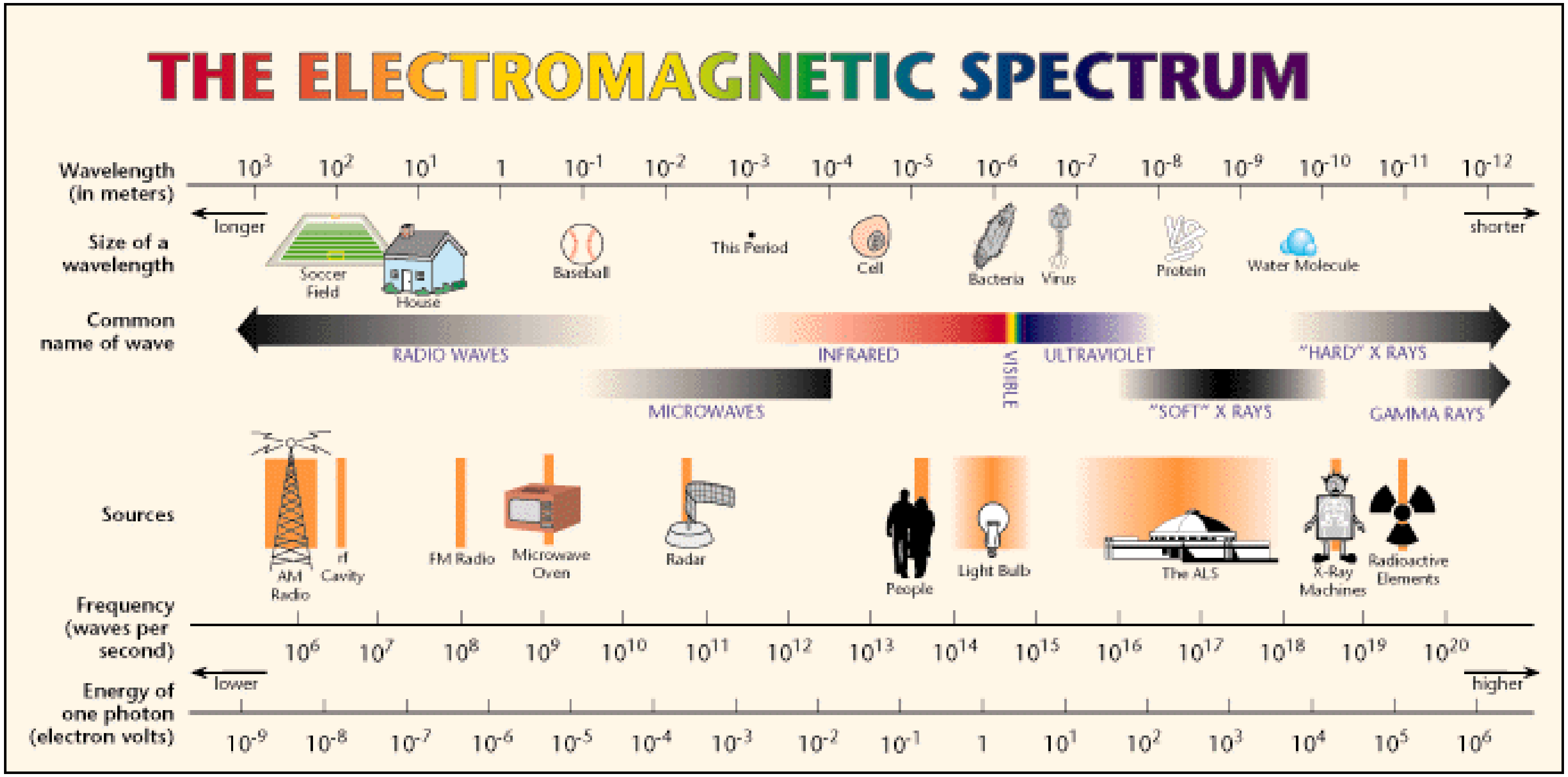
Semiconductor sensors:

Ch2: Optoelectronic Sensors

Lecturer: Dr. N. A. Sheini
Shahid Chamran University of Ahvaz

طیف الکترومغناطیسی



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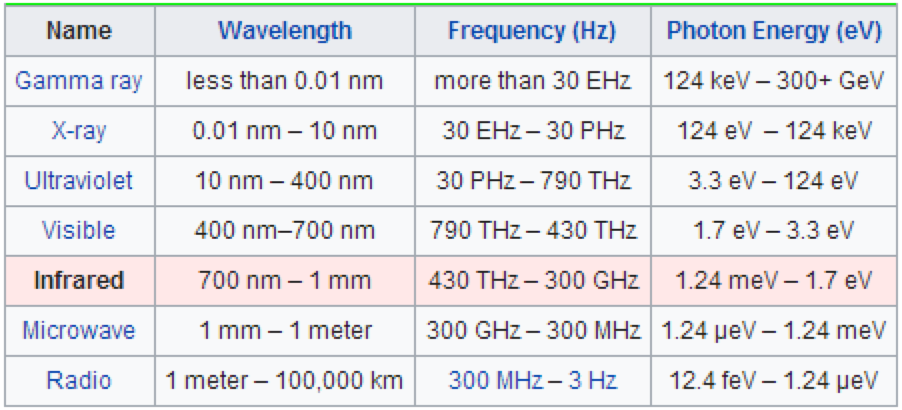
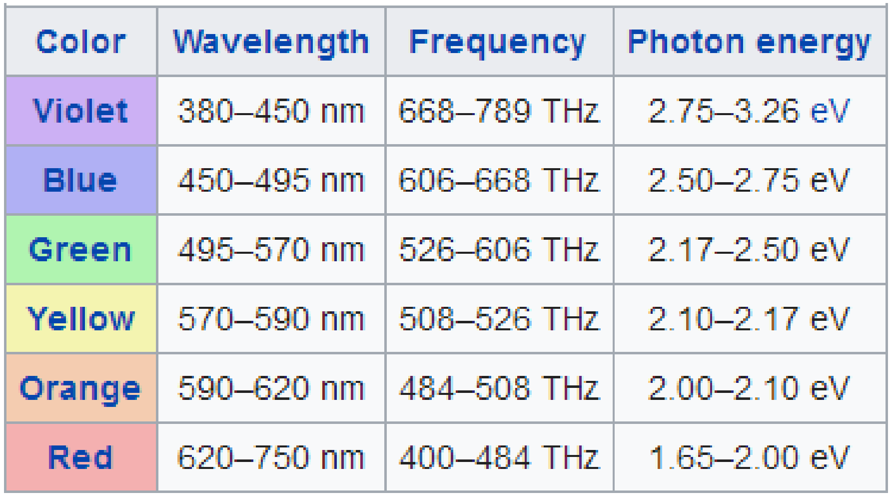


Name	Wavelength	Frequency (Hz)	Photon Energy (eV)
Gamma ray	less than 0.01 nm	more than 30 EHz	124 keV – 300+ GeV
X-ray	0.01 nm – 10 nm	30 EHz – 30 PHz	124 eV – 124 keV
Ultraviolet	10 nm – 400 nm	30 PHz – 790 THz	3.3 eV – 124 eV
Visible	400 nm–700 nm	790 THz – 430 THz	1.7 eV – 3.3 eV
Infrared	700 nm – 1 mm	430 THz – 300 GHz	1.24 meV – 1.7 eV
Microwave	1 mm – 1 meter	300 GHz – 300 MHz	1.24 µeV – 1.24 meV
Radio	1 meter – 100,000 km	300 MHz – 3 Hz	12.4 feV – 1.24 µeV



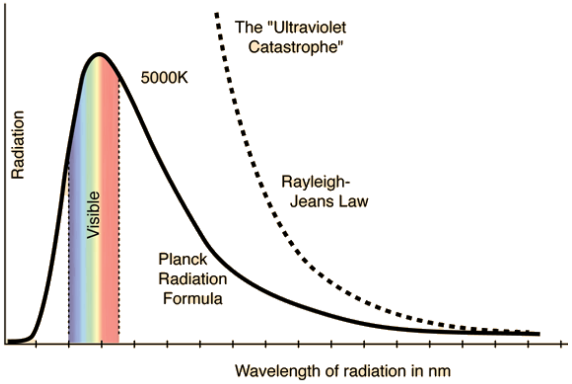
Color	Wavelength	Frequency	Photon energy
Violet	380–450 nm	668–789 THz	2.75–3.26 eV
Blue	450–495 nm	606–668 THz	2.50–2.75 eV
Green	495–570 nm	526–606 THz	2.17–2.50 eV
Yellow	570–590 nm	508–526 THz	2.10–2.17 eV
Orange	590–620 nm	484–508 THz	2.00–2.10 eV
Red	620–750 nm	400–484 THz	1.65–2.00 eV

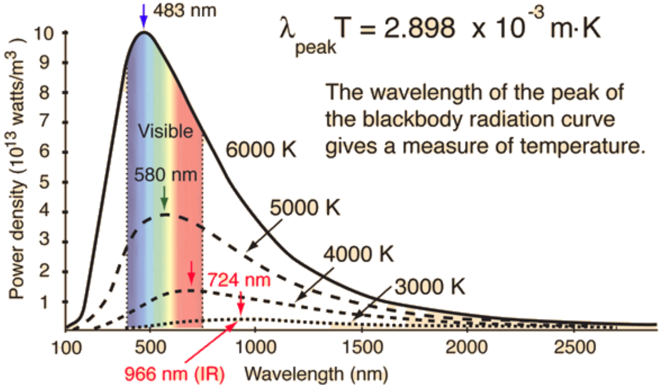
Haynes, William M., ed. (2011). CRC Handbook of Chemistry and Physics (92nd ed.). CRC Press.

تابش جسم سیاه

The (absolute) blackbody absorbs all energy, and reflects nothing, which is of course an idealization. A black-body at room temperature appears black, as most of the energy it radiates is infra-red and cannot be perceived by the human eye. Black-body radiation has a characteristic, continuous frequency spectrum that depends only on the body's temperature.

The thermal radiation emitted by many ordinary objects can be approximated as blackbody





Wien's displacement **law** indicates that the maximum of the energy distribution is displaced within the radiation spectrum of a blackbody in case of a change in temperature.

$$\lambda_{\max} T = b$$

where b is called Wien's displacement constant, is equal to 2.89×10^{-3} Km.

The **Stefan–Boltzmann law** states that the power emitted by the surface of a black body is directly proportional to the fourth power of its absolute temperature and, of course, its surface area A:

$$P = \sigma T^4 A$$

where $\sigma \approx 5{,}67 \cdot 10\text{-}8 W/(m^2K^4)$ is the Stefan–Boltzmann constant.

تابش جسم سیاه

سوال: بیشترین تابش بدن انسان در چه طول موجی و در چه محدوده ای از طیف الکترومغناطیسی است؟ با فرض اینکه سطح بدن یک انسان ۲متر مربع باشد، توان تابشی چقدر است؟

طیف مادون قرمز:

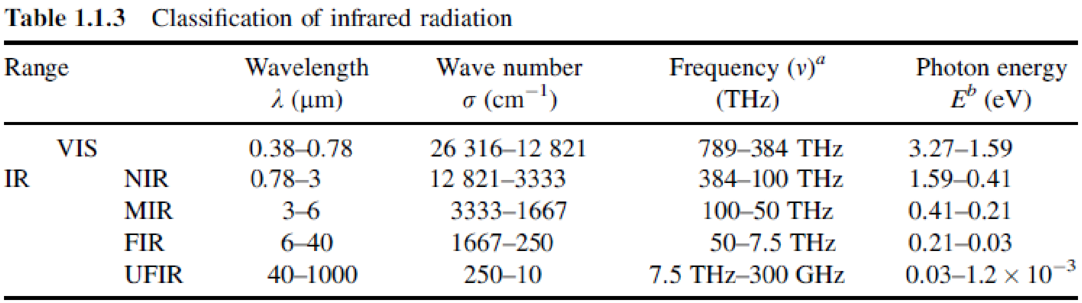
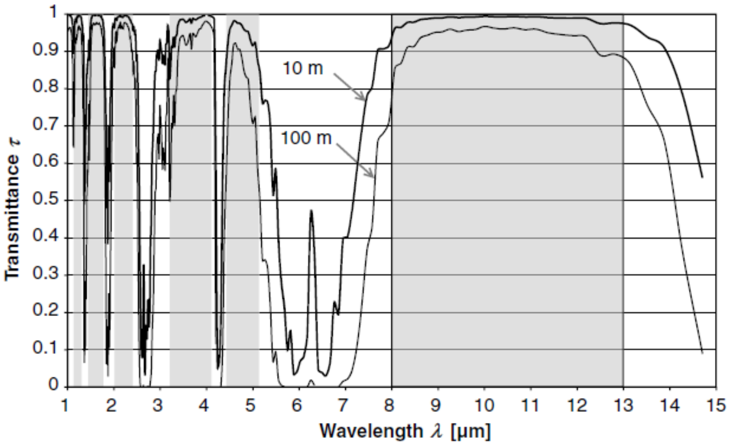


Table 1.1.3 Classification of infrared radiation

Range		Wavelength λ (μm)	Wave number σ (cm^{-1})	Frequency (ν)^a (THz)	Photon energy E^b (eV)
VIS		0.38–0.78	26 316–12 821	789–384 THz	3.27–1.59
IR	NIR	0.78–3	12 821–3333	384–100 THz	1.59–0.41
	MIR	3–6	3333–1667	100–50 THz	0.41–0.21
	FIR	6–40	1667–250	50–7.5 THz	0.21–0.03
	UFIR	40–1000	250–10	7.5 THz–300 GHz	$0.03–1.2 \times 10^{-3}$

جذب مادون قرمز در هوا:



Ebook: Thermal Infrared sensors- Willy 2011.

واحد شدت نور:

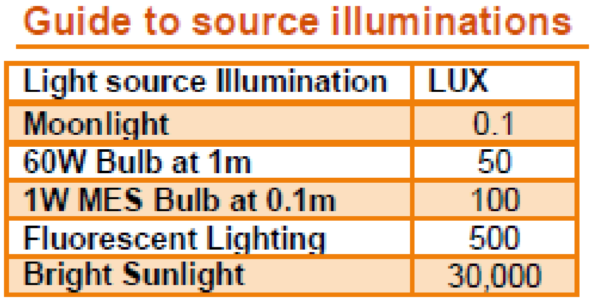
Candela (cd)
Unit of luminous intensity of a light source in a specific direction. Also called *candle*.
Technically, the radiation intensity in a perpendicular direction of a surface of 1/600000 square meter of a black body at the temperature of solidification platinum under a pressure of 101,325 newtons per square meter.

Footcandle (fc or ftc)
Unit of light intensity, measured in lumens per square foot. The brightness of one candle at a distance of one foot. Approximately 10.7639 lux.

Lumen (lm)
Unit of light flow or luminous flux. The output of artificial lights can be measured in lumens.

Lux (lx)
Unit of illumination equal to one lumen per square meter. The metric equivalent of foot-candles (one lux equals 0.0929 footcandles). Also called meter-candle.

Miniature Edison Screw (MES)



Guide to source illuminations

Light source Illumination	LUX
Moonlight	0.1
60W Bulb at 1m	50
1W MES Bulb at 0.1m	100
Fluorescent Lighting	500
Bright Sunlight	30,000

آثار نوری (فوتونی)

- اثر فتو الکتریک
- اثر فتوکانداکتیو
- آثار فتودیودی
  - فتو ولتاییک
  - PN، PIN، APD
- اثر تزویج بار CCD
- اثر فتو دی الکتریک
- آثار فتولومینسانس
  - اثر فولورسانس
  - اثر فسفرسانس
  - اثر الکترولومینسانس

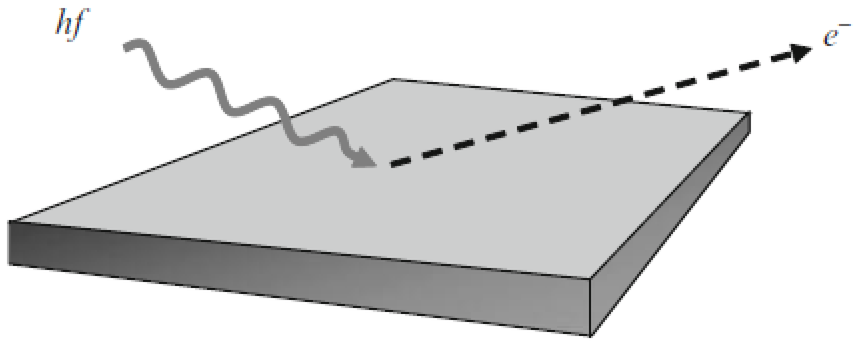
اثر فتوالکتریک

When a material is irradiated by photons, electrons may be ejected from it. The ejected electrons are called *photoelectrons*, and their kinetic energy, E_K, is equal to the incident photon’s energy, hf, minus some threshold energy, known as the *material’s work function* ϕ, which needs to be exceeded for the material to release electrons. The effect is illustrated in Fig. 3.3 and is governed by:

$$E_K = hf - \varphi, \tag{3.18}$$

where h is the Planck’s constant ($h = 6.625 \times 10^{-34}$ J s) and f is the photon’s frequency.

Fig. 3.3 Photoelectric effect: incident of a photon and release of an electron as a result



تاریخچه اثر فتوالکتریک

HEINRICH RUDOLF HERTZ
1857 - 1894

In 1887, Heinrich Hertz and his assistant Philipp Lenard observed that when light was shone on certain substances, the substances gave out cathode rays (electrons); only the number of electrons emitted, and not their energy, increased when the strength (intensity) of the incident light was increased. (Incidentally, a nephew of Heinrich Hertz, Gustav Ludwig Hertz, won the Physics Nobel Prize for 1925 along with James Franck for their discovery of the laws governing the impact of an electron upon an atom.}

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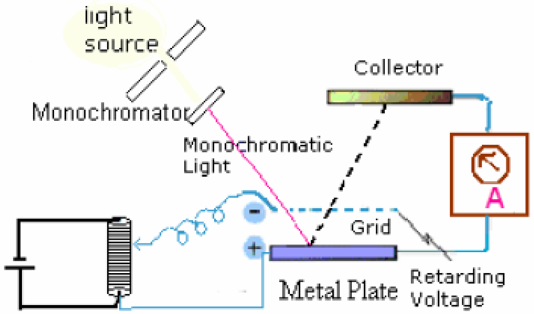
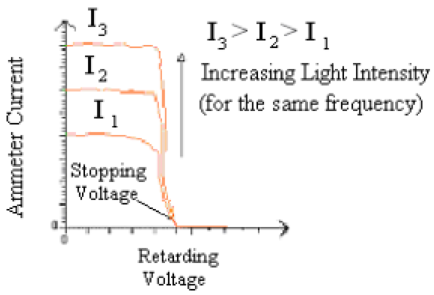
Picture 4:
Philipp Lenard [13]

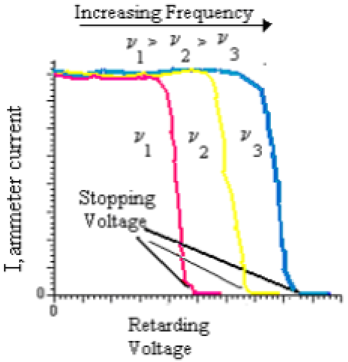
White light is sent through a monochromator and is then incident on a thin metal plate. The incident light is absorbed by the metal plate which then ejects electrons from it. These electrons are attracted toward a collector at which they arrive, but only if they have sufficient kinetic energy to get past a grid (a fine wire mesh) to which a retarding potential is applied, as shown in the figure. The kinetic energy of the electrons emitted from the thin metal foil could thus be gauged by varying the retarding voltage. The 'plate to collector' electron current, being measured by an ammeter. Lenard made the surprising discovery of a 'cutoff frequency'.



تاریخچه اثر فتوالکتریک



`Fig.2:`
A sufficiently negative voltage on the grid prevents electrons from making it to the collector, *regardless of the intensity of the incident light*.



`Fig.3:`
The stopping potential is higher for larger frequency, and the two have a linear relationship.

Until Einstein wrote this paper, it was assumed that electromagnetic radiation traveled as waves. Einstein considered the quantization of light into packets of energy called quanta in the context of propagation of EM energy. Wrote Einstein: "*According to the assumption considered here, when a light ray starting from a point is propagated, the energy is not continuously distributed over an ever increasing volume, but it consists of a finite number of energy quanta, localized in space, which move without being divided and which can be absorbed or emitted only as a whole*".

تاریخچه اثر فتوالکتریک

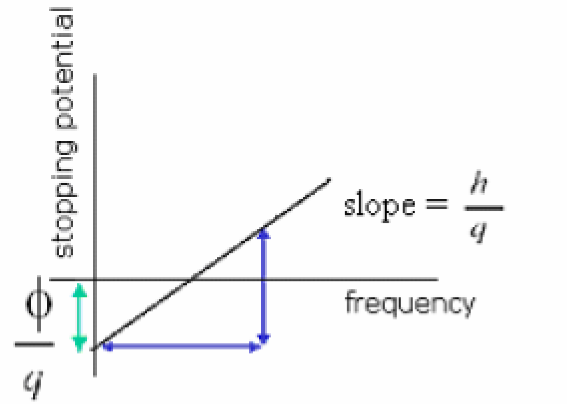
$$h\nu = \phi + \text{K.E.} \qquad (1)$$

As mentioned earlier, the ejected electron is detected at the collector only if its kinetic energy overcomes the retarding potential qV. Thus we get the following relation:

$$h\nu = \phi + qV_s \qquad (2a)$$

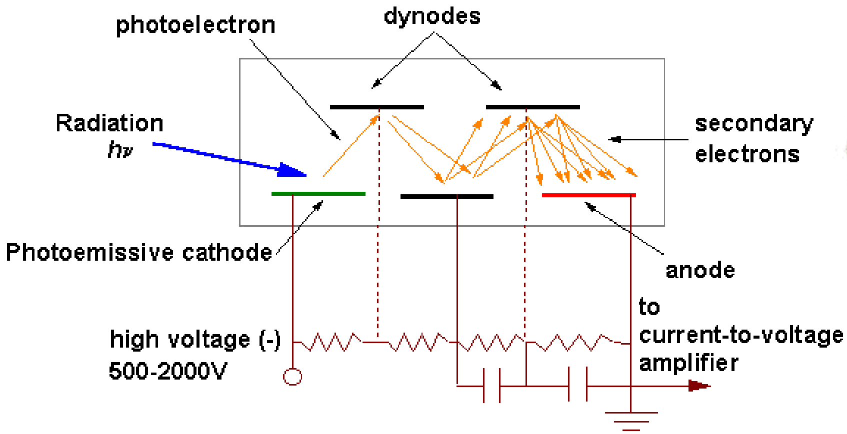
i.e., $V_s = (h/q)\nu - \phi/q.$ (2b)

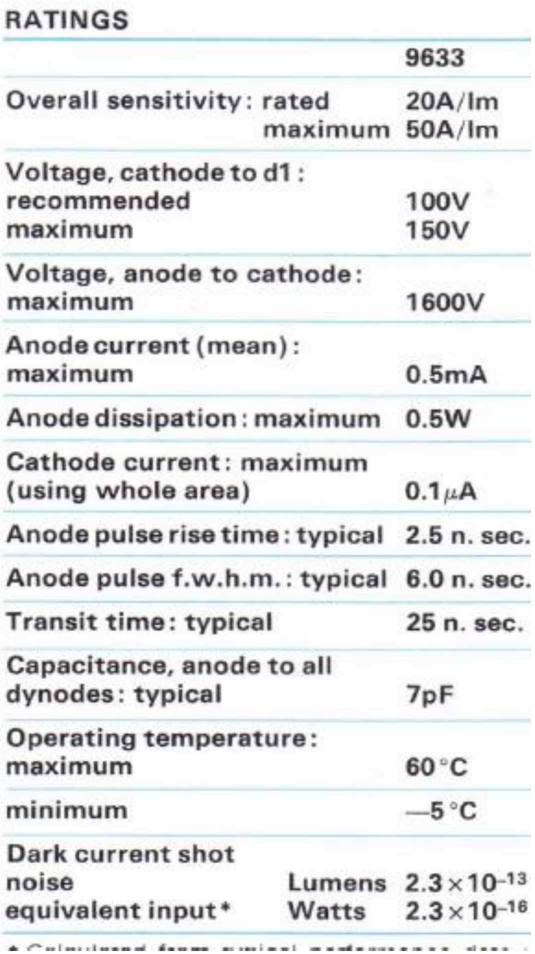
**Picture 6:
Robert Andrews
Millikan [19]**



Having determined accurately the charge carried by an electron using the elegant and famous "falling drop method"; Millikan carried out the first direct 'photoelectric' determination of Planck's constant h (1912-1915) using Einstein's Eq. 2b. (*Besides, Millikan carried out important experiments on the Brownian movements in gases*).

حسگر فتوالکتریک





RATINGS

		9633
Overall sensitivity: rated		20A/lm
	maximum	50A/lm
Voltage, cathode to d1:		
recommended		100V
maximum		150V
Voltage, anode to cathode:		
maximum		1600V
Anode current (mean):		
maximum		0.5mA
Anode dissipation: maximum		0.5W
Cathode current: maximum (using whole area)		0.1 μA
Anode pulse rise time: typical		2.5 n. sec.
Anode pulse f.w.h.m.: typical		6.0 n. sec.
Transit time: typical		25 n. sec.
Capacitance, anode to all dynodes: typical		7pF
Operating temperature:		
maximum		60 °C
minimum		—5 °C
Dark current shot noise equivalent input*	Lumens	2.3×10^{-13}
	Watts	2.3×10^{-16}

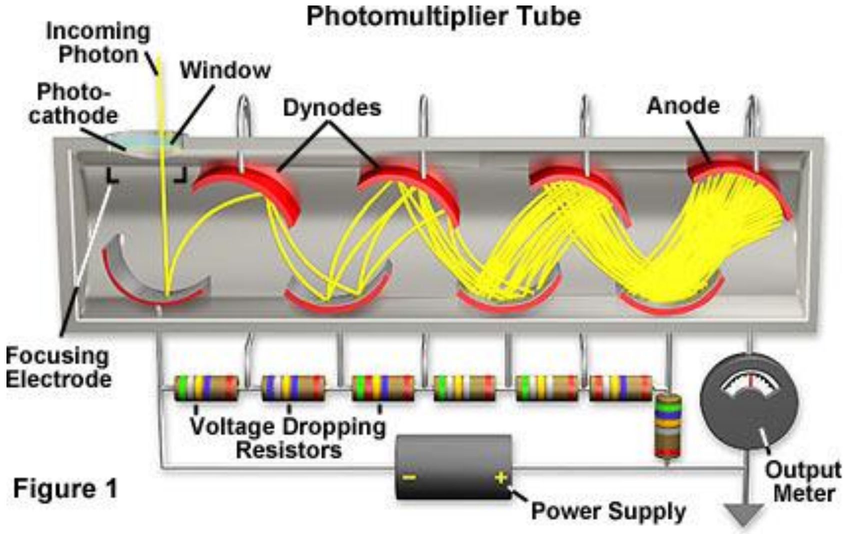
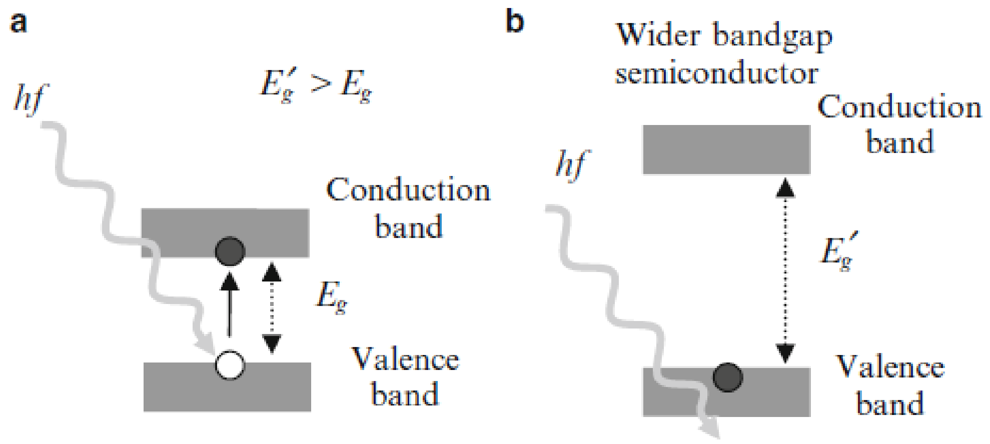


Figure 1

اثر فتوکانداکتیو

Photoconductivity occurs when a beam of photons impinges a semiconducting material, causing its conductivity to change. The incident photons excite electrons from the conduction band to the valence band, which occurs if the light striking the semiconductor has sufficient energy (*hf* is the energy of the incident photon that has the frequency of *f*). Light response depends on the *bandgap* of the materials. A simple depiction of electronic band structures for two semiconductors with different bandgaps is shown in Fig. 3.4. Obviously for a wider bandgap material larger energy is required to excite an electron from the valence band to the conduction band.



حسگر فتوکانداکتیو

The photoconductive effect is widely utilized in electromagnetic radiation sensors, and such devices are termed *photoconductors*, *light-dependent resistors* (*LDR*), or *photoresistors*. *Cadmium sulfide* (CdS—bandgap of ~2.42 eV, which is approximately the wavelength of 512 nm in the violet region) and *cadmium selenide* (CdSe— ~1.73 eV, which is approximately the wavelength of 716 nm in the yellow region) are the current materials of choice for the fabrication of photoconductive devices and sensors. Very commonly to make a photoresistor, a film of these materials is deposited onto parallel electrodes (Fig. 3.5). Devices based on semiconductors such as CdS can have a wide range of resistance values, from about a few ohms, when the light has high intensity, to several mega ohms in darkness.

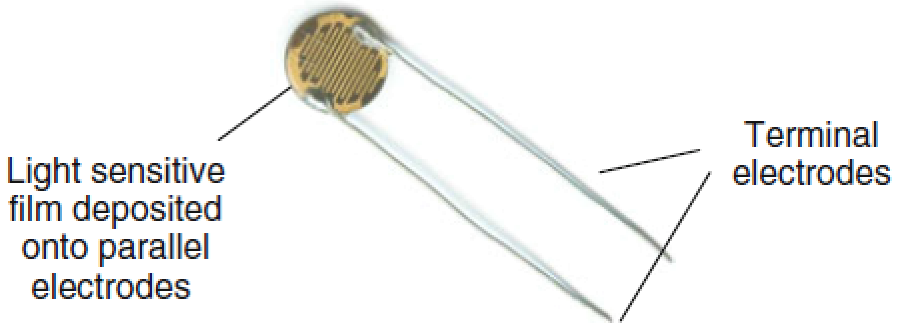
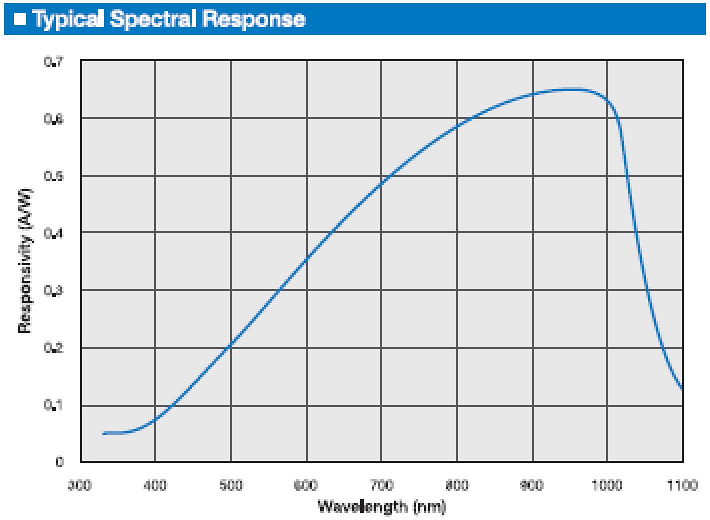


Fig. 3.5 Photo of a commercial LDR based on CdS

حسگر فتوکانداکتیو

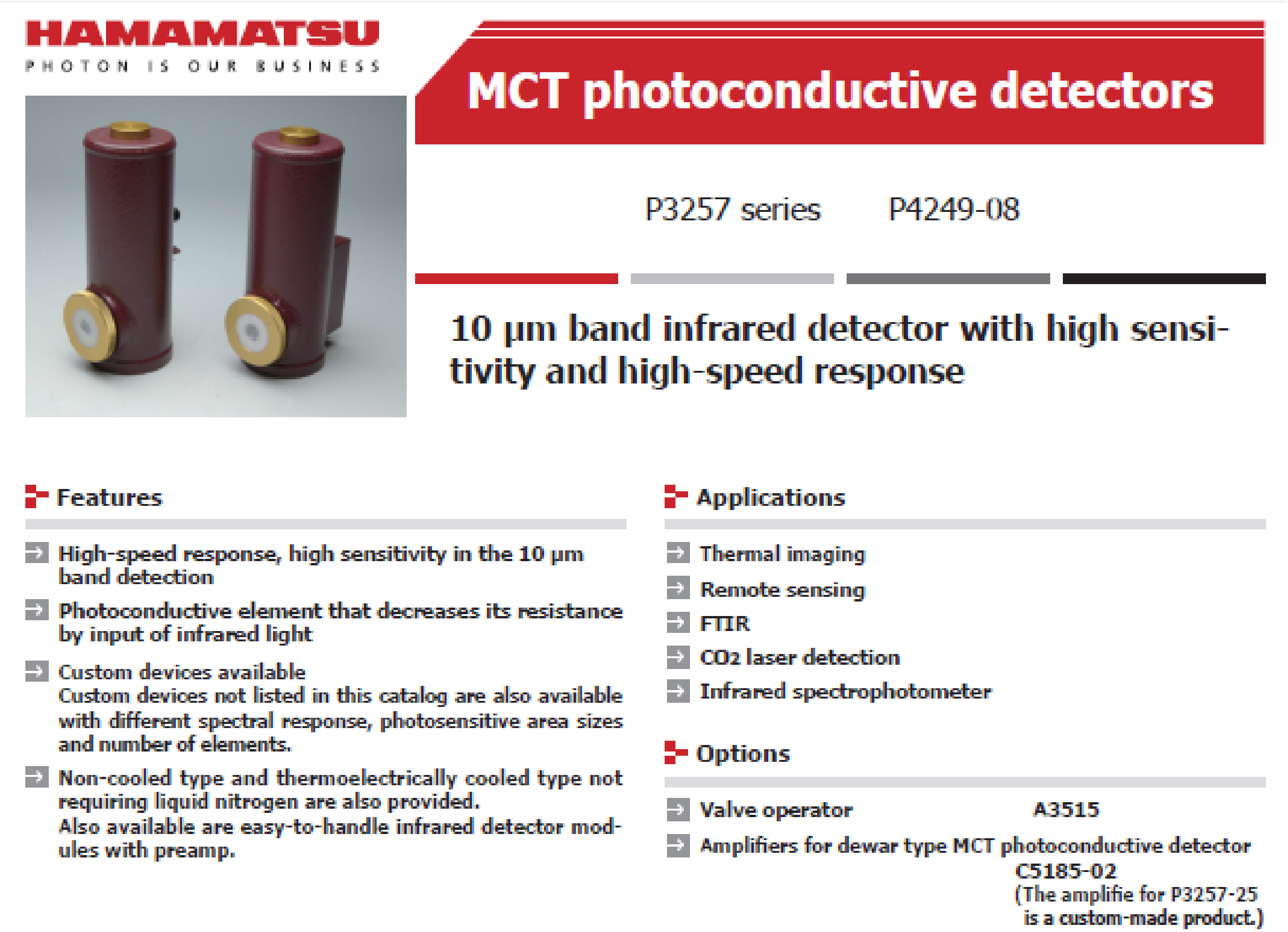
- **APPLICATIONS**
  - Pulse Detectors
  - Optical Communications
  - Bar Code Readers
  - Optical Remote Control
  - Medical Equipment
  - High Speed Photometry

- **FEATURES**
  - High Speed Response
  - Low Capacitance
  - Low Dark Current
  - Wide Dynamic Range
  - High Responsivity



Typical Spectral Response

حسگر فتوکانداکتیو در طیف مادون قرمز:



HAMAMATSU

PHOTON IS OUR BUSINESS

MCT photoconductive detectors

P3257 series P4249-08

10 µm band infrared detector with high sensitivity and high-speed response

Features

- High-speed response, high sensitivity in the 10 µm band detection
- Photoconductive element that decreases its resistance by input of infrared light
- Custom devices available
  Custom devices not listed in this catalog are also available with different spectral response, photosensitive area sizes and number of elements.
- Non-cooled type and thermoelectrically cooled type not requiring liquid nitrogen are also provided.
  Also available are easy-to-handle infrared detector modules with preamp.

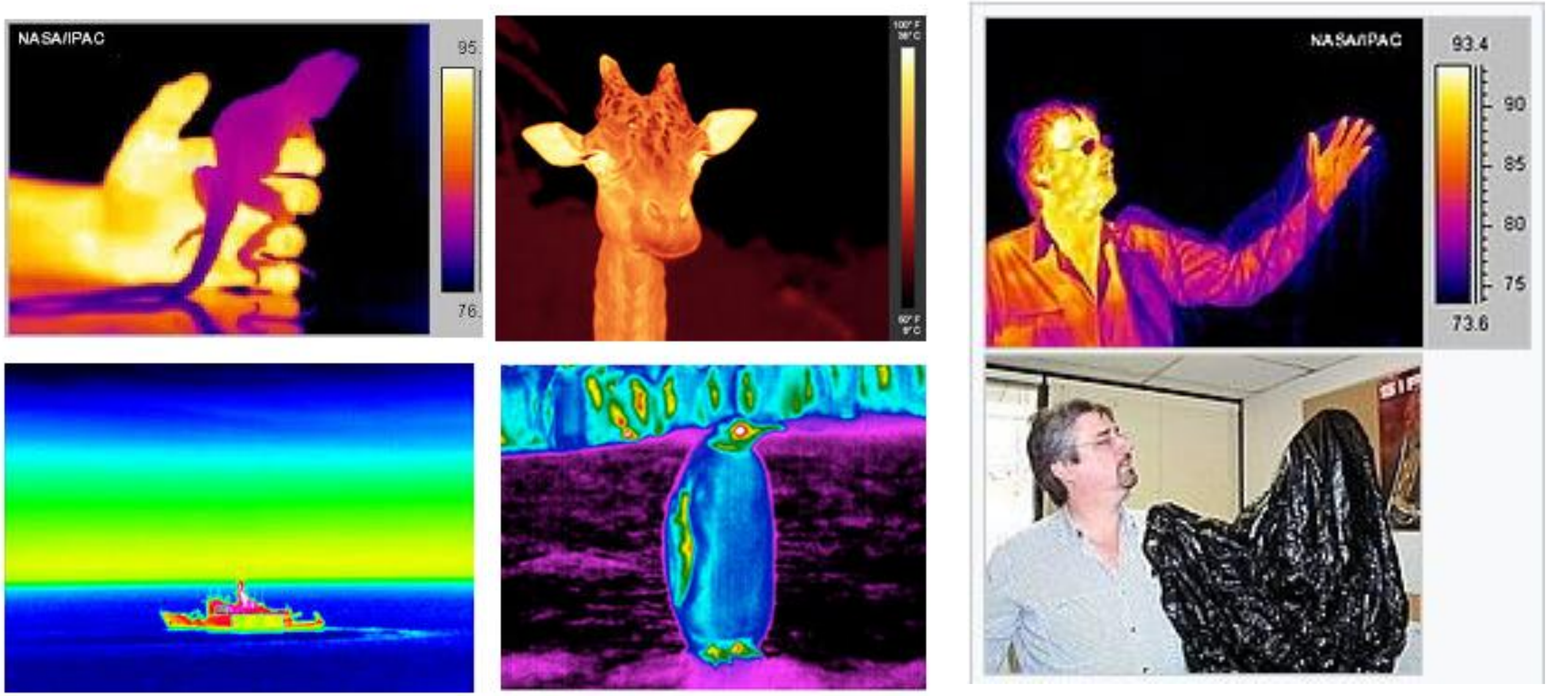
Applications

- Thermal imaging
- Remote sensing
- FTIR
- CO_2 laser detection
- Infrared spectrophotometer

Options

- Valve operator A3515
- Amplifiers for dewar type MCT photoconductive detector C5185-02
  (The amplifie for P3257-25 is a custom-made product.)

تصاویر حرارتی مادون قرمز:



اثر فتوولتاییک

In the photovoltaic effect, a voltage is induced by absorbed photons at a junction of two dissimilar materials (it is also called a *heterojunction*). The absorbed photons produce free charge carriers (electrons and holes) as can be seen in Fig. 3.6.

A typical photovoltaic device is seen in Fig. 3.6. They generally consist of a large area semiconductor p–n junction or diode. A photon impinging on the junction is absorbed, if its energy is greater than or equal to the semiconductor's bandgap energy. This can cause a valance band electron to be excited into the conduction band, leaving behind a hole, and thus creating a mobile electron–hole pair. If the electron–hole pair is located within the depletion region of the p–n junction, then the existing electric field will either sweep the electron to the n-type side or the hole to the p-type side. As a result, a current is generated as below:

$$I = I_S[e^{\frac{qV}{kT}} - 1], \tag{3.19}$$

where q is the electron charge (1.602×10^{-19} C), k is the Boltzmann's constant (1.38×10^{-23} J/K^{-1}), and T is the temperature of the p–n junction in Kelvin.

حسگر فتوولتاییک

Photovoltaic cells and sensors are commonly made from materials that absorb photons in the infrared, visible, and UV ranges: materials such as silicon (wavelengths between 190 and 1,100 nm), germanium (800–1,700 nm), indium gallium arsenide (800–2,600 nm), and lead sulfide (1,000–3,500 nm) are generally used.

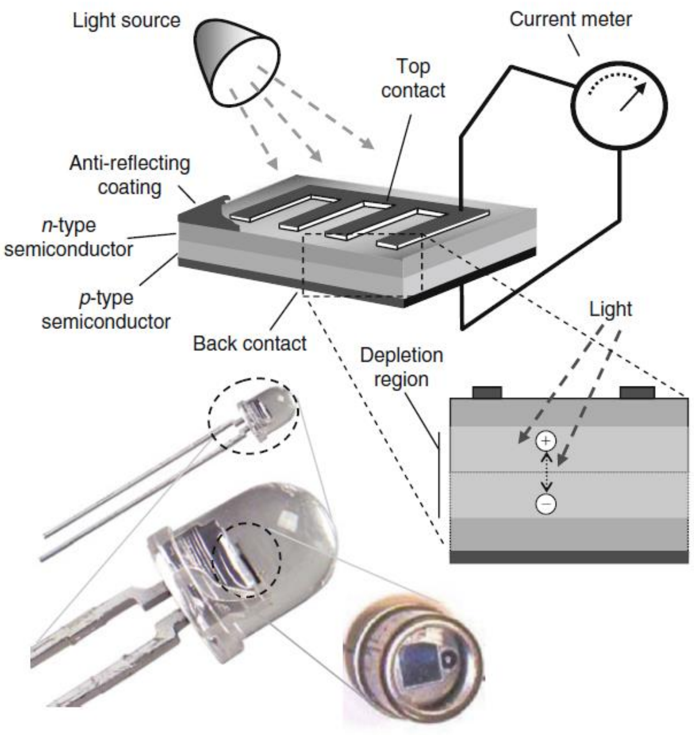
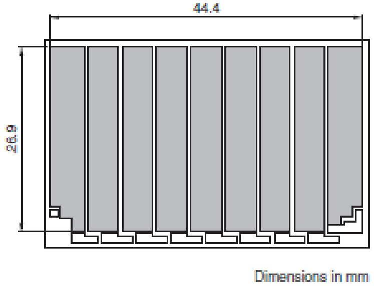


Fig. 3.6 Schematic of a photovoltaic device and the photo of a typical photovoltaic sensor

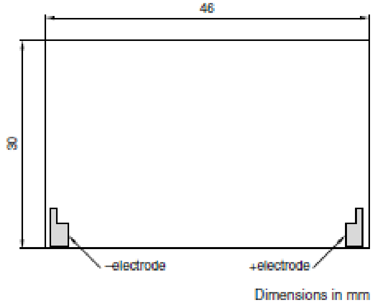
سلول فتوولتاییک

DESIGN EXAMPLES BCS4630B9
SHAPES AND DIMENSIONS

Photoactive side
Hatching areas: Photoactive area

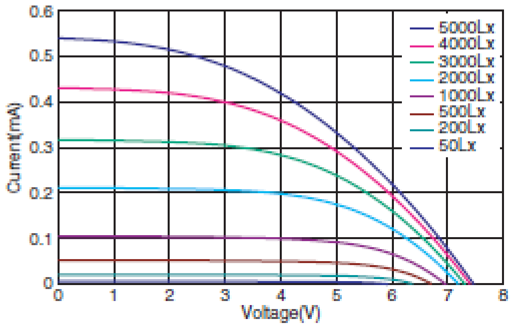


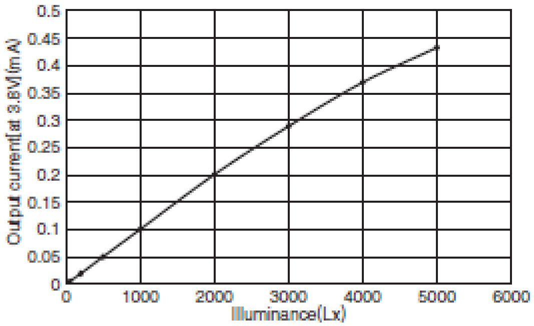
Electrode side
Hatching areas: Electrodes



APPLICATIONS

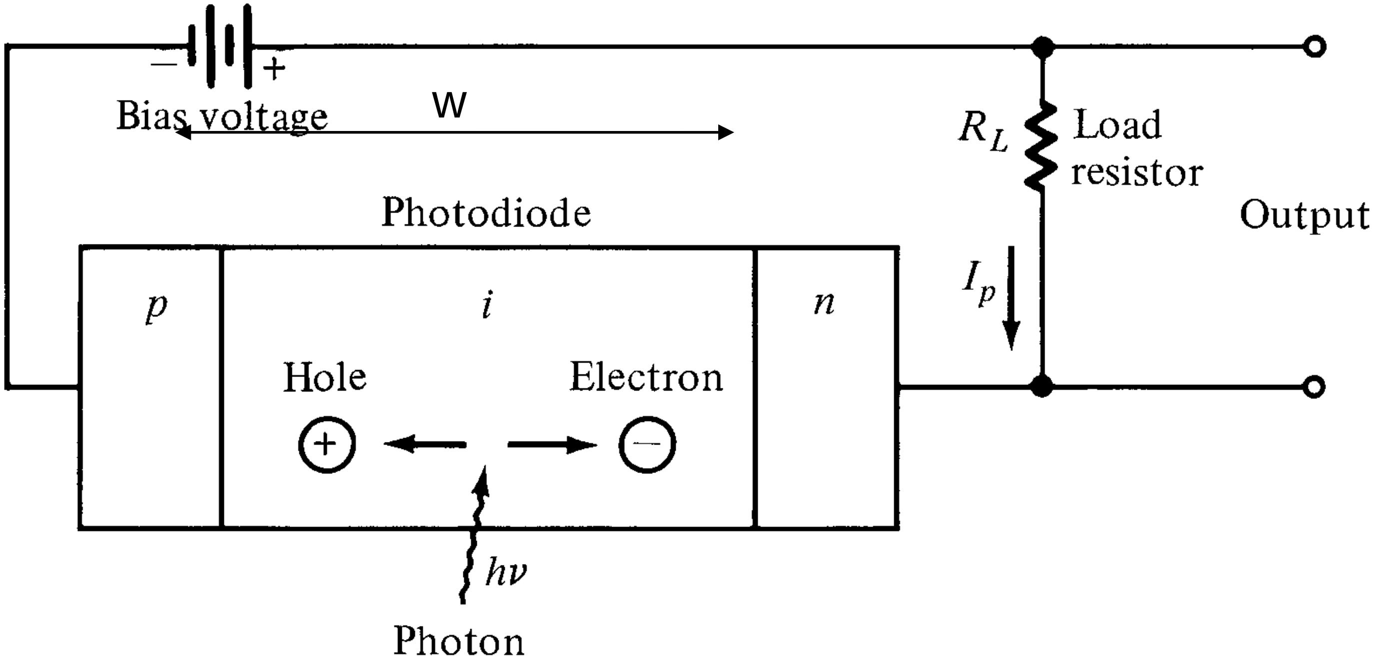
- Wristwatches
- Multifunctional IC cards with display
- Energy harvesting elements
- Digital books
- Charging and power supply applications for other electronic devices





حسگر PIN:

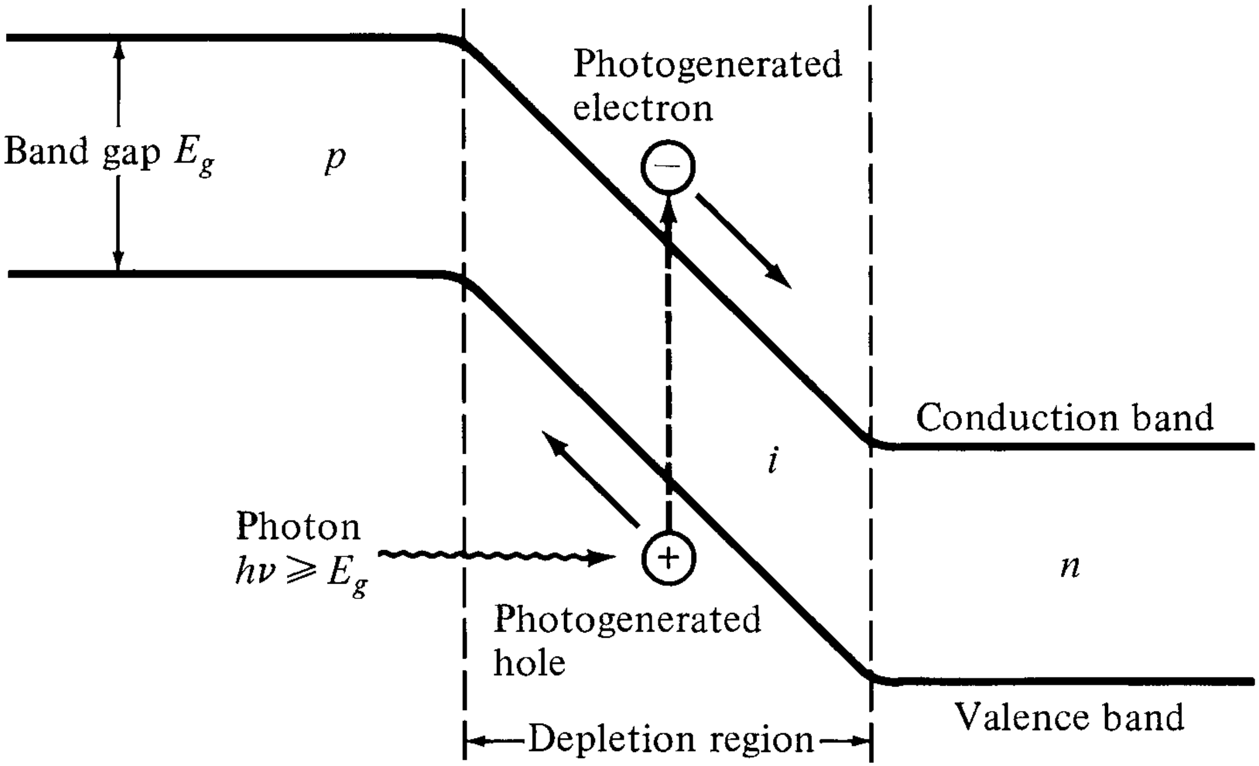
pin Photodetector:



The high electric field present in the depletion region causes photo-generated carriers to Separate and be collected across the reverse –biased junction. This give rise to a current Flow in an external circuit, known as **photocurrent**.

حسگر PIN:

نمایش نوارهای انرژی با اعمال بایاس و ساز وکار حسگری در PIN:



جذب نور در ناحیه تخلیه:

- Optical power absorbed, $P(x)$ in the depletion region can be written in terms of incident optical power, P_0 :

$$P(x) = P_0(1 - e^{-\alpha_s(\lambda)x})$$

- Absorption coefficient $\alpha_s(\lambda)$ strongly depends on wavelength. The upper wavelength cutoff for any semiconductor can be determined by its energy gap as follows:

$$\lambda_c = \frac{hC}{E_g} \qquad \lambda_c(\mu\mathrm{m}) = \frac{1.24}{E_g(\mathrm{eV})}$$

- Taking entrance face reflectivity into consideration, the absorbed power in the width of depletion region, w, becomes:

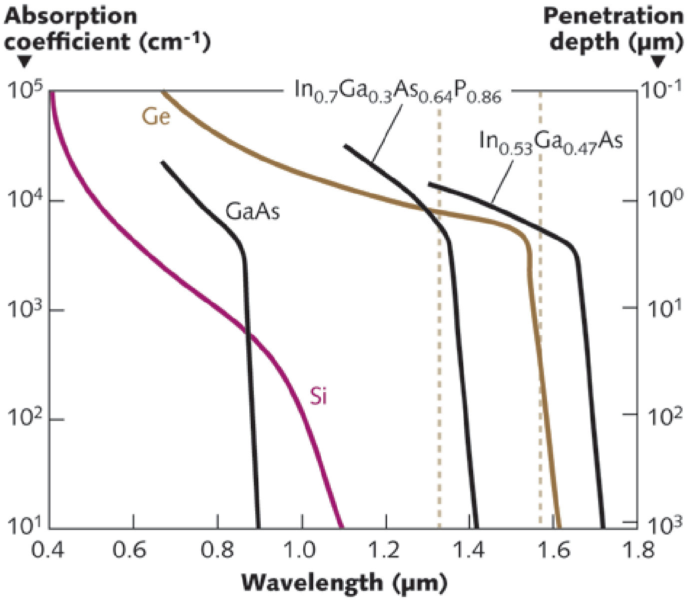
$$P_{absorb} = (1 - R_f)P(w) = P_0(1 - e^{-\alpha_s(\lambda)w})(1 - R_f)$$

جذب نور در ناحیه تخلیه:

جریان الکتریکی ناشی از جذب نور:

$$I_p = q\frac{P_{absorb}}{h\nu} = \frac{q}{h\nu}P_0(1-e^{-\alpha_s(\lambda)w})(1-R_f)$$

ضریب جذب نوری نیمه هادی های مختلف:



http://www.laserfocusworld.com/articles/print/volume-46/issue-8/features/avalanche-photodiodes.html

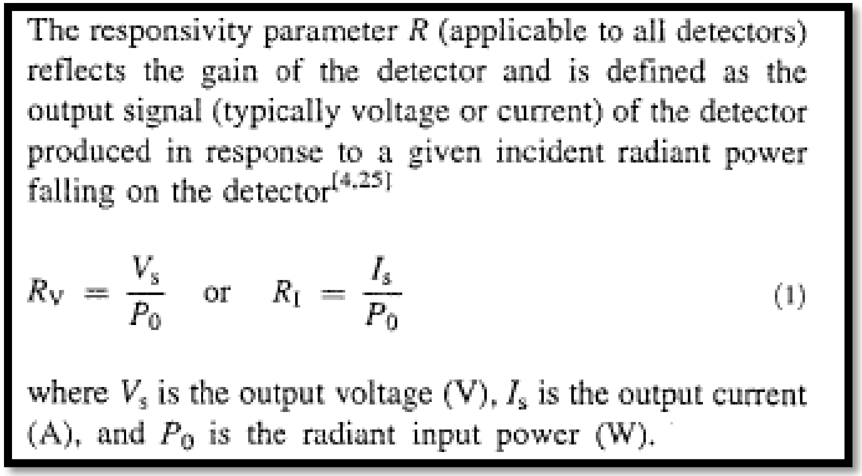
کمیتهای مقایسه ای حسگرهای نوری:

- محدوده پاسخدهی
- طول موج قطع (λ_C)
- جریان تاریک (جریان نور نخورده)
- پاسخدهی (Responsivity)
- بازده کوانتمی (Quantum Efficiency)
- توان معادل نویز Noise Equivalent Power (NEP)
- گیرندگی (Detectivity)

پاسخدهی و بازده کوانتمی:

- **Responsivity:**

$$R = \frac{I_P}{P_0} \quad [\mathrm{A/W}]$$



The responsivity parameter R (applicable to all detectors) reflects the gain of the detector and is defined as the output signal (typically voltage or current) of the detector produced in response to a given incident radiant power falling on the detector[4,25]

$$R_V = \frac{V_s}{P_0} \quad \text{or} \quad R_I = \frac{I_s}{P_0} \qquad (1)$$

where V_s is the output voltage (V), I_s is the output current (A), and P_0 is the radiant input power (W).

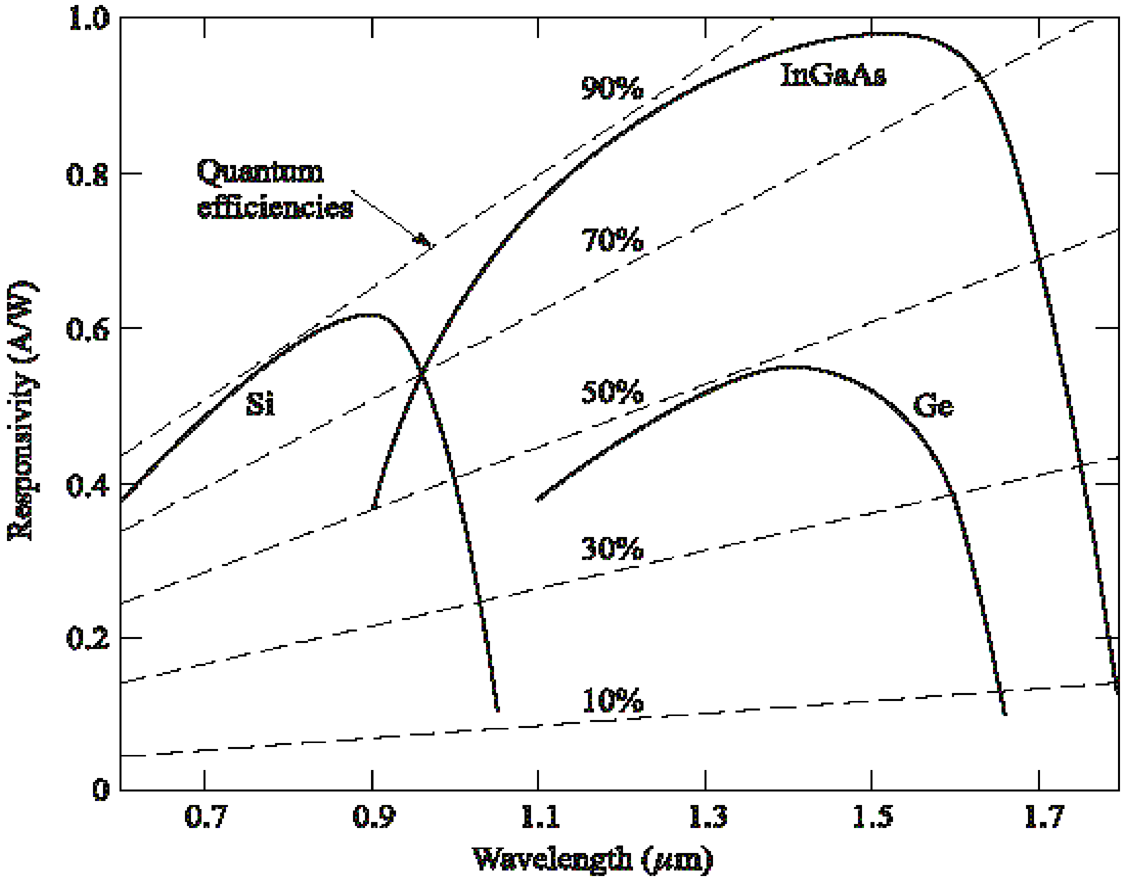
- **Quantum Efficiency:**

$$\eta = \frac{\text{\# of electron-hole photogenerated pairs}}{\text{\# of incident photons}}$$

- **Responsivity Vs. Quantum efficiency:**

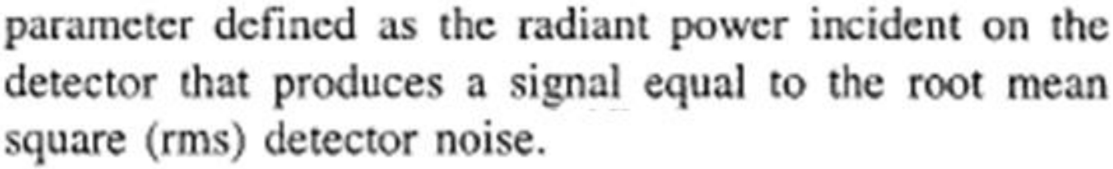
$$\eta = \frac{I_P / q}{P_0 / h\nu} = R\frac{h\nu}{q} \quad \rightarrow \quad R = \eta\frac{q}{h\nu}$$

پاسخدهی و بازده کوانتمی:



NEP و گیرندگی:

- **Noise Equivalent Power:**

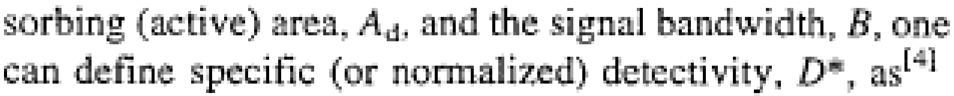


parameter defined as the radiant power incident on the detector that produces a signal equal to the root mean square (rms) detector noise.

- **Detectivity:**

$$D = \frac{1}{NEP}$$

- **Normalize Detectivity (D*):**



sorbing (active) area, A_d, and the signal bandwidth, B, one can define specific (or normalized) detectivity, D^*, as[4]

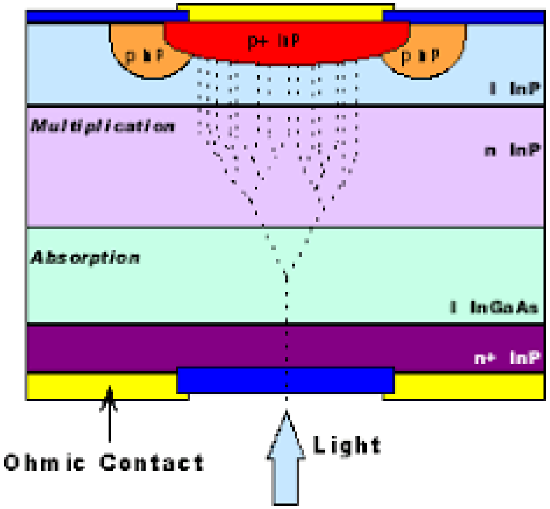
$$D^* = \frac{\sqrt{A_d B}}{NEP}$$

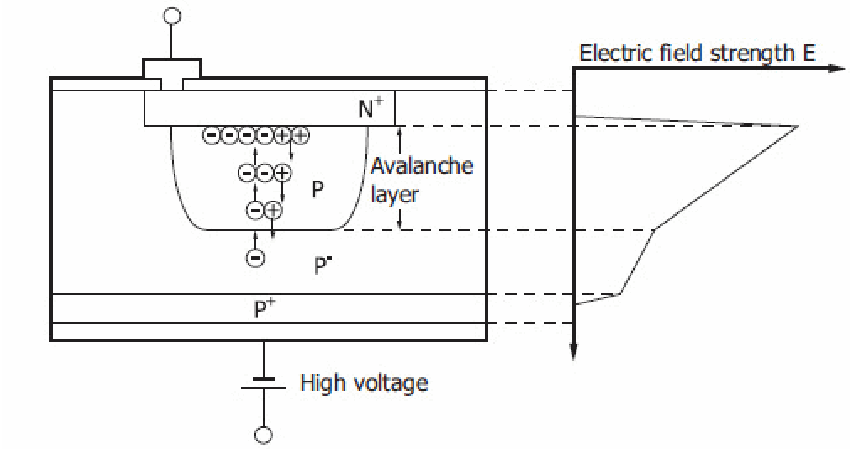
Datskos, P. G., & Lavrik, N. V. (2003). Detectors—figures of merit. *Encyclopedia of Optical Engineering*, *349*.

Avalanche Photodiode (APD) حسگر دیود نوری بهمنی:

APDs internally multiply the primary photocurrent before it enters to following circuitry.

In order to carrier multiplication take place, the photogenerated carriers must traverse along a high field region. In this region, photogenerated electrons and holes gain enough energy to ionize bound electrons in VB upon colliding with them. This multiplication is known as **impact ionization**.





پاسخدهی حسگر بهمنی:

- The multiplication factor (current gain) M for all carriers generated in the photodiode is defined as:

$$M = \frac{I_M}{I_p}$$

- Where I_M is the average value of the total multiplied output current & I_P is the primary photocurrent.

- The responsivity of APD can be calculated by considering the current gain as:

$$\boxed{R_{\mathrm{APD}} = \frac{\eta q}{h\nu} M = R_0 M}$$

[6-7]