

OPTOELECTRONICS (2)

Lecture 2.3

Optical Detectors

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References

□ Main references

➤ Textbook:

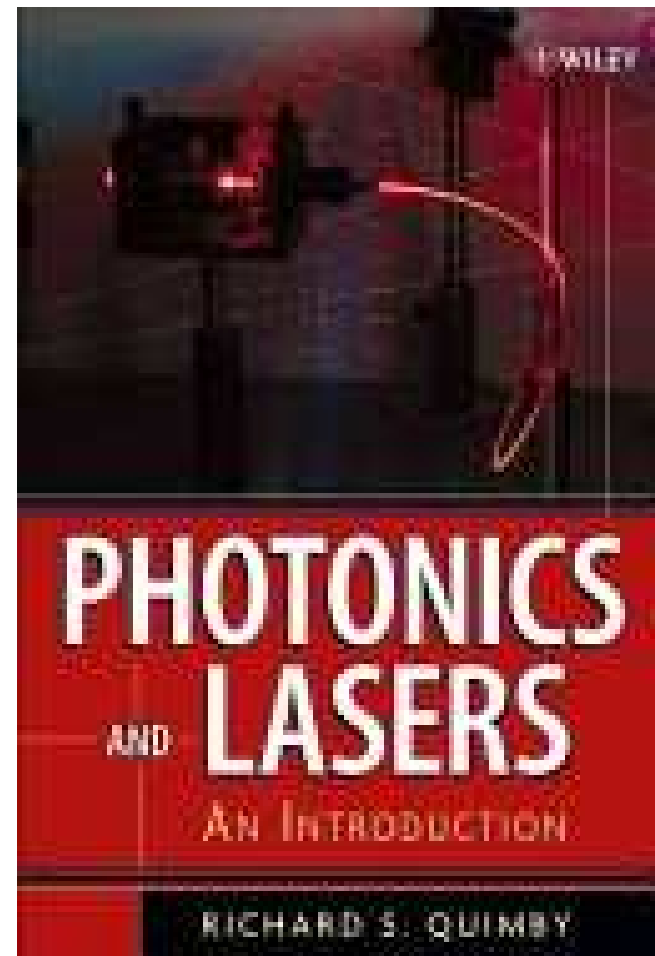
● **Richard S. Quimby**

Photonics and Lasers: An Introduction

JOHN WILEY & SONS, INC. 2006

(Chap.13)

با تشکر از خانم مهندس ایران هاشمی، برای تهیه پاورپوینت



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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

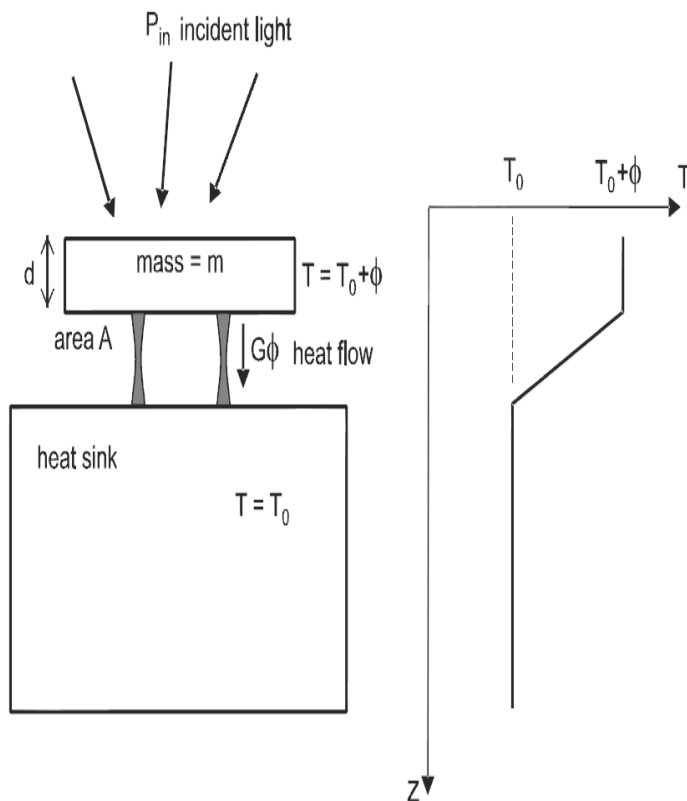
THERMAL DETECTORS

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

Time Response

$$\left[\begin{array}{c} \text{increase in} \\ \text{heat energy} \end{array} \right] = \left[\begin{array}{c} \text{light energy} \\ \text{absorbed} \end{array} \right] - \left[\begin{array}{c} \text{heat lost} \\ \text{by conduction} \end{array} \right]$$

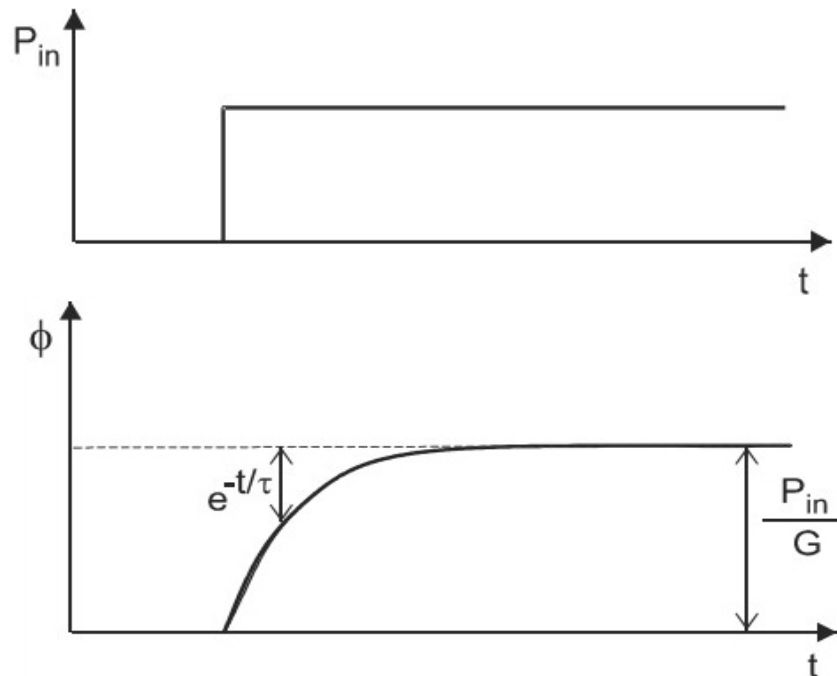
$$mC \Delta\phi = (P_{in} - G\phi) \Delta t$$



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

G : thermal conductance

Time Response



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

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

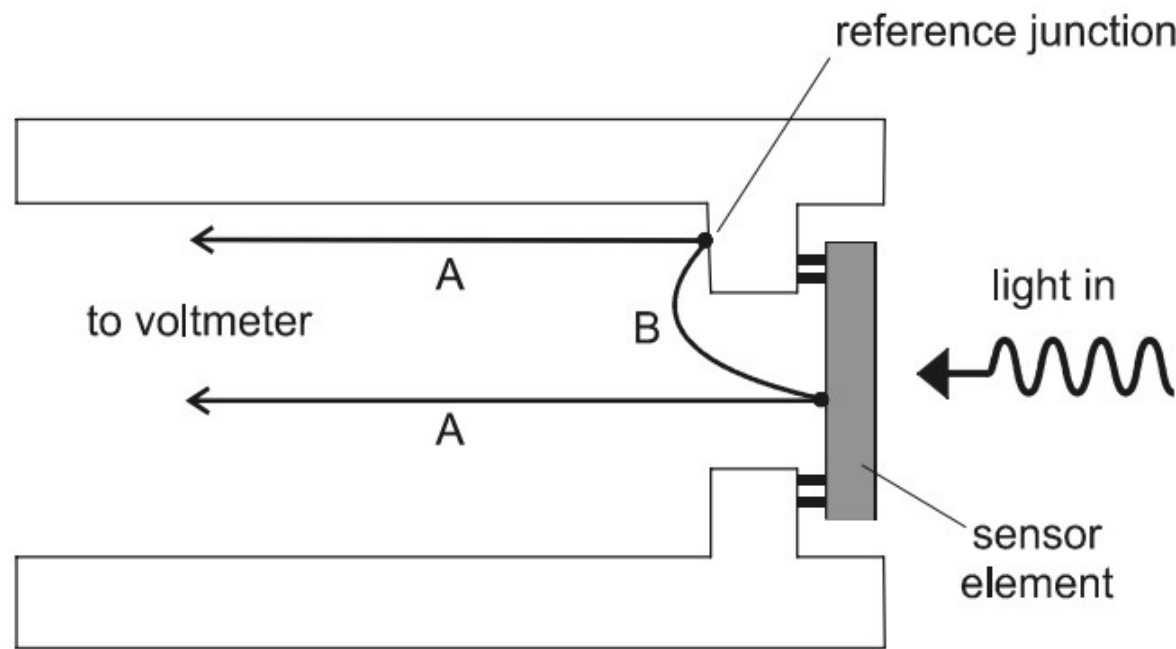
$$\phi_{\max} = \frac{P_{\text{in}}}{G}$$

✓ **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 P_{in} is reduced

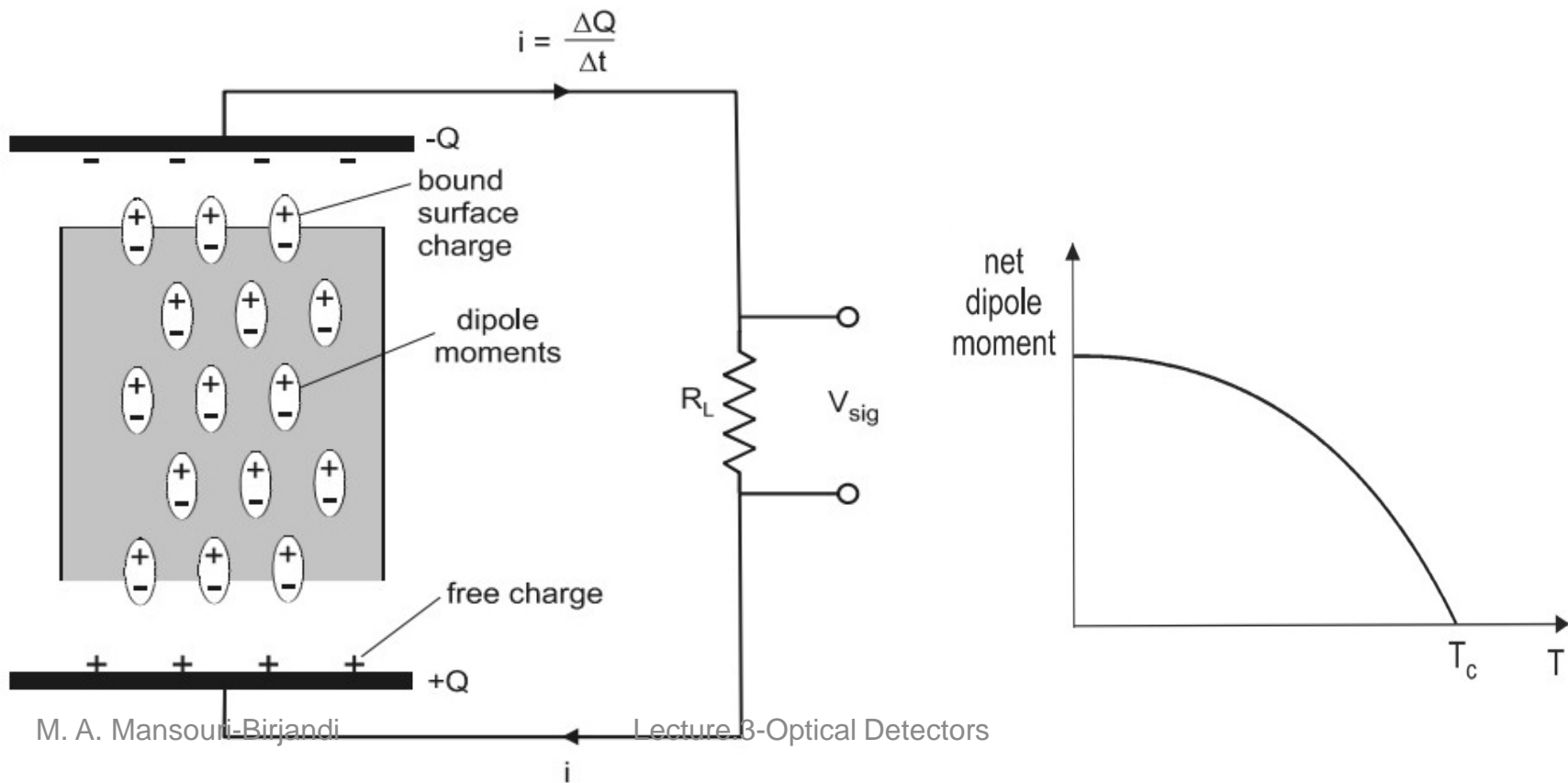
Thermoelectric Detector

- 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, therefore, 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

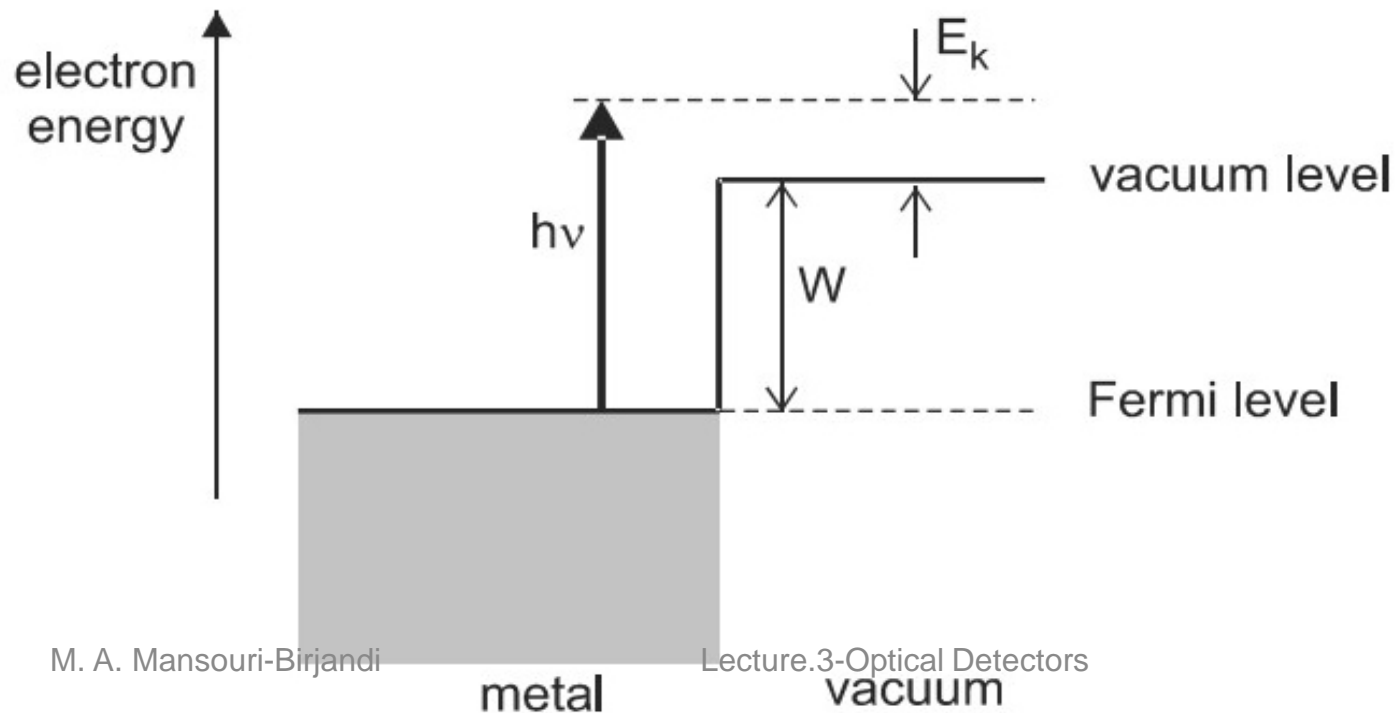
- ✓ In 1905, Einstein ,light consists of energy packets: photons
- ✓ in an absorption process,photon energy is given to an electron in the material
- ✓ energy of each photon is $h\nu$, h is *Planck's constant* , ν is the *frequency*

Photoelectric Effect

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

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

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



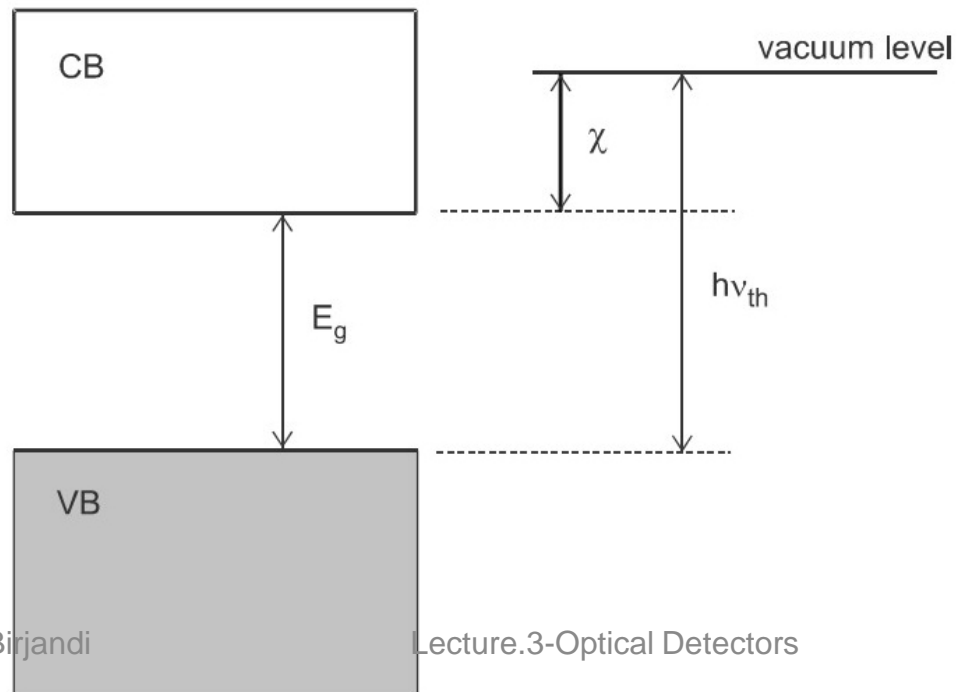
Photoelectric Effect

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

Photoelectric Effect

- ✓ Metallic alloys are much more suited for photoemission-type detectors.
- ✓ electron affinity , χ , represents the energy required to eject an electron initially in the conduction band
- ✓ most of the electrons are initially in the valence band

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



Photoelectric Effect

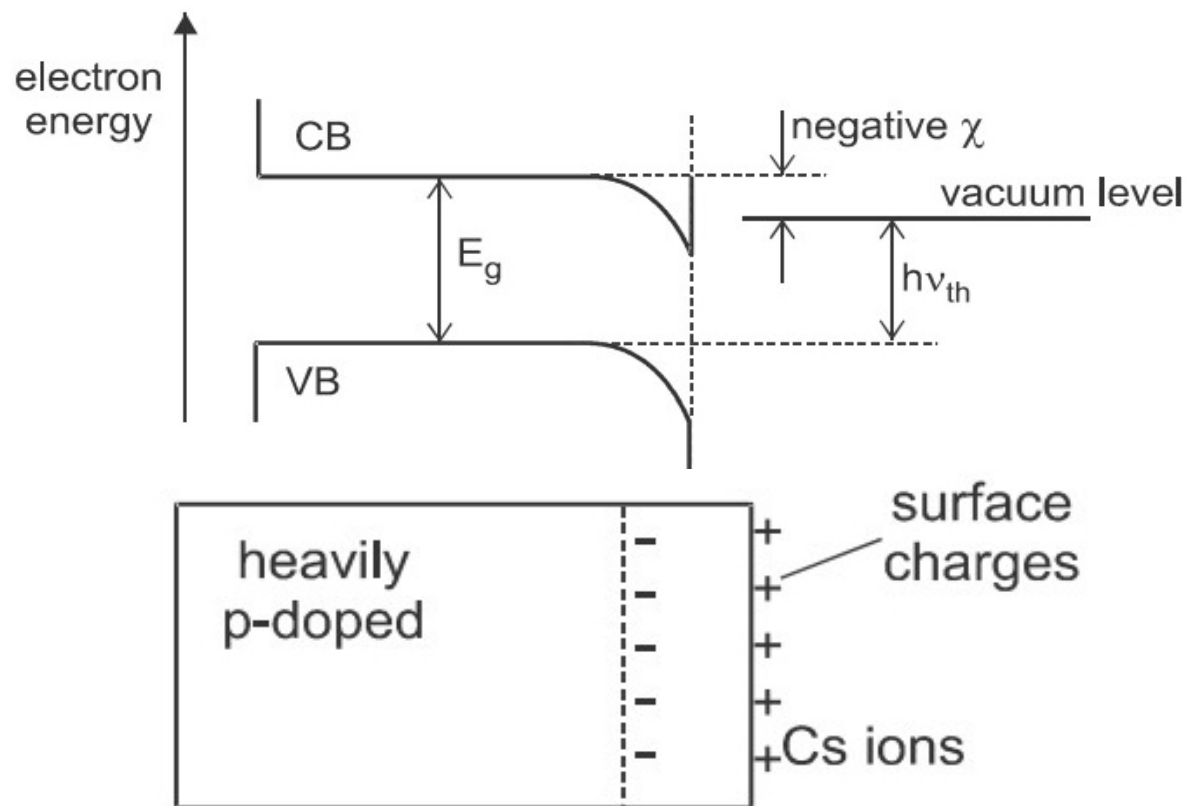
- escape efficiency for semiconductors is higher than for metals, there are very few free electrons in the conduction band to cause collisions with the ejected Electron
- Metallic alloys also have the advantage that the threshold energy *can be much* lower than for any elemental metal Metallic
- alloys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

Photoelectric Effect

- to reduce the effective χ , 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

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

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

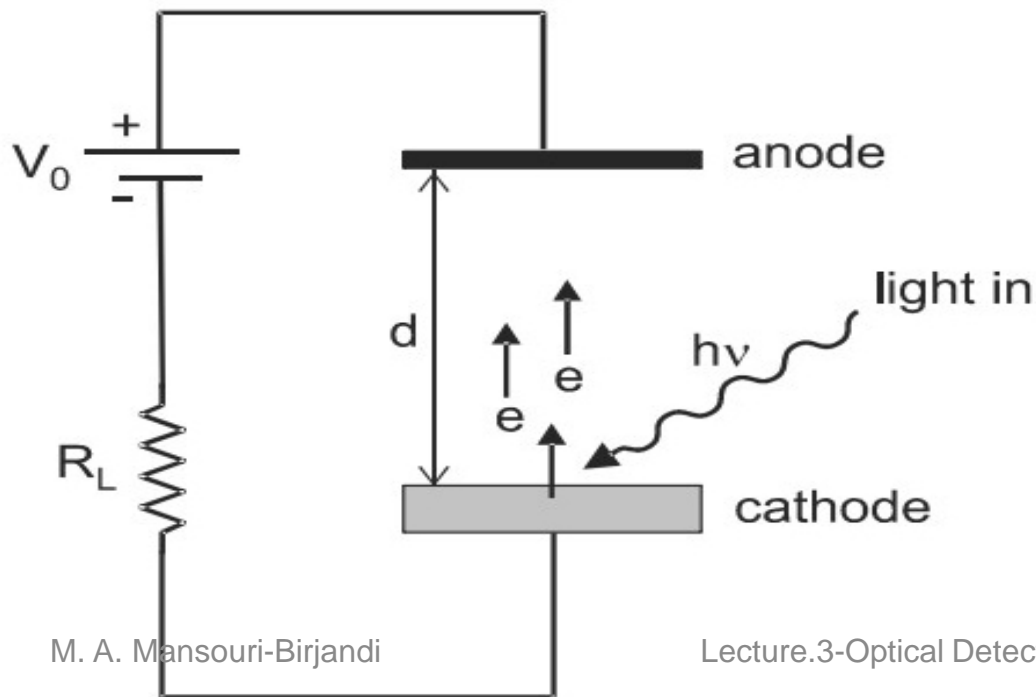


Vacuum Photodiode

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

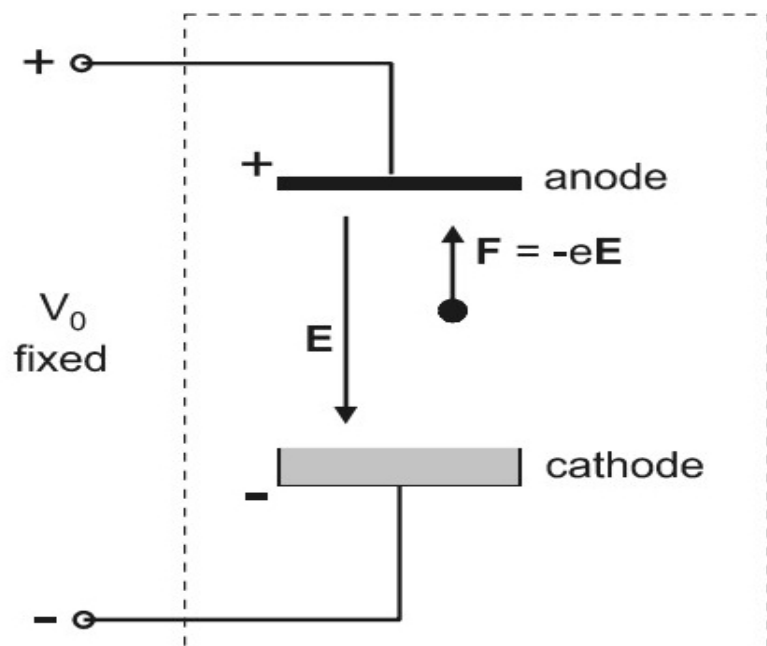
$$i = \frac{P_{\text{in}}}{h\nu} e\eta \quad \eta \text{ efficiency incident photons}$$

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



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

$$a = eE/m$$

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

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

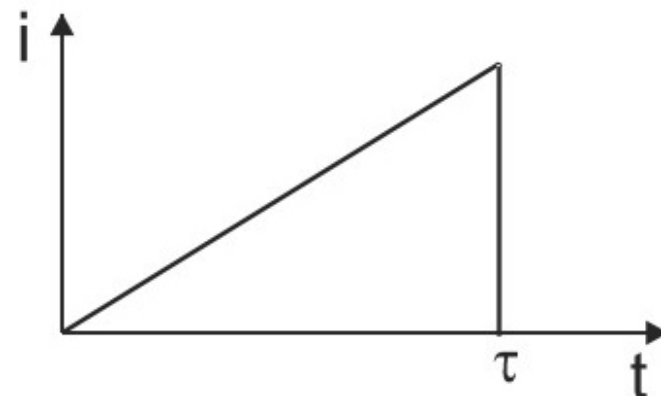
$$d = \frac{1}{2} \frac{eE}{m} \tau^2$$

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

(vacuum photodiode response time)

✓The time response is be better (smaller) for large voltage V_0 ,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

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

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

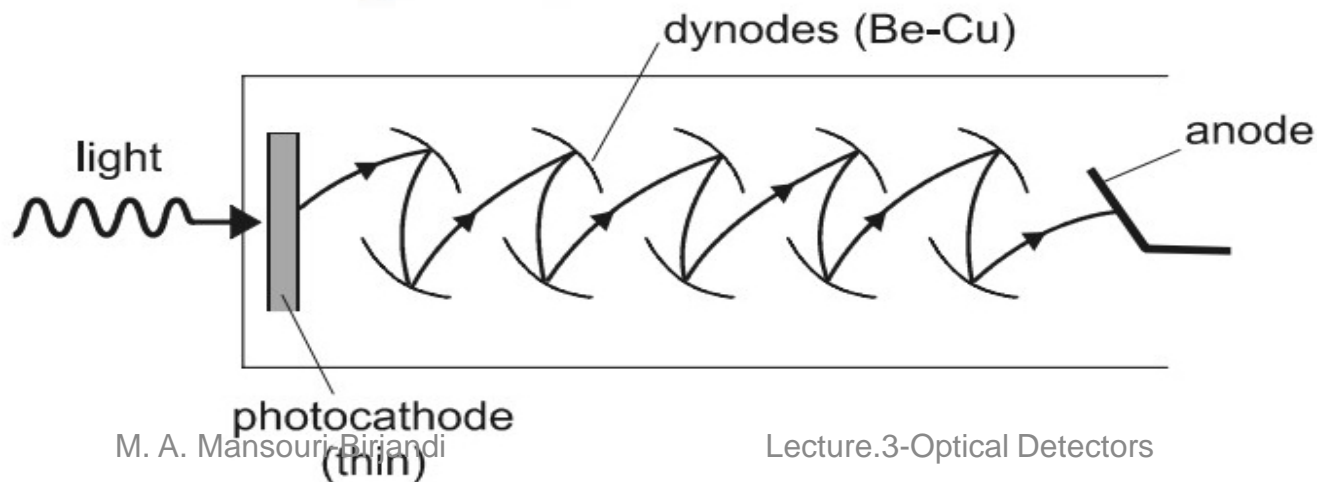
$$Q = \frac{e}{d} \int_0^d dx = e \quad E = V_0/L$$

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

Photomultiplier

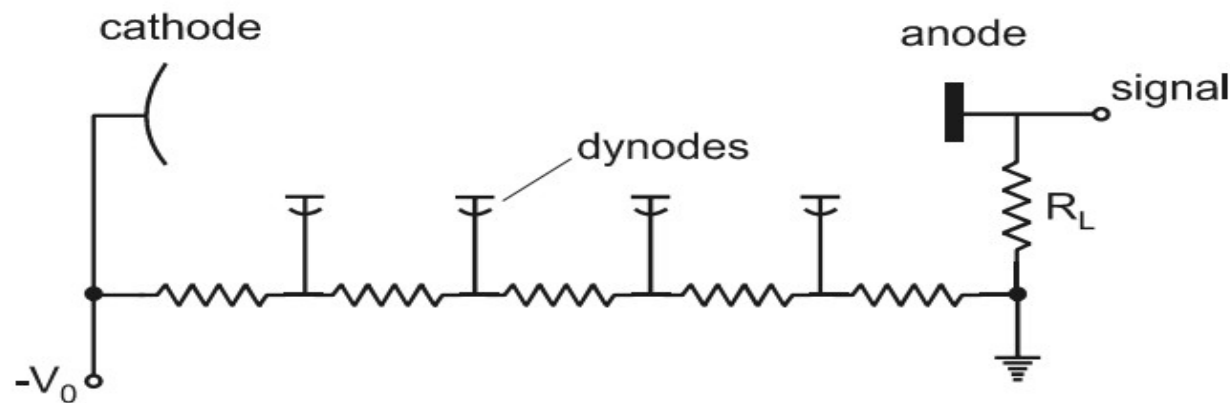
- vacuum photodiode has the advantage of **simplicity** and **reliability** for precise power measurements , it is **not very sensitive** to low light levels.
- One way to increase the sensitivity is to add an amplification section (**photomultiplier**) between the photocathode and anode

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



Photomultiplier

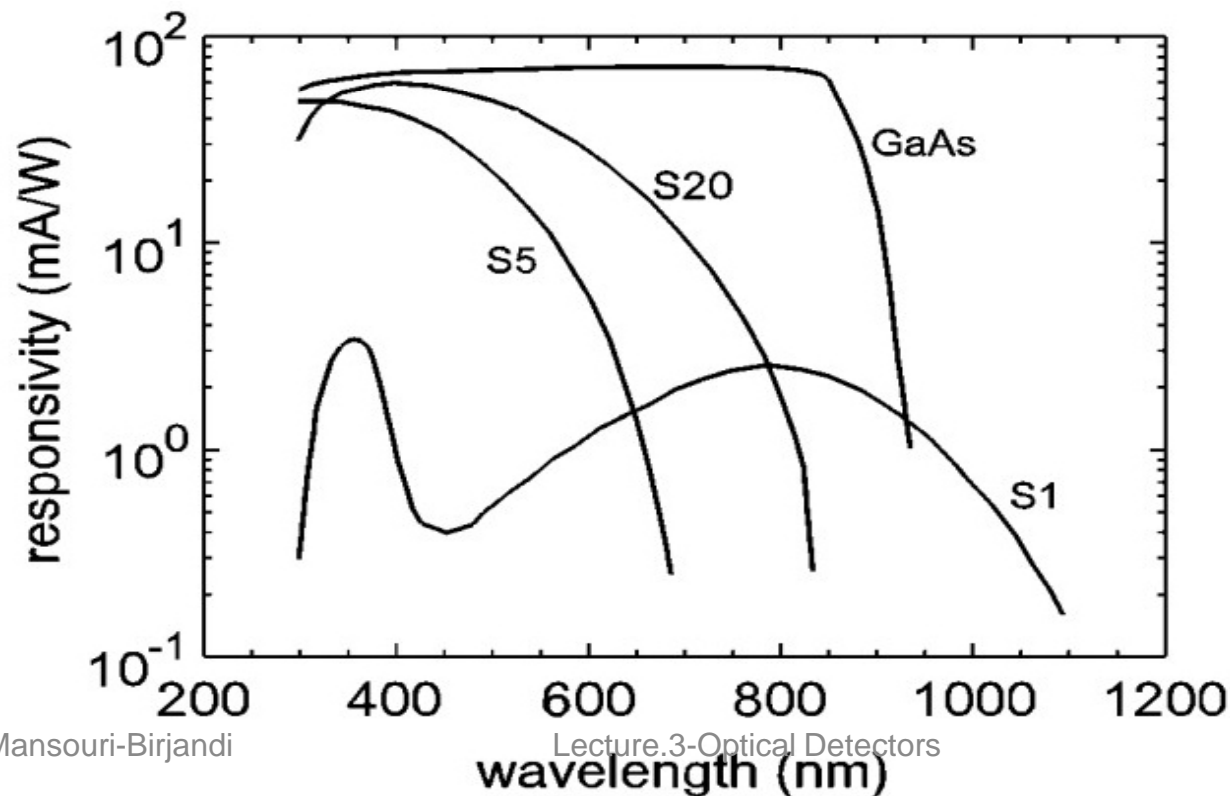
❖ It is important to note that the two electrical connections for the signal output are both near ground potential and, therefore, safe to touch and connect to equipment.



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 photomultiplier that denoted by an “S” number



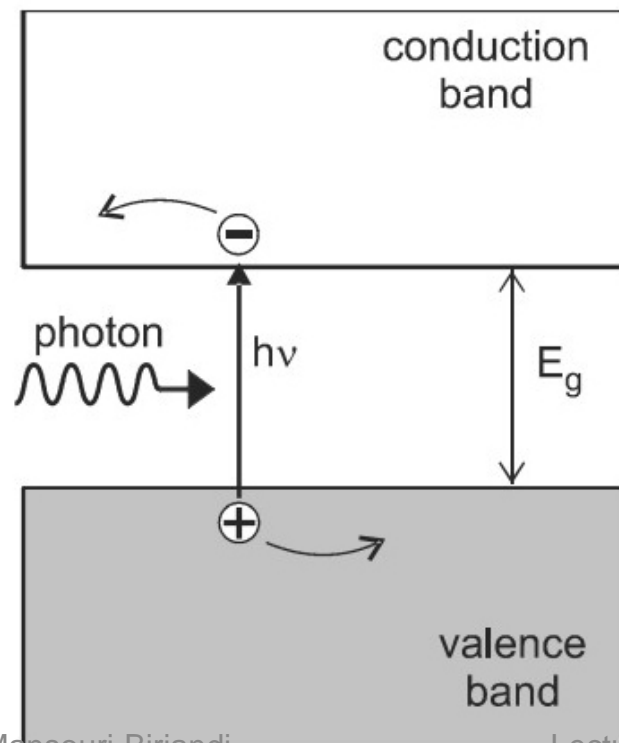
Photomultiplier

- **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

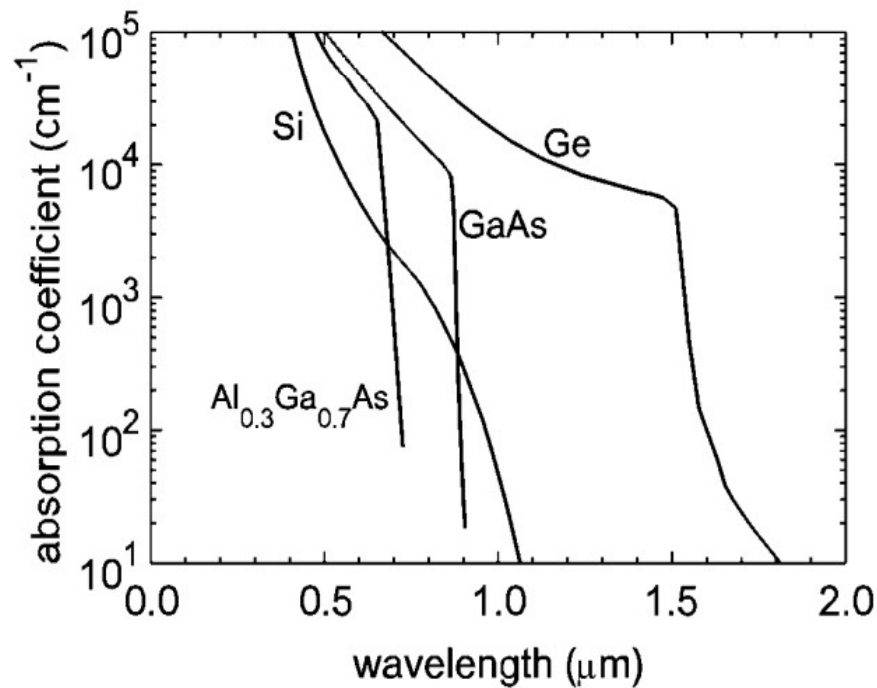
□ **Photoconductivity** : increase in a material's conductivity with absorption of light



Photoconductive Detectors

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

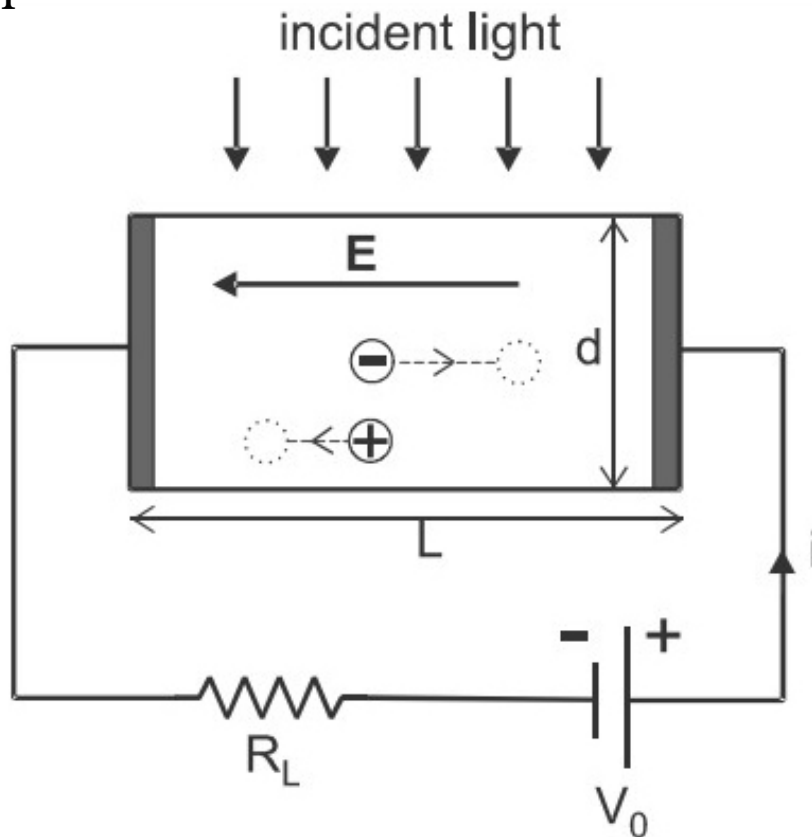
Beer's law, $I(x) = I(0) \exp(-\alpha x)$, where $I(0)$ is the intensity just inside the surface



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

Photoconductive Detectors

One important characteristic photocell is ,a background current i_0 , *even when there is no incident light* ,the semiconductor intrinsically has small electrical conductivity, due to thermally generated electron-hole pairs.



$$E = V_0/L$$

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

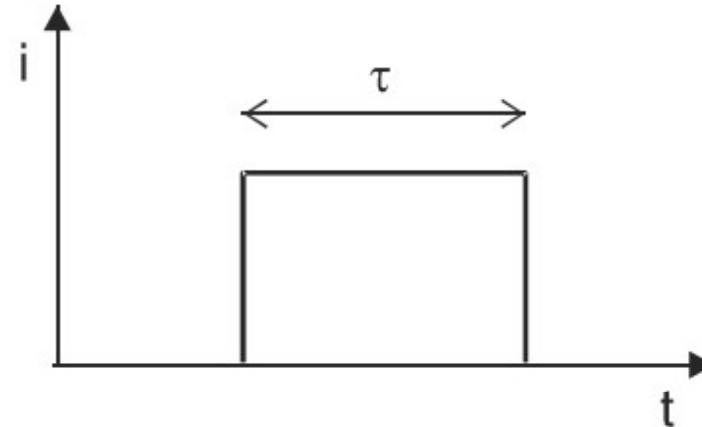
$$i = i_0 + i_s$$

Photoconductive Detectors

➤ both holes and electrons contribute to the signal current

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

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



➤ 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 V_0 increases

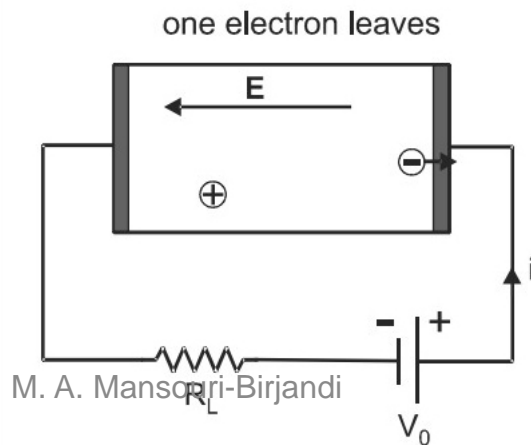
Photoconductive Detectors

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

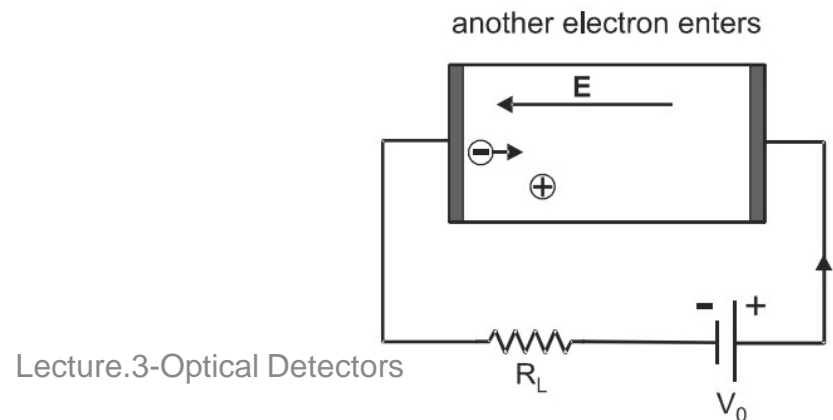
$$G = \frac{\tau}{t_{tr}}$$

❖ 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 t_{tr} , 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

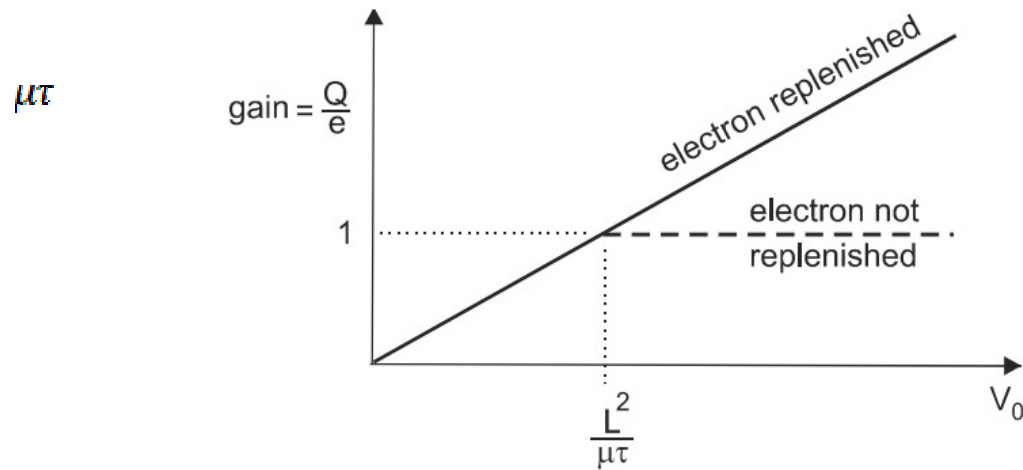


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Lecture.3-Optical Detectors

Photoconductive Detectors



□ 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 $P_{in}/h\nu$

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

- ✓ applications is the **slow response time, determined** by the **electron lifetime** .
- ✓ This can range from **0.1 s to 0.1 μs**, 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

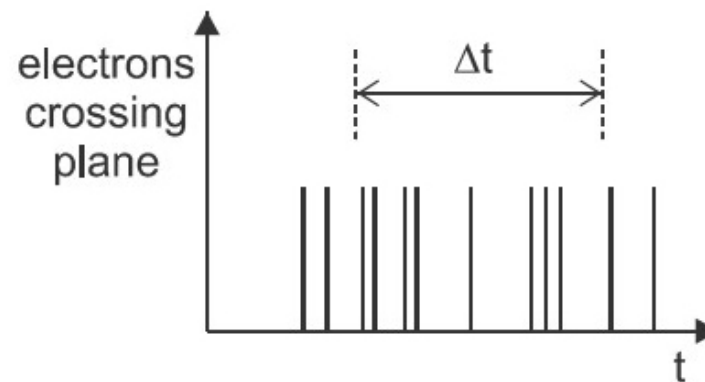
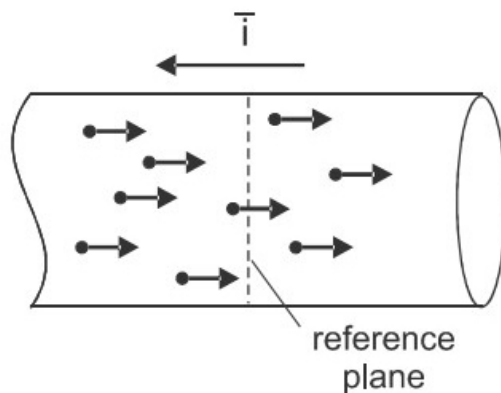
1. Shot Noise

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**

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



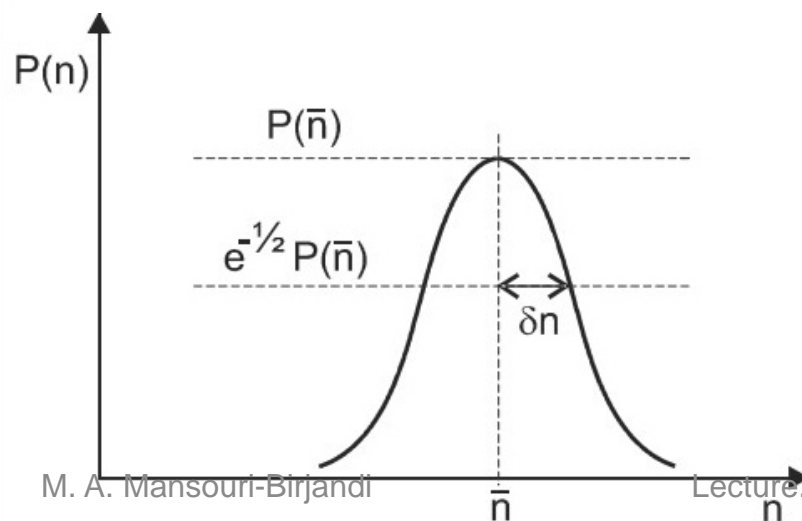
SHOT NOISE

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

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

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

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



SHOT NOISE

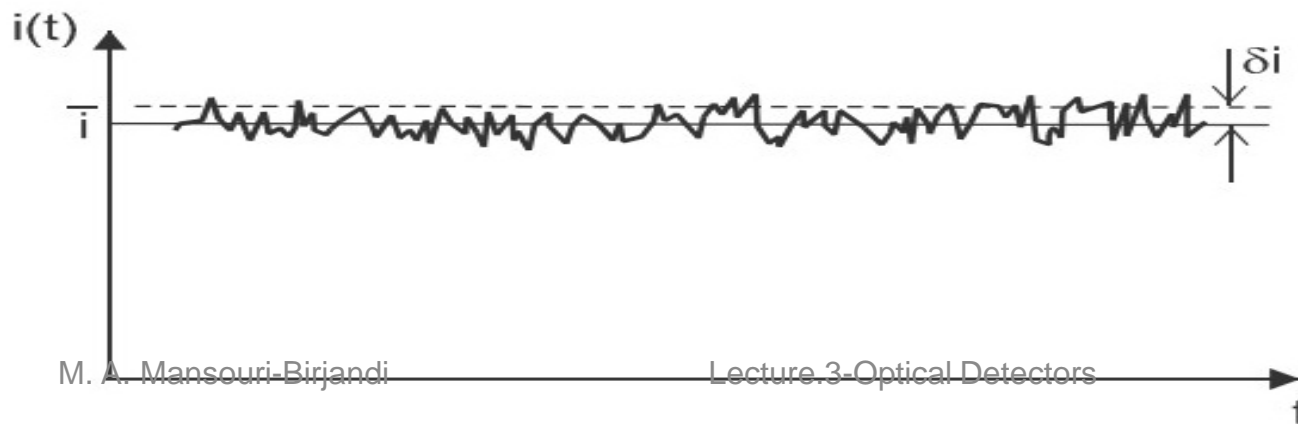
□ If the number n of electrons crossing the reference plane in time t varies

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

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

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

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



SHOT NOISE

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

$$\delta i = \sqrt{2eiB} \quad (\text{shot noise})$$

❖ **One way to reduce the noise** : reduce the detection bandwidth with appropriate electrical filters, restricting the range of modulation frequencies that can be detected side 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.

$$\delta E = k_B T$$

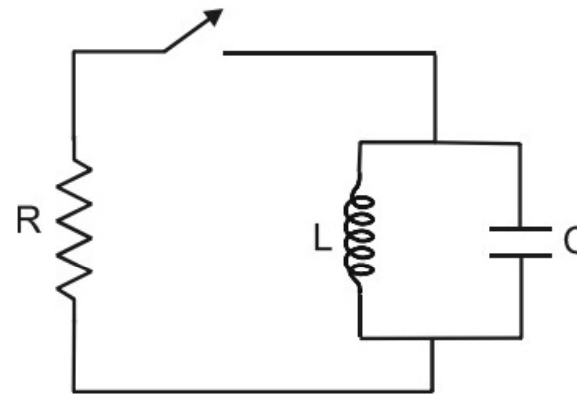
$$\delta P \sim \frac{\delta E}{\Delta t} \sim \frac{k_B T}{\Delta t}$$

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

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

$$B = \frac{\mathcal{K}}{\Delta t} \quad \mathcal{K} = 1/4$$

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

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

Lecture.3-Optical Detectors



**Thanks For
Your Attention**