher voltage power supply

Photoconductive Detector is also based on the internal photoelectric effect





Electrons are excited to CB by light. Due to the electrical conductivity, the electron-hole pairs are swept into external circuit using an electric field from a battery.

- For Photodiodes
  - usually reverse biased
  - conduction only when light is incident
  - Background current i_o without light is due to thermal generation of electron-hole pairs

    $$i_o = \frac{V_o}{R_L + R_d}$$
- V_o is the battery voltage and R_d is the semiconductor resistance

$$i_{total} = i_o + i_s$$

Where the signal current is i_s, the measured voltage drop is iR_L and R_L is the load resistance.
The Drift velocity of electrons, $v_e(t)$ is not linear because of collisions.

$v_e = \mu_e E$ (Electron Drift Velocity)
$v_h = \mu_h E$ (Hole Drift Velocity)
μ_e and μ_h are hole and electron mobilites
$\mu_e >> \mu_h$ so holes are unimportant
$i_s = (qE/V_o)\ v(t) = q\ \mu_e E/L$

Where L is the length of the semiconductor
Note that $v_e(t)$ is linear for vacuum photodiodes
The total charge, Q is the effective charge transfer due to 1 photon

$$Q = \int i_s\, dt = q\ \mu_e V_o \tau / L^2$$

- Photoconductive Gain, $G = Q/q = \mu_e V_o \tau / L^2 = \tau / t_{transit}$
- $t_{transit}$ = time to move across semiconductor

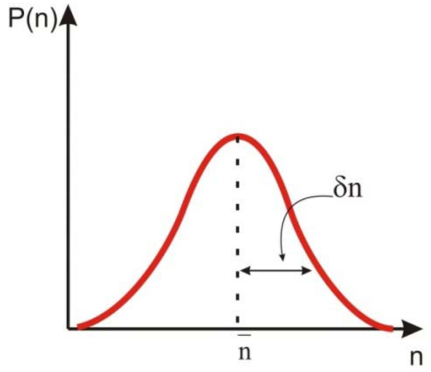
$$t_{transit} = L/v_e = L^2/\ \mu_e V_o$$

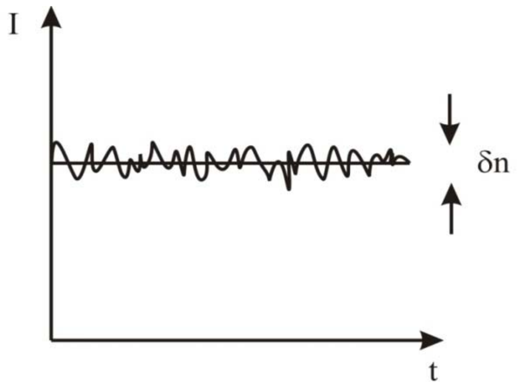
- if τ in CB is longer than $t_{transit}$ then $G > 1$
  - this is possible if electron that left the semiconductor is replenished
  - Otherwise the gain medium will saturate as a function of V_o
- signal current, i_s due to incident light

  $$i_s = (P/h\nu)\eta_{abs} G q$$
- η_{abs} is the fraction of photons that are absorbed

Remarks about Shot Noise

Shot noise is associated with the distribution of electron arrival times in a circuit.





The statistical distribution of arrival times can be described by a Poisson distribution given by

$$P(n) = \frac{(\bar{n})^{n} \exp[-\bar{n}]}{n!}$$

P(n) is the probability of electron arrival in Δt

- n is the number of electrons
- $\bar{n}$ is the average number in time Δt

$$\bar{n} = (\bar{\imath} / q)\, \Delta t$$

- where i is the average current
- for large n, the Possion becomes Gaussian and the FWHM δn is given by

$$\delta n = \frac{\sqrt{\bar{n}}}{\bar{n}} = \frac{1}{\sqrt{\bar{n}}}$$

The distribution is sharper for larger $\bar{n}$

$$i_{inst} = \frac{qn}{\Delta t}$$

$$\delta i_{inst} = \left(\frac{q}{\Delta t}\right) \delta n = \sqrt{\frac{q\bar{\imath}}{\Delta t}}$$

Note that the current noise increases for smaller Δt

The detection bandwidth $B = \frac{const}{\Delta t}$

$$\delta i_{inst} = \sqrt{2q\bar{\imath}B}$$

This result shows that shot noise can be reduced by decreasing the bandwidth. This would result in an increase in measurement time.
Alternatively, achieving an increase in current can reduce shot noise.

However, $i_{total} = i_o + i_s$ where $i_o = V_o/(R_L+R_D)$
The contribution of shot noise from i_o can be reduced by increasing R_L. However, this increases Johnson Noise.

Johnson Noise is due to thermal motion of elections as they travel through a circuit. It can be shown that the Johnson Noise current is given by

$$i_N = \sqrt{\frac{4k_B T B}{R_L}}$$