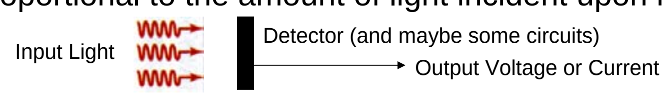
OPTI 380A
Intermediate Optics Lab 3: Detectors

Tom Milster
Professor, College of Optical Sciences,
University of Arizona
milster@arizona.edu

What is an Optical Detector?

- An optical detector produces an electrical signal that is proportional to the amount of light incident upon it.



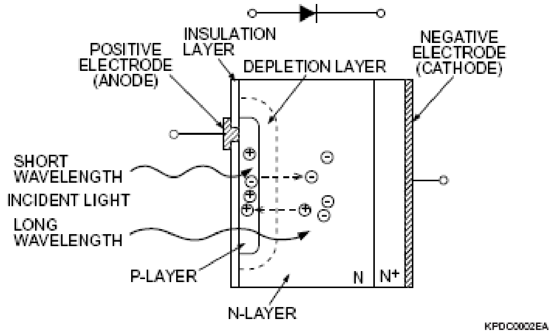
- Optical detectors can be used to
  - Measure power in a laser beam;
  - Receive light from your TV remote in order to change channels;
  - Signal a police officer to pull you over in a speed trap that uses optical radar; and
  - Allow computer networks to connect to each other through optical fibers.
- We will NOT be discussing detector arrays, like charge-coupled devices (CCDs) and CMOS arrays used in your cell phone camera, although they work on similar principles.

Detectors Lab

- You will observe characteristics of four different types of optical detectors.
  - Photodiode
  - Photoconductor
  - Photomultiplier tube (PMT)
  - Pyroelectric

Photodiode (PN Junction)

- The photodiode is a PN junction (or PIN junction, which is similar)
- Instead of emitting light when current is pumped through the junction, like with an LED, the photodiode collects incident photons and *generates* a current (flow of electrons) from them.

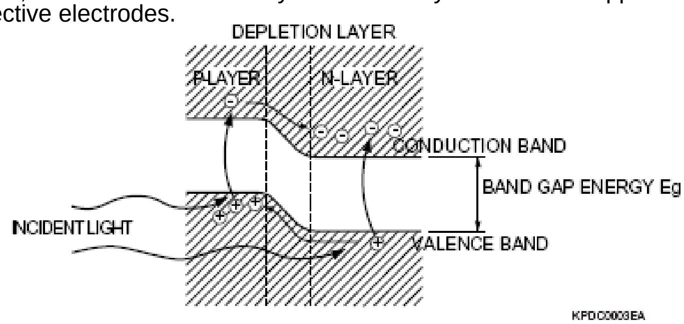


Typical Symbol for PD:

Typical symbol for LED:

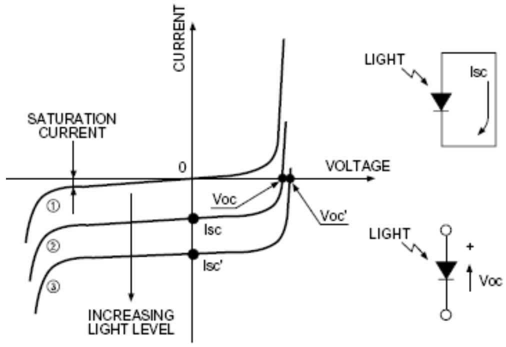
Photodiode (PN Junction)

- When a light photon strikes a photodiode, an electron within the crystal structure becomes stimulated. If the light energy is greater than the band gap energy Eg, the electrons are pulled up into the conduction band, leaving holes in their place in the valence band. The electric field accelerates these electrons toward the N-layer and the holes toward the P-layer. Electron-hole pairs are generated in proportion to the amount of incident light are collected in the N- and P-layers. If an external circuit is connected between the P- and N-layers, electrons will flow away from the N-layer, and holes will flow away from the P-layer toward the opposite respective electrodes.



Photodiode (PN Junction)

- The current vs voltage characteristic of a PD is shown below.
- As light level increases, the curve shifts down.

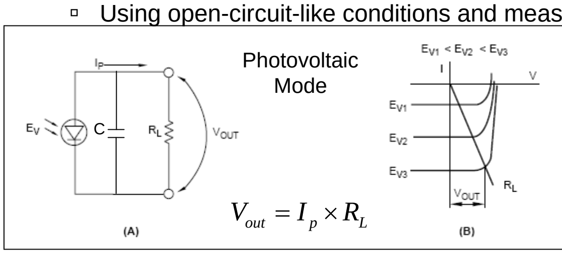


Short-circuit current is a measure of current output at the V = 0 axis. Isc is extremely linear with respect to a change in the light level.

Open-circuit voltage is a measure of voltage output at the I = 0 axis. Voc varies logarithmically with respect to a change in the light level.

Photodiode (PN Junction)

- The photodiode can be hooked up in a couple of ways.
  - Using open-circuit-like conditions and measuring voltage (nonlinear):

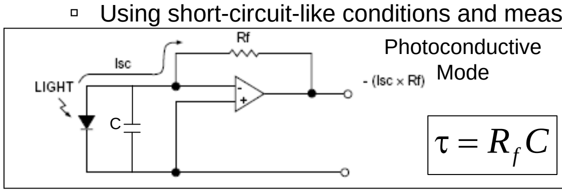


A simple load resistor, like the input impedance of an oscilloscope, provides R_L. C is the capacitance of the diode and cables. The time constant is:

$$\tau = R_L C$$

(We will look at this relation in the lab.)

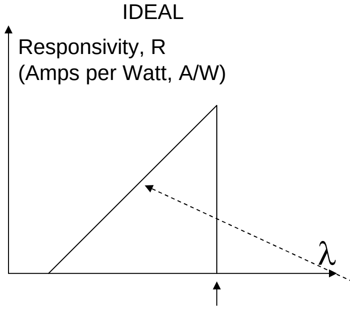
  - Using short-circuit-like conditions and measuring current (linear):



With an operational amplifier (transimpedance amplifier) we can effectively measure Isc with very high gain. Rf is selectable on the New Focus detector we will use.

Photodiode (PN Junction)

- The spectral response of a PD depends on the bandgap and properties of the intrinsic region.
- An ideal PD response (every incident photon converted to an e-h pair, Quantum Efficiency = 1) is a linear function of wavelength that peaks at the wavelength corresponding to the bandgap energy (Eg for Si is about 1.11 eV).



$$\lambda_g = \frac{1.24}{E_g\ (\text{eV})}\ (\mu\text{m})$$

At shorter wavelengths, each photon contains more energy according to:

$$E_{photon} = \frac{1.24}{\lambda_{photon}(\mu\text{m})}\ (\text{eV}) \quad ,$$

but each photon only produces one e-h pair and contributes the same amount of current (amps) as a long-wavelength photon. If N_p is the number of photons/sec in the illumination, the beam power in watts is:

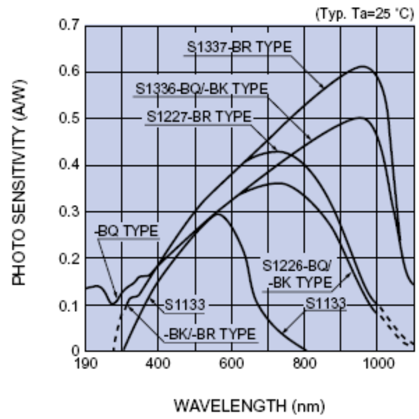
$$\Phi_p = N_p \times \frac{1.24}{\lambda_{photon}(\mu\text{m})} \times \frac{1.602\times10^{-19}\text{J}}{\text{eV}} \quad .$$

The number of electrons per second = Np, so the ratio of output current in amps to input light in watts is:

$$R = \frac{\lambda_{photon}(\mu\text{m})}{1.24}\ (\text{A/W}) \quad ,$$

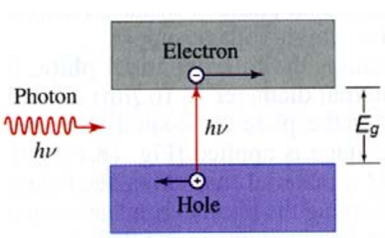
Photodiode (PN Junction)

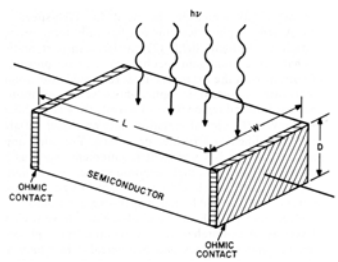
- Actual spectral responses are shown below for several photodiodes.
- Reflection and absorption reduces responsivity from the ideal values.



Photoconductors

- Photoconductors are solid pieces of semiconductor material with metal contacts on two sides.
- When a photon with enough energy is absorbed in the semiconductor material, an e-h pair is generated.
- The extra charge carriers reduce *resistivity* of the semiconductor.
- Carriers are NOT swept across a pn junction, like with a photodiode, because there is no junction.
- There is NO exponential VI relationship in a photoconductor. We simply measure the change in resistance.



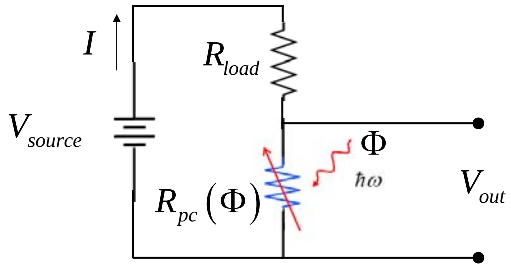


Photoconductors

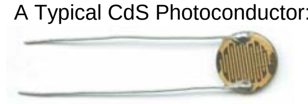
- We measure the resistance by passing a current through the material and measuring the voltage across it.
- As more light illuminates the photoconductor, the number of carriers increase, thus decreasing the resistance and the voltage.
- A common photoconductor material is CdS, which is an *extrinsic* semiconductor that allows lower energy photons to excite charge carriers into the conduction band.
- Photoconductors also exhibit capacitance C (not shown), which limits their frequency response.

$$V_{out} = IR_{pc}(\Phi)$$

$$= \frac{V_{source}}{R_{pc}(\Phi) + R_{load}} R_{pc}(\Phi)$$

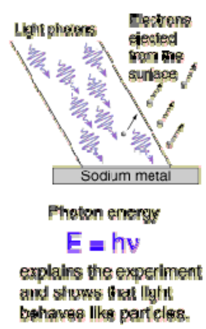


A Typical CdS Photoconductor:



Photomultiplier Tube (PMT)

- Photomultiplier tubes work on the basis of the *photoelectric effect**, where an electron is ejected from certain materials (like metals) when a photon of sufficient energy strikes it.
- The *work function* W of the material is the difference between the kinetic energy (KE) of the ejected electron and the energy of the incident photon.
- The incident photon must have $h\nu \geq W$ in order to eject an electron.



$$h\nu = W + K.E.$$

Example work functions (in eV):

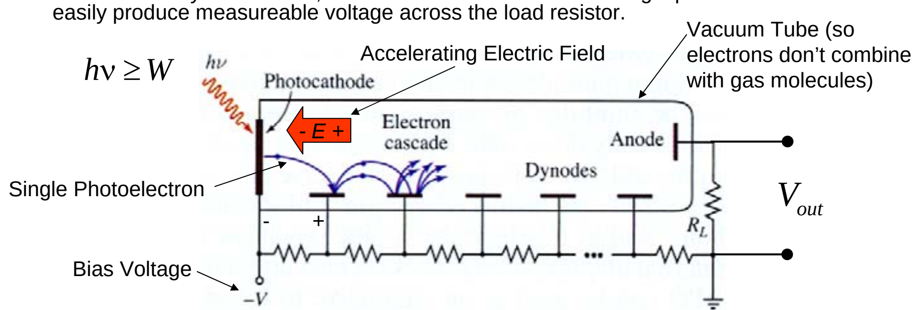
Potassium	2.3
Platinum	6.35
Selenium	5.11
Silver	4.73
Sodium	2.28
Uranium	3.6
Zinc	4.3

*Einstein won the Nobel prize in 1921 for realizing that the photoelectric effect is due to the quantum nature of light. This discovery started the field of quantum mechanics.

Photomultiplier Tube (PMT)

College of Optical Sciences
THE UNIVERSITY OF ARIZONA

- A photomultiplier tube consists of a vacuum tube, photocathode, dynodes and an anode. Output voltage is measured across the load resistor at the anode.
- The photocathode has an associated work function W, where incident photons can create ejected electrons.
- The ejected electrons (photoelectons) are accelerated to a neighboring dynode through an electric field.
- The photoelectrons reaching the first dynode have enough kinetic energy to kick off more electrons there, which are called *secondary electrons.*
- Each secondary electron is then accelerated to the next dynode, and produces more secondary electrons there.
- After several dynode chains, the electron cascade due to a single photoelectron can easily produce measureable voltage across the load resistor.



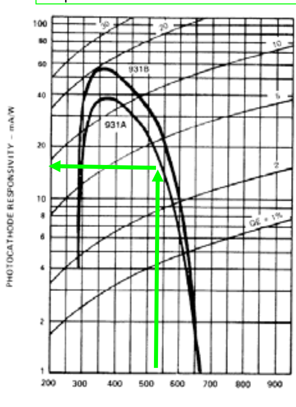
Photomultiplier Tube (PMT)

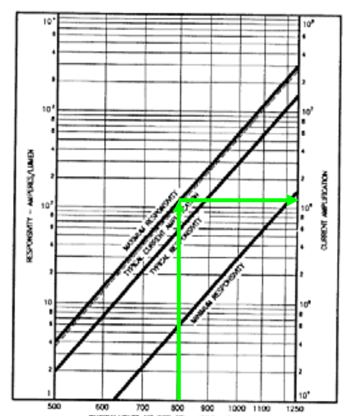
College of Optical Sciences
THE UNIVERSITY OF ARIZONA

- Modern PMTs are very sensitive to light level and can be extremely low noise.
- Example: Burle 931A PMT operating at 530nm and -800V bias.

η_{pc} = PC sensitivity ~ 15mA/W

G = Current Amplification ~ 10^6

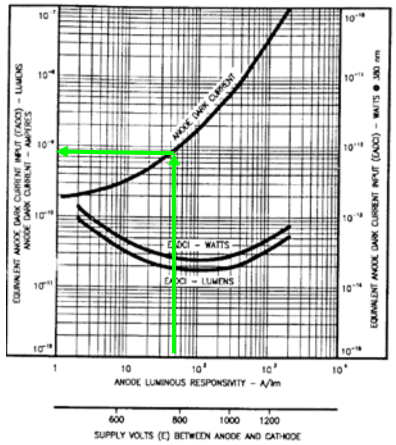




College of Optical Sciences
THE UNIVERSITY OF ARIZONA

Photomultiplier Tube (PMT)

- Example: Burle 931A PMT operating at 530nm and -800V bias.



Anode Dark Current (Noise) ~ 8x10^{-10} A

Important relationships:

$$I_{anode} = \eta_{pc} G \Phi$$

$$SNR = I_{anode} / I_{dark\,current}$$

For a signal-to-noise ratio (SNR) of 100, the amount of light incident on the PC must be:

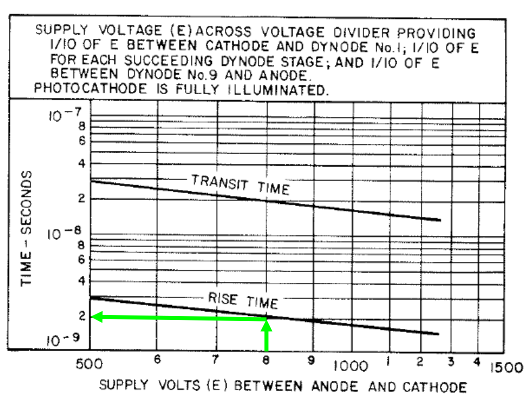
$$\Phi = \frac{I_{dark\,current} \times SNR}{\eta_{pc} \times G} \approx 5.3 \times 10^{-12}\,\mathrm{W}$$

$$\approx 14 \times 10^{6} \frac{\text{photons}}{\text{sec}}$$

College of Optical Sciences
THE UNIVERSITY OF ARIZONA

Photomultiplier Tube (PMT)

- Example: Burle 931A PMT operating at 530nm and -800V bias.



Rise time ~ 2nsec

Pyroelectric Detectors

- The pyroelectric detector is a *thermal* detector that senses a change in temperature. It does not create photocariers or photoelectrons due to absorption. Instead, incident light heats the material, and the *change in heat* is detected.
- To maximize the heating effect, thermal detectors are usually painted black. They are insensitive to changes in wavelength, so they have a broad spectral response.
- Because of their flat spectral response, thermal detectors can sense long-wavelength photons that arise from warm materials, which are call *infrared photons*.
- Pyroelectric detectors work on the principle of the *pyroelectric effect*, where certain crystals experience an electric field along the crystal axis that is a function of temperature
- The voltage (or current) created by the field can be measured by connecting the detector to a circuit.
- Because the detector acts like a capacitor, it does not respond to slow changes in light level. It must be used in an "ac" mode. A chopper wheel is often used to provide a changing light level from a thermal source.