Semiconductor Optoelectronic Devices

Chapter 13:
Optical Detectors

By: Iran Hashemi
Supervisor : Dr. Mohmmad Ali Mansouri Birjandi

contents

- ❖THERMAL DETECTORS
  - ✓Time Response
  - ✓Thermoelectric Detector
  - ✓Pyroelectric Detector
- ❖PHOTON DETECTORS
  - ✓Photoelectric Effect
  - ✓Vacuum Photodiode
  - ✓Photomultiplier
  - ✓Photoconductive Detectors
- ❖NOISE IN PHOTON DETECTORS
  - ✓Shot Noise
  - ✓Johnson Noise

Optical detectors

Optical detectors :light is detected and converted into an electrical signal

1. Thermal : optical absorbed converted into a voltage.

tend to be slow , not very sensitive,detect light over a very wide wavelength range

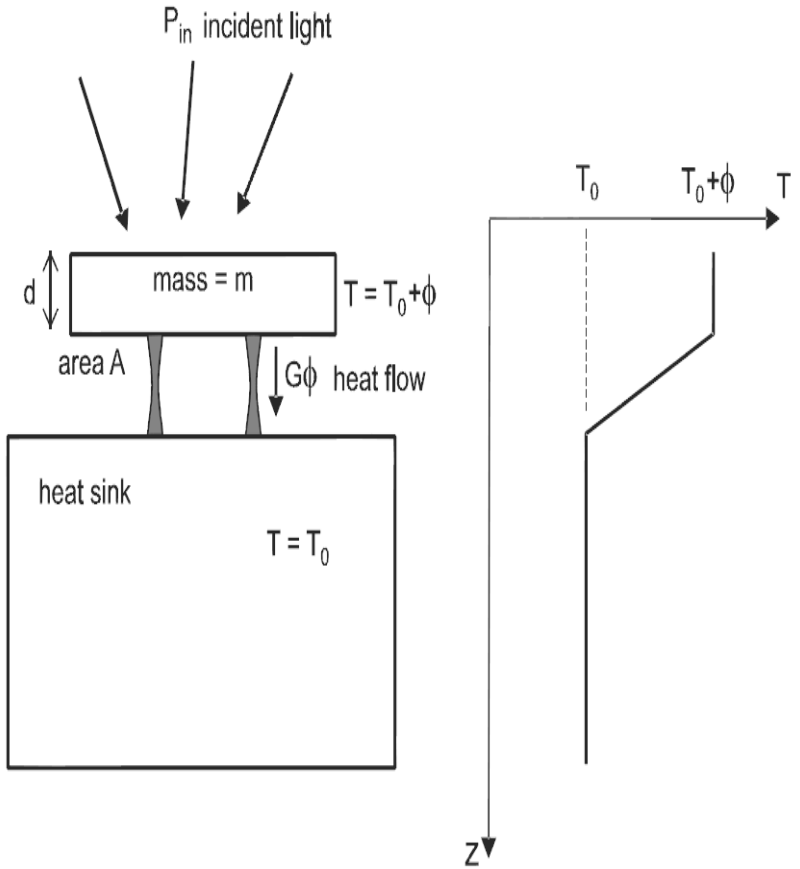
2.Photon : light absorbed directly creates charge carriers, which give rise to a photocurrent and signal voltage.

being faster , more sensitive, with a more restricted wavelength range

THERMAL DETECTORS

➢how the flow of heat limits the time response and sensitivity in thermal detectors.

Time Response



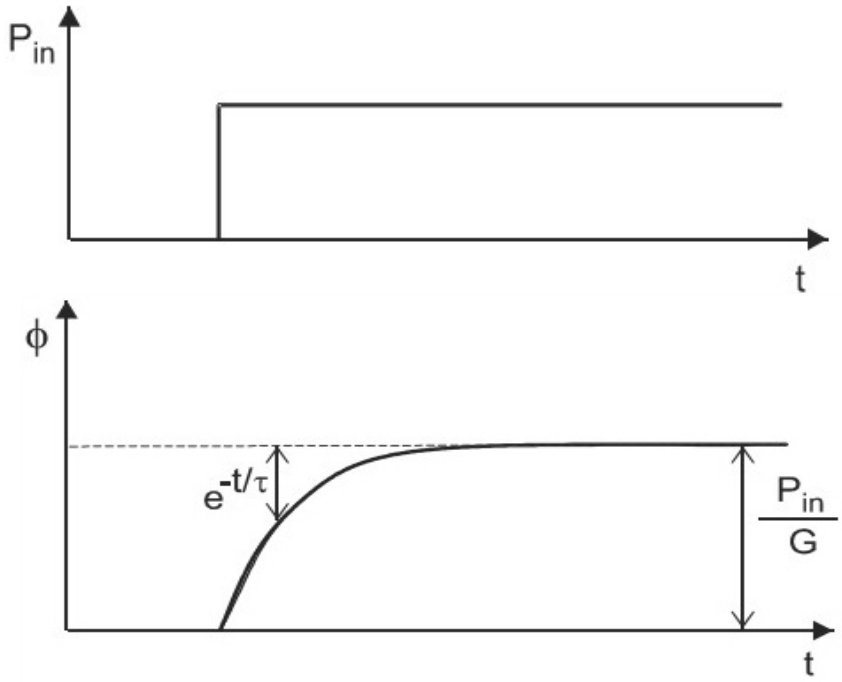
$$\begin{bmatrix}\text{increase in}\\ \text{heat energy}\end{bmatrix} = \begin{bmatrix}\text{light energy}\\ \text{absorbed}\end{bmatrix} - \begin{bmatrix}\text{heat lost}\\ \text{by conduction}\end{bmatrix}$$

$$mC\,\Delta\phi = (P_{in} - G\phi)\,\Delta t$$

$$\frac{d\phi}{dt} + \frac{G}{mC}\phi = \frac{P_{in}}{mC}$$

G : thermal conductance

Time Response



$$\phi(t) = \phi_{\max}(1 - e^{-t/\tau})$$

$$\tau = \frac{mC}{G}$$

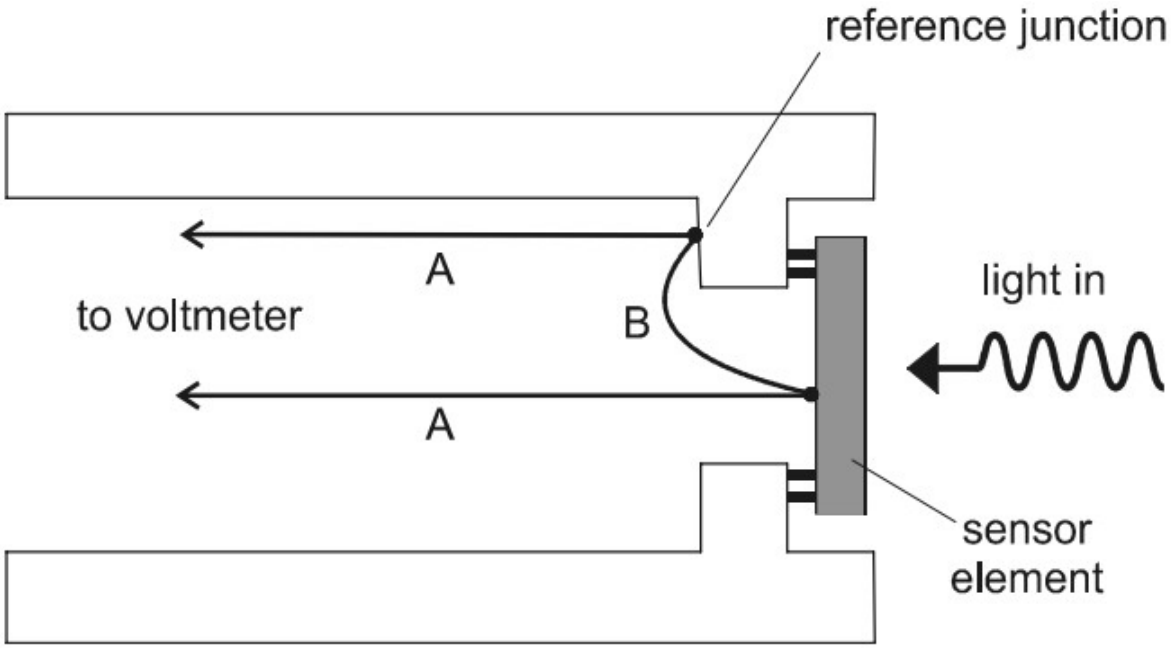
$$\phi_{\max} = \frac{P_{\text{in}}}{G}$$

✓**choice of *G* : trade-off between speed and sensitivity**

✓a smaller mass gives an improved time response, made small in all dimensions , not intercept the incident light, then *Pin is* reduced

Thermoelectric Detector

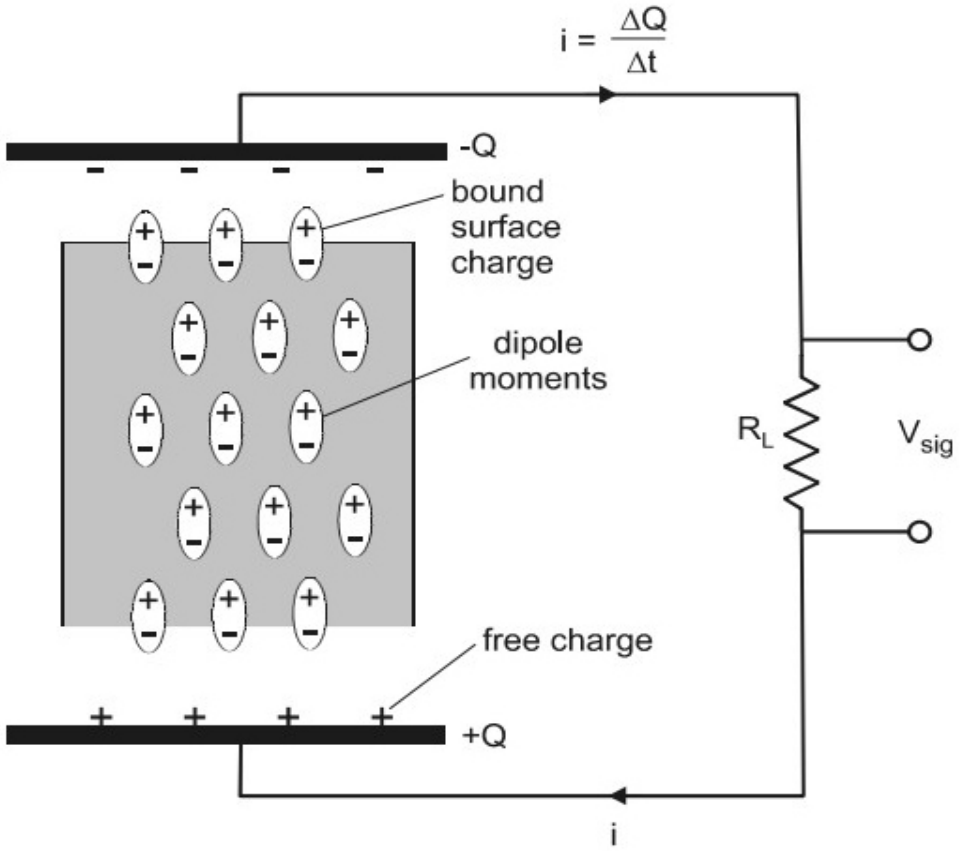
- One method converting the temperature rise into an electrical signal uses a *thermocouple*
- *Thermopile* : thermocouples configured in series *to* increase sensitivity *(*continuous-wave (CW) lasers)

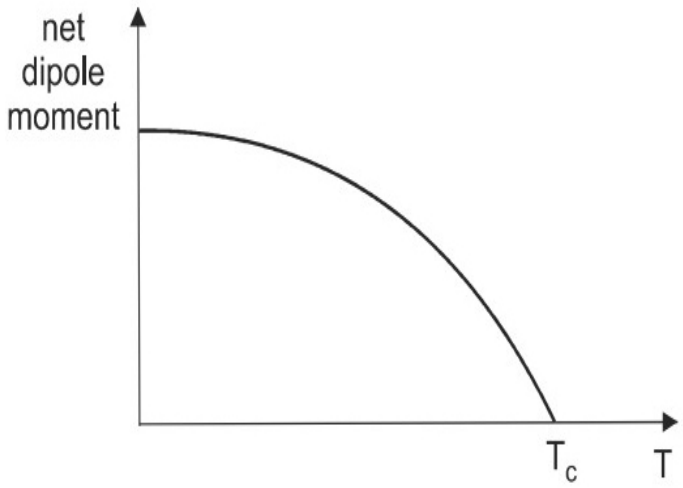


Pyroelectric Detector

➢Another method for detecting the temperature rise uses special crystalline materials :ferroelectrics

➢ pyroelectric effect : conversion of temperature to an electric current or voltage





Pyroelectric Detector

- ferroelectric materials used for pyroelectric detectors include LiNbO3 (lithium niobate) and LiTaO3 (lithium tantalate).

- sensitivity of the pyroelectric detector decreases at lower temperatures, unlike many other types of detectors no advantage to cooling the detector.

- only flows when the temperature is changing, $\Delta Q = 0$ when the temperature is constant ,therfore ,the light power being detected is constant in time, no change in temperature and no signal from the detector

- The pyroelectric detector is best suited for measuring time varying light levels

PHOTON DETECTORS

- operate by the direct conversion of photons into charge carriers

a. *Photoemission* (ejection of an electron by an absorbed photon)

b. *Photoconductivity* (change in electrical conductivity due to an absorbed photon)

Photoelectric Effect

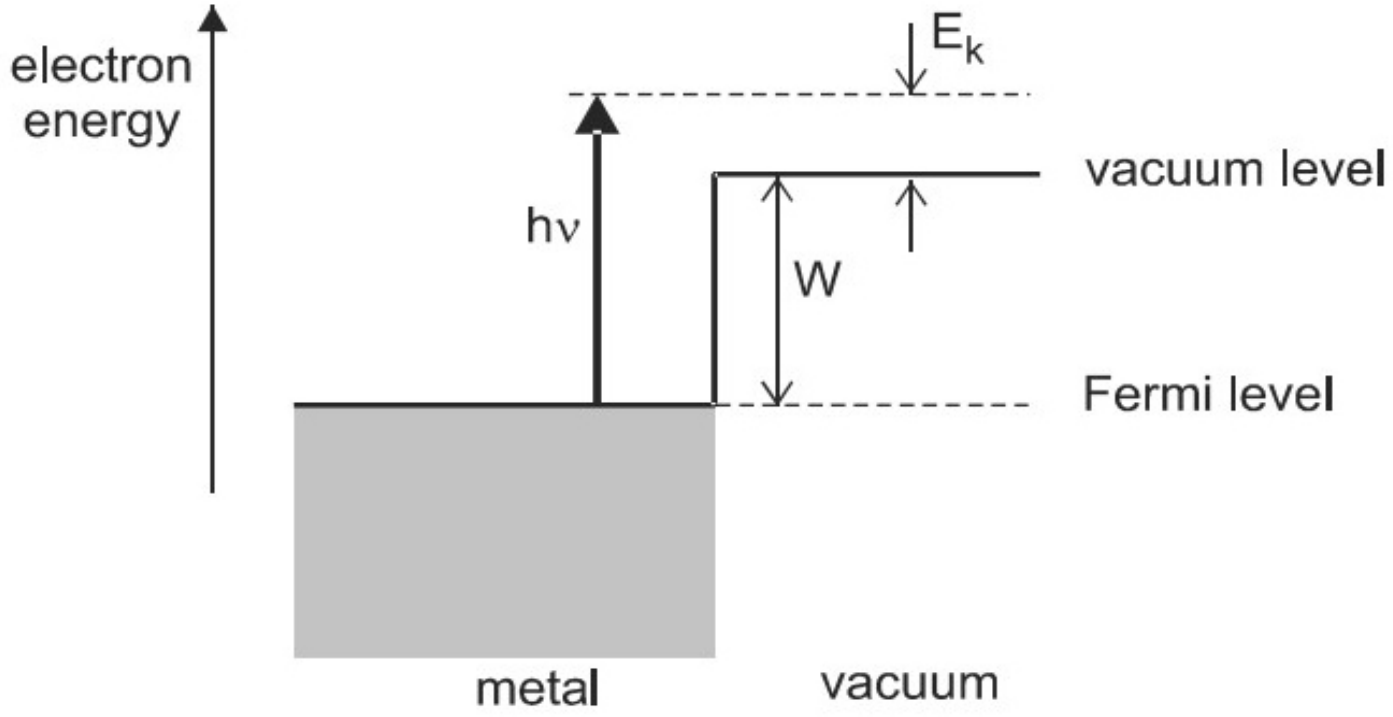
- ✓ In 1905, Einstein ,light consists of energy packets: photons
- ✓ in an absorption process,photon energy is given to an electron in the material
- ✓ energy of each photon is *hv, h is Planck's constant , v is the frequency*

Photoelectric Effect

✓Inside a metal, the electrons have a distribution of energies up to some maximum value, referred to as the Fermi leve

$h\nu > W$ (photon energy for photoemission in metal)

$E_k \leq h\nu - W$ (Electron ejected with kinetic energies)



Photoelectric Effect

- Although $h\nu > W$ *ensures that photoemission is possible, but* all electrons absorbing a photon can not ejected.
- In practice, the fraction of electrons that make it out is quite small in an elemental metal, typically..10^{-3}
- These metals also have a large work function ($W > 2\ eV$)
- not suitable for detection of near-IR wavelengths Therfore elemental metals,seldom used as photodetector materials

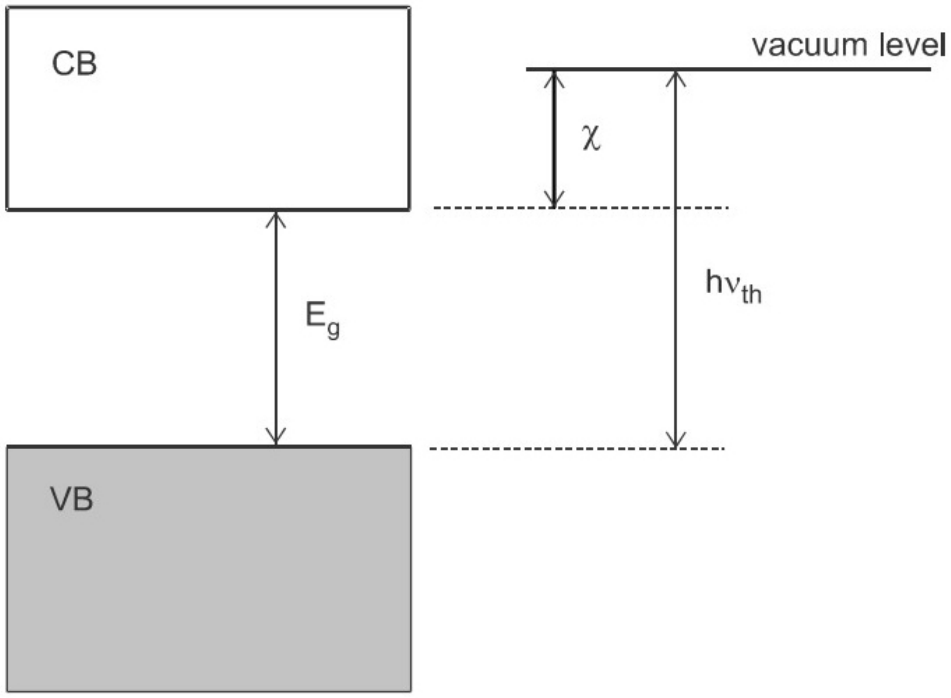
Photoelectric Effect

✓Metallic alloys are much more suited for photoemission-type detectors.

✓electron affinity , x , represents the energy required to eject an electron initially in the conduction band

✓most of the electrons are initially in the valence band

$h\nu > E_g + \chi$ (photon energy for photoemission in semiconductor)

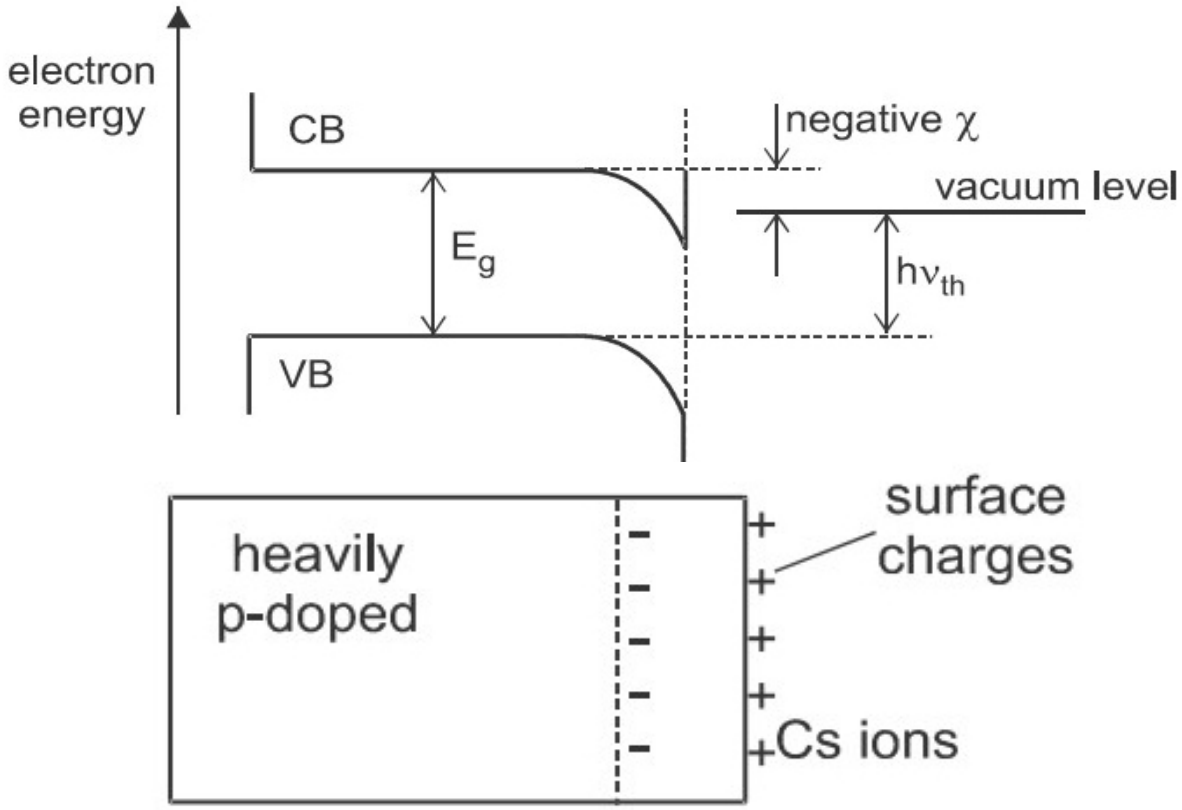


Photoelectric Effect

- escape efficiency for semiconductors is higher than for metals, there are very few free electrons in the conduction band to cause collisions with the ejected Electron
- Metallic alloys also have the advantage that the threshold energy *can be much* lower than for any elemental metal Metallic
- alloys used in photodetectors ,atoms from group I, their outermost electrons have smaller binding energies,therfore smaller bandgap energy

Photoelectric Effect

- to reduce the effective x , even make it negative, by depositing a thin film of Cs on the surface of a highly p-doped semiconductor such as GaAs
- This is important for response of photoemissive detectors to longer wavelengthst



$$\chi_{\text{eff}} = h\nu_{th} - E_g$$

$$h\nu_{th} < E_g$$

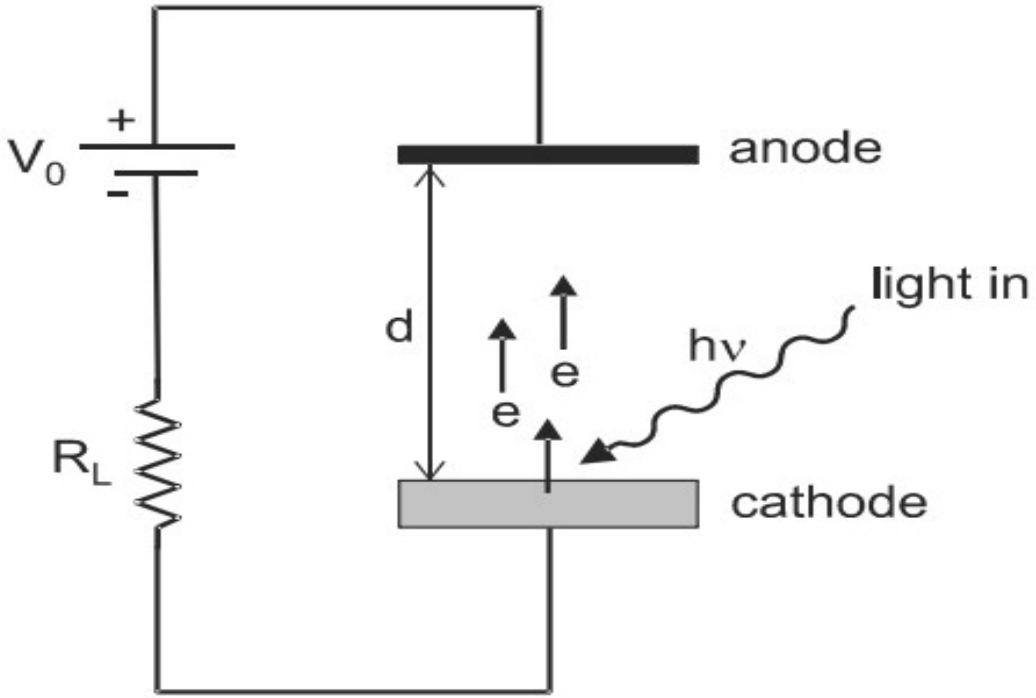
Vacuum Photodiode

- After electrons are ejected from a photoemissive material, they must collected do with vacuum photodiode to obtain a signal.

$$i = \frac{P_{\text{in}}}{h\nu} e\eta$$

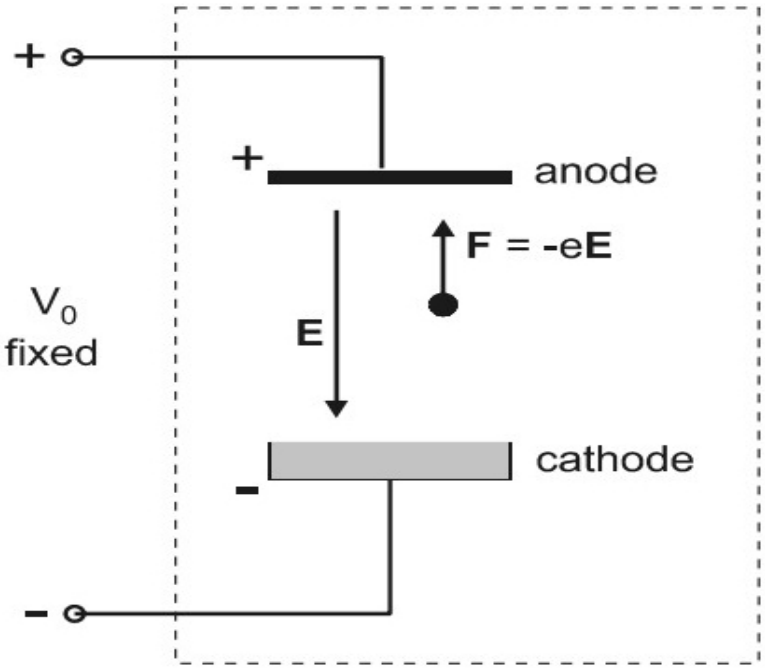
η *efficiency* incident photons

$$\mathcal{R} \equiv \frac{i}{P_{\text{in}}} = \frac{e\eta}{h\nu} \quad \text{(detector responsivity)}$$



Vacuum Photodiode

- what does the time dependence of the current pulse look like when a single electron is ejected from the photocathode and travels to the anode? It might be supposed that the current pulse is only observed when the electron arrives at the anode, where it is "collected."
- The correct answer: current flows constantly during the time that the electron is in transit between electrodes



$$\Delta W = F\Delta x = eE\Delta x$$

$$= eEv\Delta t$$

$$v = \Delta x/\Delta t$$

$$E = V_0/d$$

$$P = \Delta W/\Delta t = eEv$$

$$P_{supplied} = V_0 i = eEv$$

$$i(t) = \frac{eE}{V_0} v(t)$$

Vacuum Photodiode

$$a = eE/m$$

$$v(t) = at = \frac{eE}{m}\,t$$

$$x(t) = \frac{1}{2}at^2 = \frac{1}{2}\,\frac{eE}{m}t^2$$

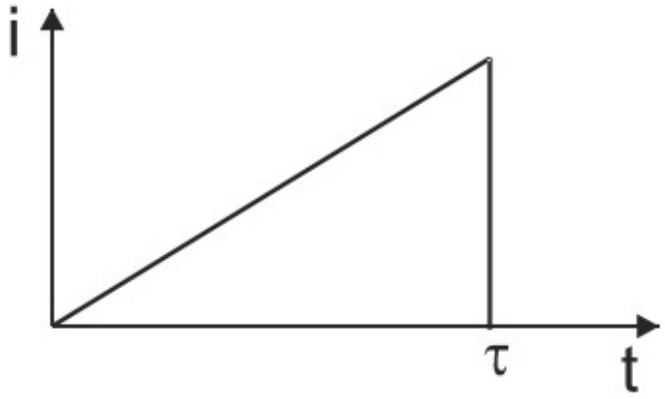
$$d = \frac{1}{2}\,\frac{eE}{m}\tau^2$$

$$\tau = \sqrt{\frac{2md}{eE}} = d\sqrt{\frac{2m}{eV_0}}$$

(vacuum photodiode response time)

✓The time response is be better (smaller) for large voltage *V0* ,small electrode separation *d.*

✓The requirement of a high-voltage power supply limits the practical utility of vacuum photodiodes,



Vacuum Photodiode

- one important parameter for any photodetector is the total charge sent around the external circuit in response to a single absorbed Photon

$$i(t) = \frac{eE}{V_0} v(t)$$

$$Q = \int_0^\tau i(t)\, dt = \frac{e}{d} \int_0^\tau v(t)\, dt$$

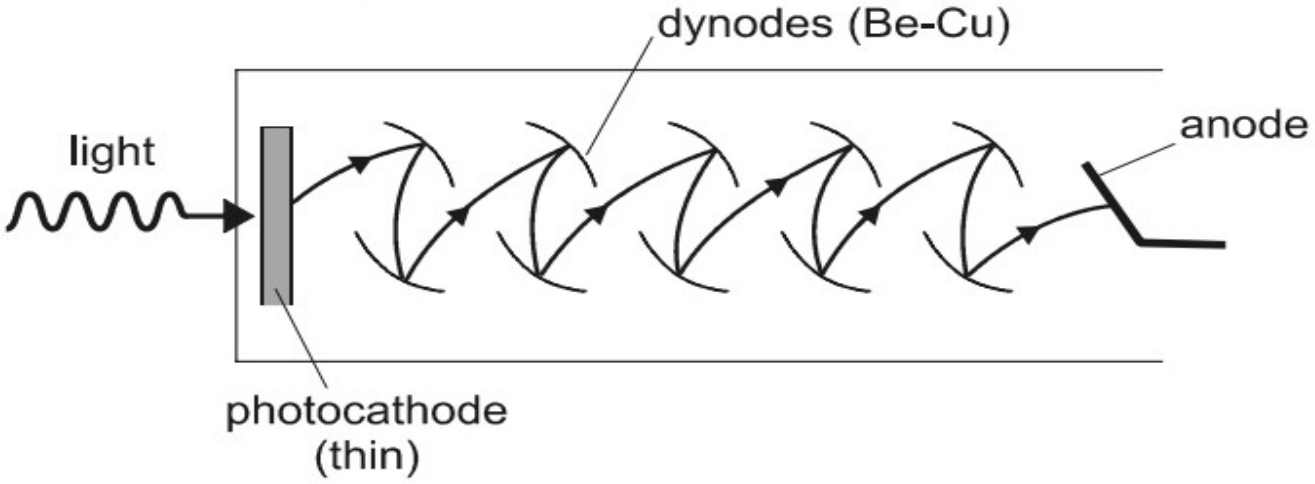
$$Q = \frac{e}{d} \int_0^d dx = e \qquad E = V_0 / L$$

✓**Result: total charge sent around the circuit while one electron is making its transit between the electrodes is just *e***

Photomultiplier

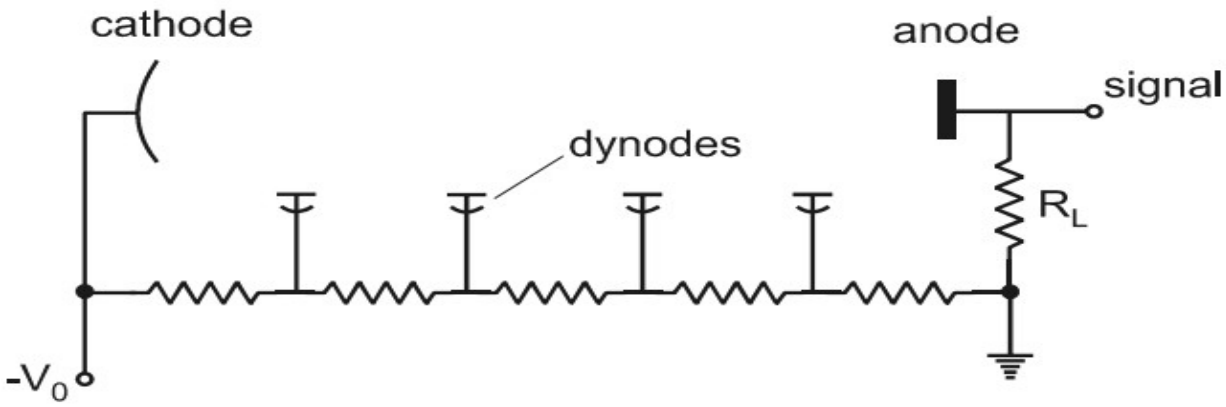
- vacuum photodiode has the advantage of simplicity and reliability for precise power measurements , it is not very sensitive to low light levels.
- One way to increase the sensitivity is to add an amplification section (*photomultiplier*) between the photocathode and anode

$$G = \frac{Q}{e} = \delta^N$$



Photomultiplier

❖It is important to note that the two electrical connections for the signal output are both near ground potential and, therefore, safe to touch and connect to equipment.

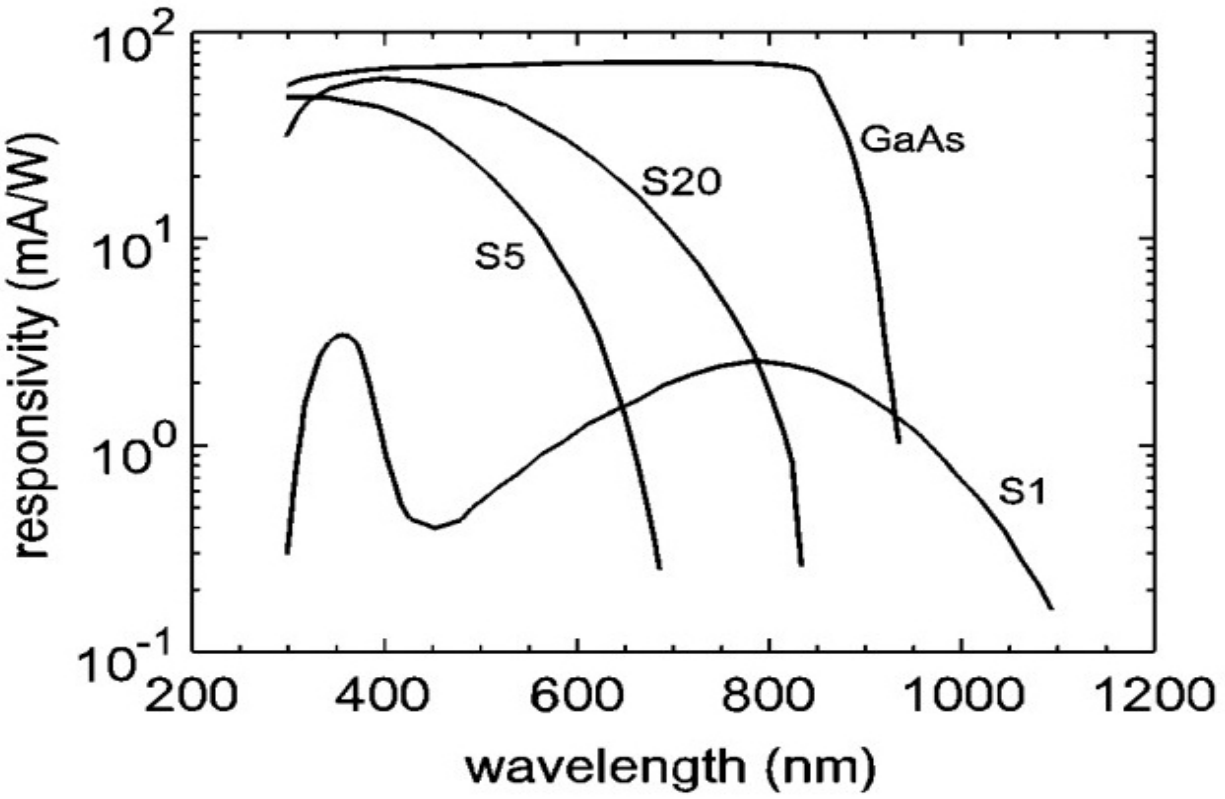


electrical connections inside a photomultiplier tube.

Photomultiplier

❖The spectral response of the photomultiplier depends on the type of photocathode material used.

❖*R values given are for single electron emission from the photocathode, and must be multiplied* by *G to obtain the actual sensitivity of the photomultipler that* denoted by an “S” number



Photomultiplier

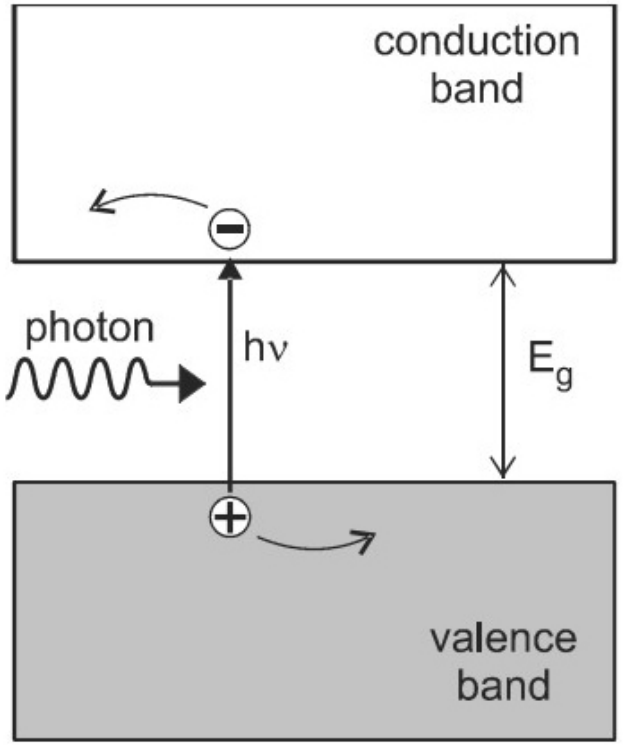
- Na2KSb:S20 :extends from the near UV region out to 800 nm in the IR region. popular photocathode type for measurements in the visible region.

- Ag-O-Cs :S1 : efficiency is relatively low, response extending out past 1000 nm

Photoconductive Detectors

- **internal photoelectric effect** : **an electron in the valence band promoted to the conduction band without being ejected from the material**

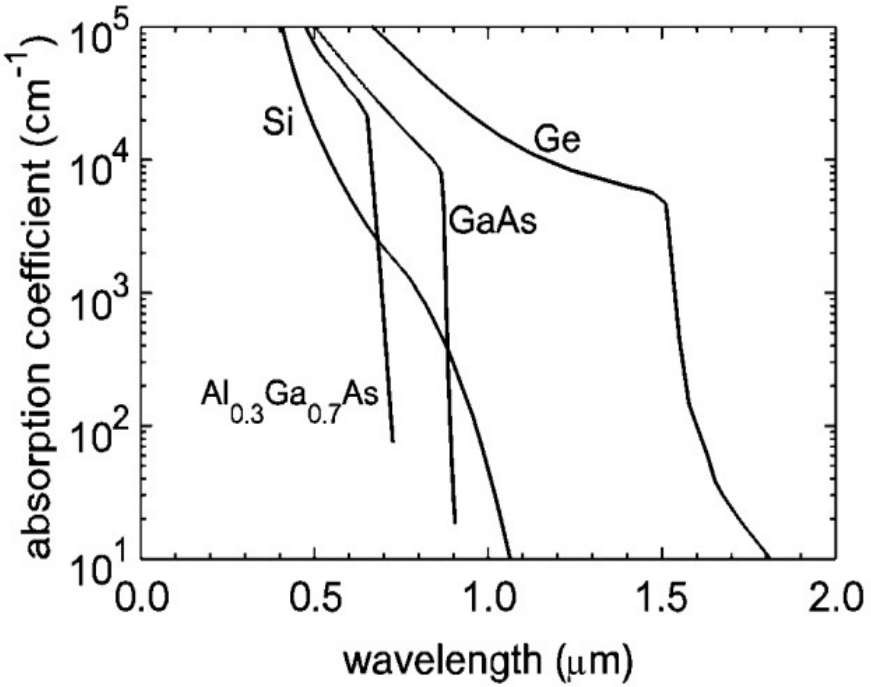
- **Photoconductivity** : **increase in a material's conductivity with absorption of light**



Photoconductive Detectors

- Photons entering the material are absorbed with a probabili α per unit length, where α is the attenuation coefficient

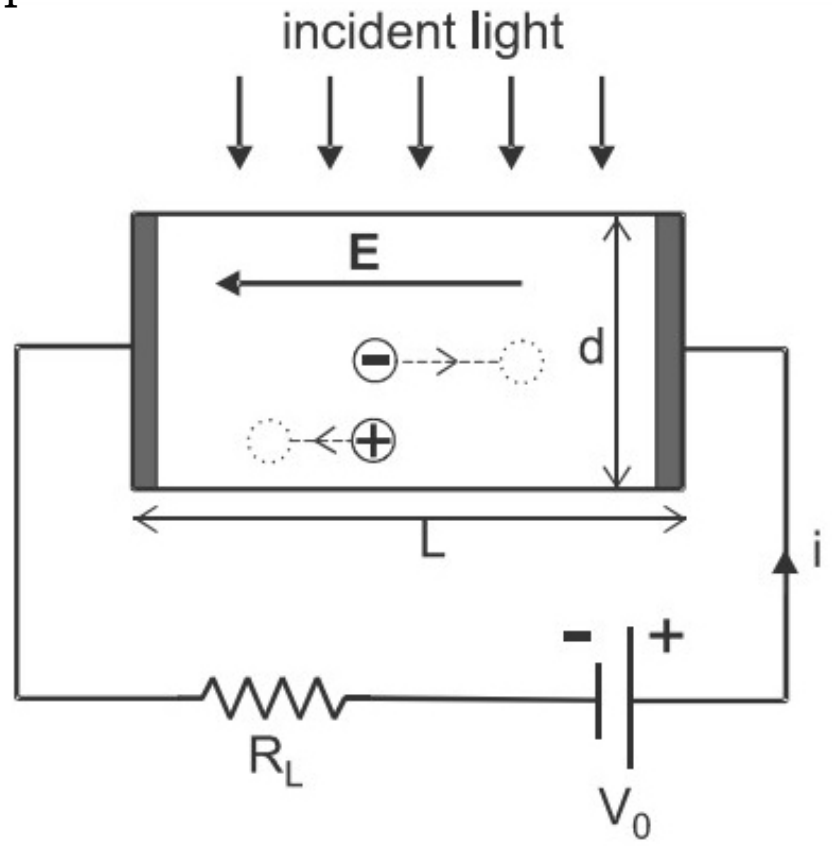
Beer's law, $I(x) = I(0)\exp(-\alpha x)$, where $I(0)$ is the intensity just inside the surfac



$$\eta_{\text{abs}} = \frac{P_{\text{abs}}}{P_{\text{in}}} = (1-R)(1-e^{-\alpha d})$$

Photoconductive Detectors

One important characteristic photocell is ,a background current *io, even when there is no incident light* ,the semiconductor intrinsically has small electrical conductivity, due to thermally generated electron–hole pairs.



$$E = V_0 / L$$

$$i_0 = V_0 / (R_L + R_d)$$

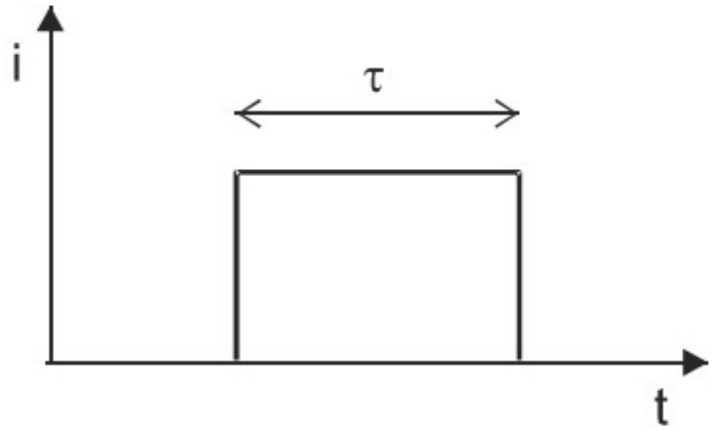
$$i = i_0 + i_s$$

Photoconductive Detectors

➢**both holes and electrons contribute to the signal current**

$$v_e = \mu_e E \qquad i(t) = \frac{eE}{V_0} v(t)$$

$$E = V_0/d \qquad i_s(t) = \frac{e\mu_e E}{L}$$



➢This current is maintained as long as the electron remains in the conduction band, limited by the electron lifetime

$$Q = \int i_s(t)dt = \frac{e\mu_e E\tau}{L} = \frac{e\mu_e V_0\tau}{L^2}$$

$$G \equiv \frac{Q}{e} = \frac{\mu_e V_0\tau}{L^2}$$

➢detected charge (and gain) increases as the applied voltage *V0 increases*

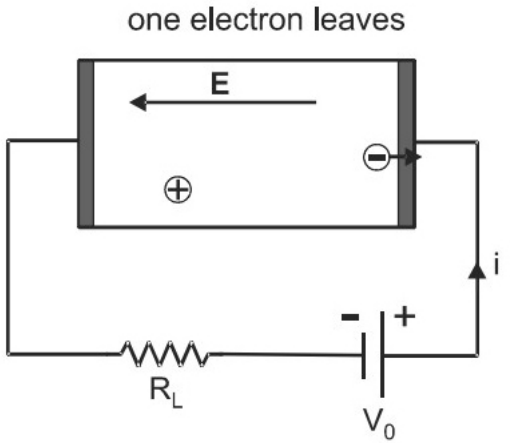
Photoconductive Detectors

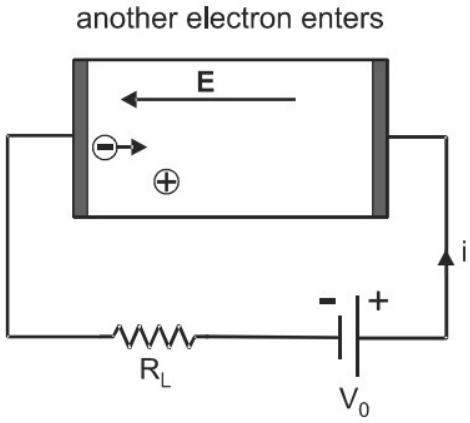
$$t_{tr} = \frac{L}{v_e} = \frac{L}{\mu_e E} = \frac{L^2}{\mu_e V_0} \qquad \text{(electron transit time)}$$

$$G = \frac{\tau}{t_{tr}}$$

❖gain is greater than unity when the electron stays in the CB longer than the time it takes to traverse the semiconductor

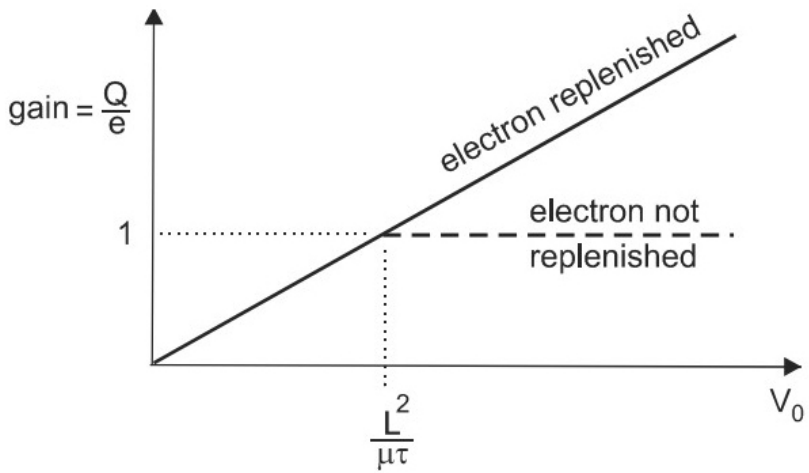
❖The effective τ would then be limited by the transit time *ttr, and the gain limited* to unity. if no additional electrons are released into the semiconductor to take the place of the one that has left





Photoconductive Detectors

$\mu\tau$



- The photoconductive gain increases linearly with applied voltage, and can exceed unity if electrons are replenished after reaching the electrode.

Photoconductive Detectors

- The number of photons striking the semiconductor per unit time will be Pin/h

$$i_s = \frac{P_{\text{in}}}{h\nu}\eta_{\text{abs}}Ge \qquad \text{(photoconductive signal current)}$$

✓applications is the slow response time, determined by the electron lifetime .
✓This can range from 0.1 s to 0.1μ s, slow for high-speed data communications.
✓Photocells ,in photometry, thermometry, and other applications that require precise light-level measurements without the need for fast time response

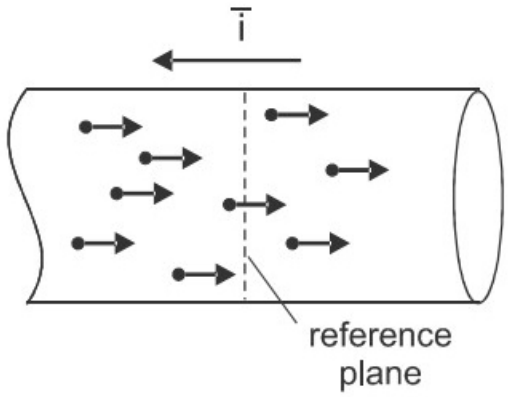
NOISE

1.Shot Noise 2. Johnson Noise

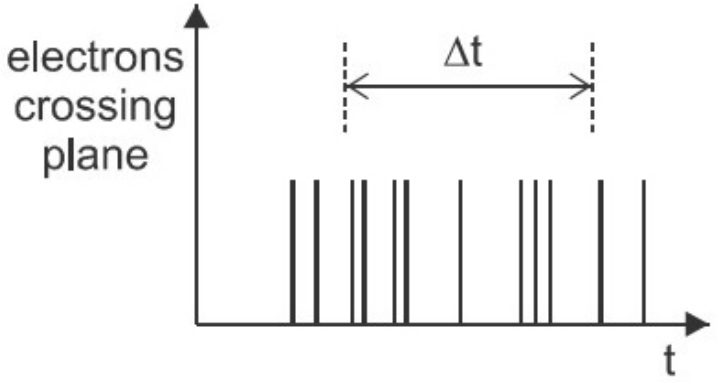
Shot Noise :moving charges give rise to a current

- If there is no correlation between the arrival times of different electrons, the arrival pattern is termed a **Poisson process**

$$P(n) = \frac{(\bar{n})^n e^{-\bar{n}}}{n!} \qquad (poisson\ distribution)$$



(a)



(b)

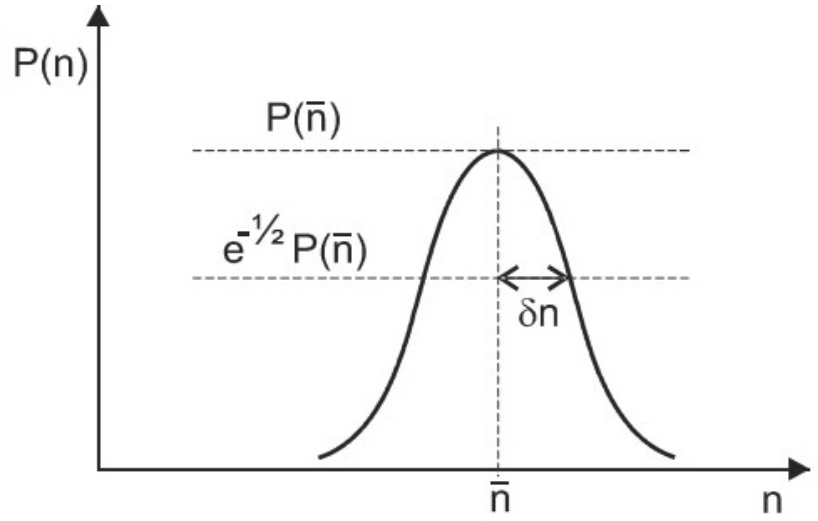
SHOT NOISE

$$\bar{n} = (\bar{i}/e)\,\Delta t$$

✓For large *n, the function P(n) can be* closely approximated by a Gaussian

$$\delta n = \sqrt{\bar{n}} \qquad \text{(width of Poisson distribution)}$$

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



SHOT NOISE

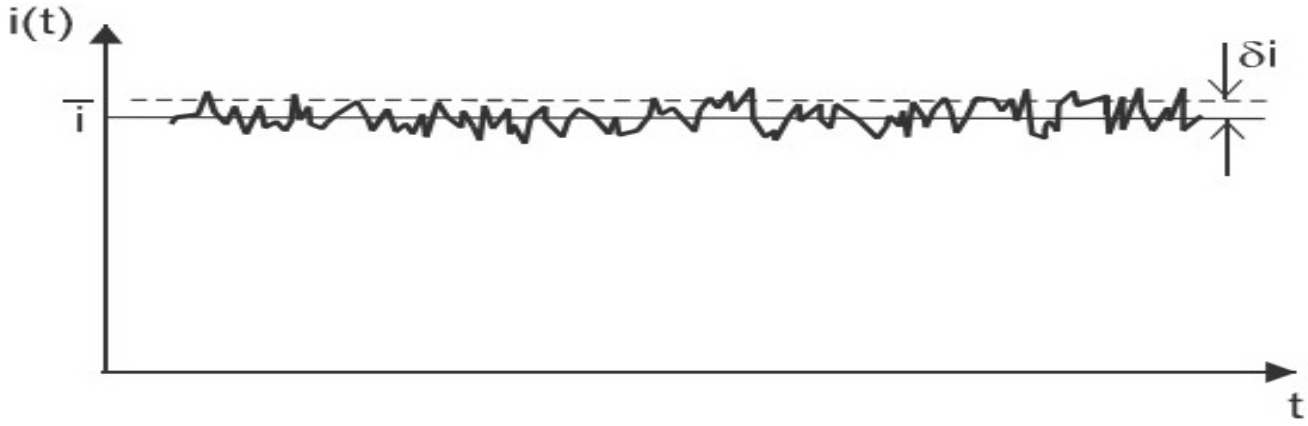
- If the number *n of electrons crossing the reference plane in time t varies*

$$i = \frac{en}{\Delta t}$$

$$\delta i = \frac{e}{\Delta t}\delta n$$

$$\delta i = \frac{e}{\Delta t}\sqrt{\bar{n}} = \frac{e}{\Delta t}\sqrt{\left(\frac{\bar{\imath}}{e}\right)\Delta t} = \sqrt{\frac{e\bar{\imath}}{\Delta t}}$$

- shorter measurement times give a higher noise, and vice versa



SHOT NOISE

$$B = \frac{\mathcal{K}}{\Delta t} \qquad K = 1/2,$$

$$\delta i = \sqrt{2e\bar{i}B} \qquad \text{(shot noise)}$$

❖**One way to reduce the noise** : reduce the detection bandwidth with appropriate electrical filters, restricting the range of modulation frequencies that can be detectedside effect which limits the time response

❖the current increases faster than the noise, and higher currents are expected to give a higher ratio of signal to noise

Johnson Noise

- voltage or current fluctuations in a resistor due to thermal agitation of the electrons in the material.

$$\delta E = k_B T$$

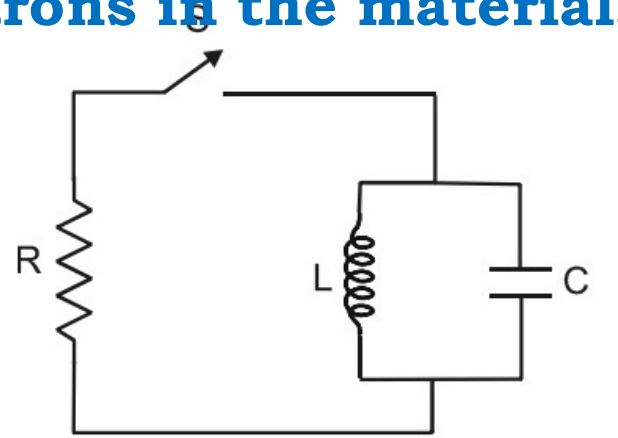
$$\delta P \sim \frac{\delta E}{\Delta t} \sim \frac{k_B T}{\Delta t}$$

$$\delta P \sim \frac{V_N^2}{R}$$

$$V_N \sim \sqrt{\frac{k_B T R}{\Delta t}}$$

$$B = \frac{\mathcal{K}}{\Delta t}$$

K=1/4



$$V_N = \sqrt{4 k_B T R B} \quad \text{(Johnson noise voltage)}$$

$$i_N = \sqrt{\frac{4 k_B T B}{R}} \quad \text{(Johnson noise current)}$$


Thanks For
Your Attention