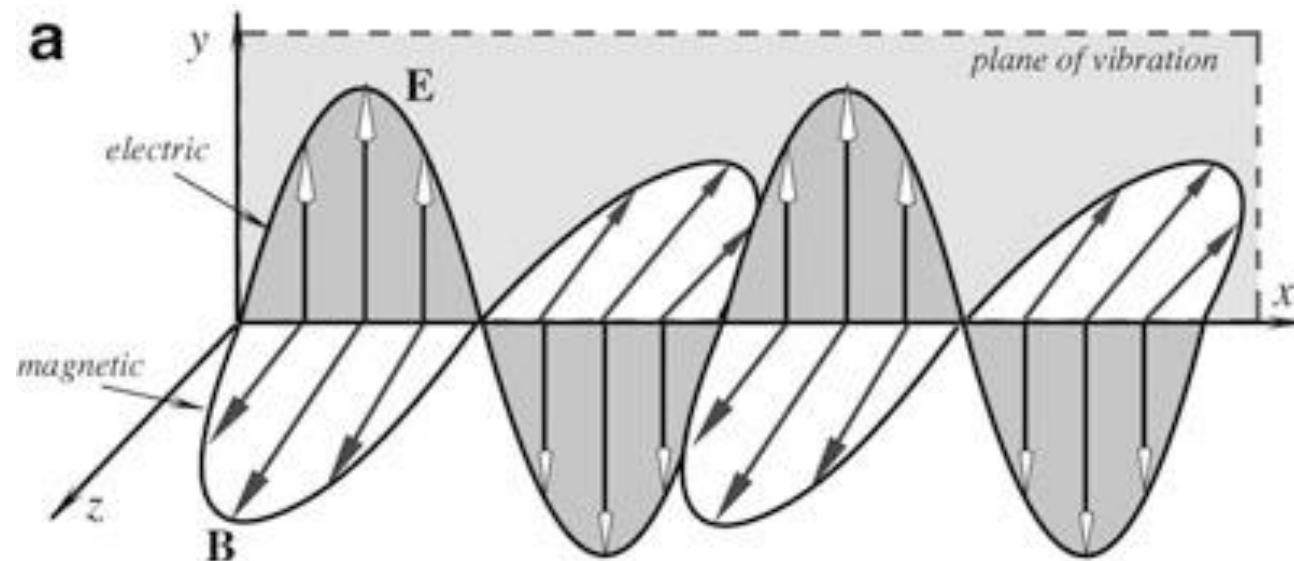
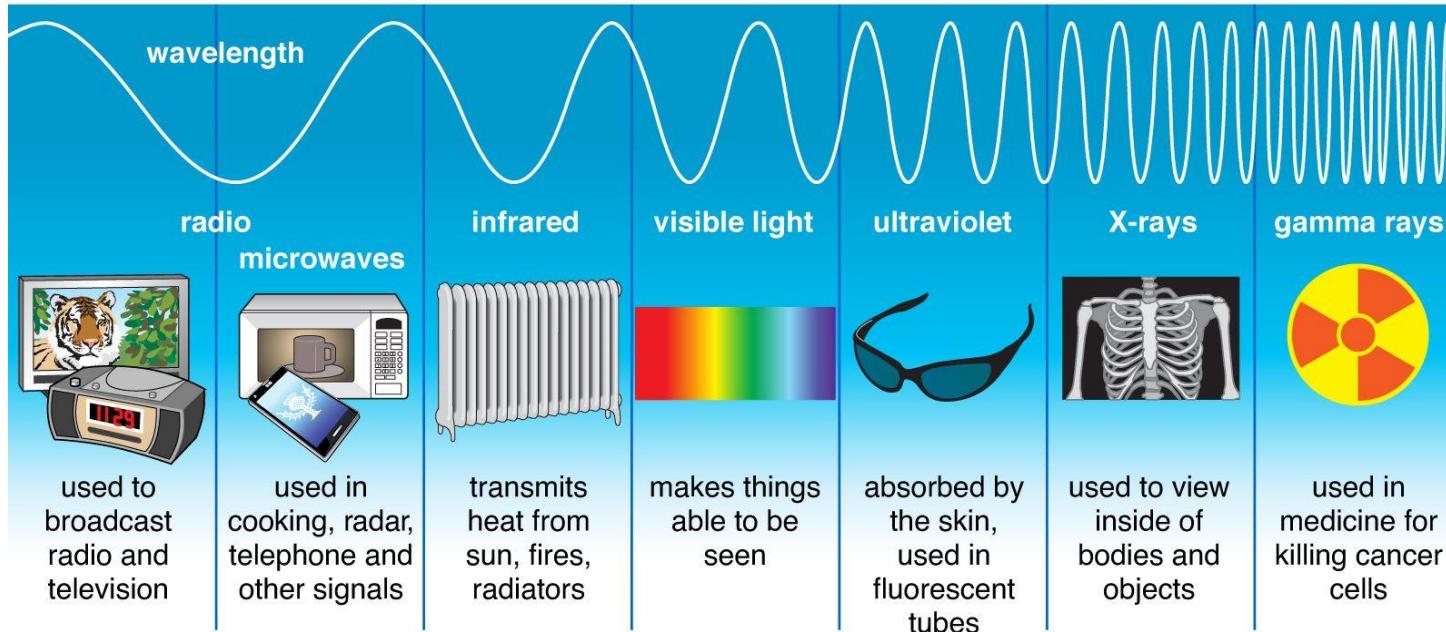


Light Detectors

Light is electromagnetic radiation (EMR) which consists of synchronized oscillations of electric and magnetic fields that propagate at the speed of light. The oscillations of the two fields are perpendicular to each other and perpendicular to the direction of energy and wave propagation.



Types of Electromagnetic Radiation



It spreads from very short wavelengths of γ -rays to the very long waves of the radio and even longer.

Physicists often say “light” when they refer to ultraviolet (UV), visible, and infrared (IR) spectral ranges.

The UV wavelengths range is approximately from 10 to 380 nm, visible range is approximately from 380 nm (violet) to 750 nm (red), while infrared is from 750 nm to about 1 mm.

EMR in the spectral range from about 3 to 20 μm is called thermal radiation since it covers natural radiation from objects being at temperatures that are not too hot to glow in the visible spectral range.

Detectors of electromagnetic radiations in the spectral range from UV to far-IR are called **light detectors**.

A photodetector or light sensor absorbs quanta of light and produces, directly or indirectly, an electrical response.

From the standpoint of a sensor designer, absorption of photons by a sensing element may result either in a quantum or thermal response.

Therefore, all photodetectors are divided into two major groups that are called **quantum** and **thermal**.

The **quantum detectors** operate from the ultraviolet to mid-infrared spectral ranges, while **thermal detectors** are mostly useful in the mid- and far-infrared spectral ranges where their efficiency at room temperatures exceeds that of the quantum detectors.

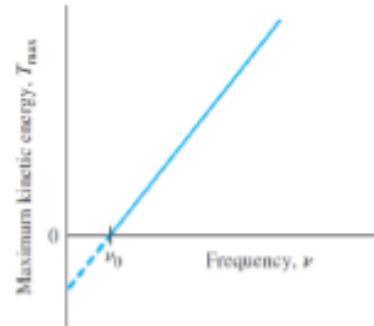
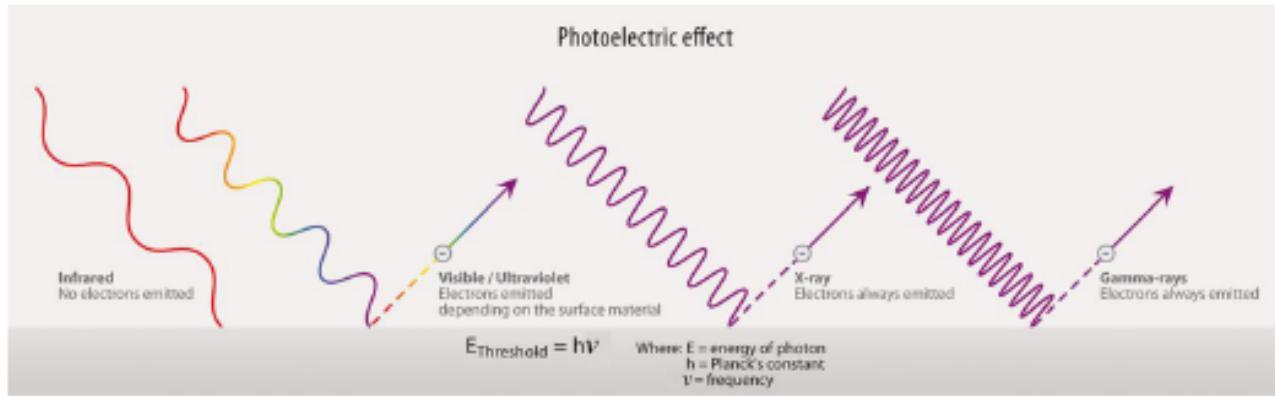
Principle of Quantum Detectors

Solid-state quantum detectors (photovoltaic and photoconductive devices) rely on the interaction of individual photons with a crystalline lattice of semiconductor materials. When we say photovoltaic we mean the sensor that generates the output electric voltage in response to light.

A photoconductive means a resistor whose electrical resistance is affected by the incident light.

Their operations are based on the photoeffect that was discovered by A. Einstein, and brought him the Nobel Prize.

More about energy quanta



* Experimental results about photoelectric effect :

- : inconsistency between experimental results and the classical theory of light
- Monochromatic light incident on a surface of a material: electrons (photoelectrons) are emitted
- Different from classical physics, the maximum kinetic energy of the photoelectron varies linearly with frequency with a limiting frequency $\nu = \nu_0$, below which no photoelectron is produced.
- c.f. incident intensity varies at a constant frequency, the rate of photoelectron emission changes, but the maximum kinetic energy remains the same.

* **Planck (1900):** thermal radiation is emitted from a heated surface in discrete packets of energy called *quanta*. The energy of these quanta is given by $E = h\nu$, where ν is the frequency of the radiation and h is a constant now known as Planck's constant ($h = 6.625 \times 10^{-34} \text{ J}\cdot\text{s}$)

* **Einstein (1905)** interpreted the photoelectric results by suggesting that the energy in a light wave is also contained in discrete packets or bundles. The particle-like packet of energy is called a photon, whose energy is also given by $E = h\nu$. A photon with sufficient energy, then, can knock an electron from the surface of the material.

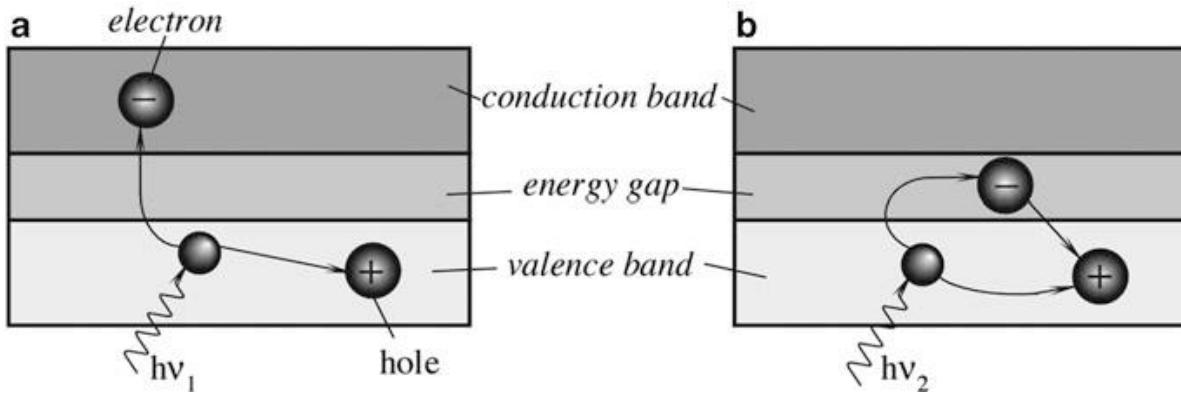
Maximum kinetic energy of the photoelectron (T)

$$T = \frac{1}{2}mv^2 = h\nu - \Phi = h\nu - h\nu_0 \quad (\nu \geq \nu_0)$$
$$\Phi = h\nu_0$$

$h\nu$: the incident photon energy

Work function (Φ): the minimum energy required to remove an electron from the surface

Interactions of photons with semiconductor materials



Photoeffect in a semiconductor for high (a) and low (b) energy photons

If light of a proper wavelength, that is having a sufficiently high energy of photons, strikes a semiconductor crystal, the concentration of charge carriers (electrons and holes) in the crystal increases, which manifests in the increased conductivity of a crystal

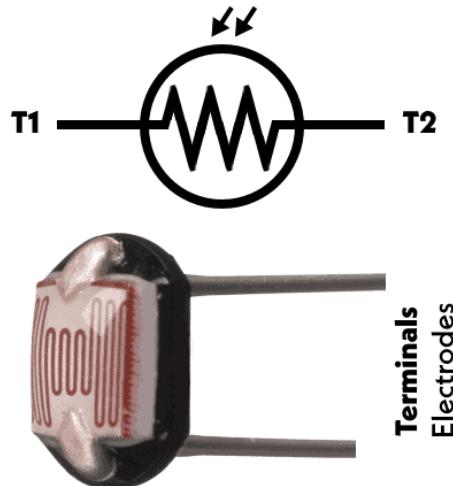
$$\sigma = e(\mu_e n + \mu_h p)$$

where e is the electron charge, μ_e is the electron mobility, μ_h is the hole mobility, and n and p are the respective concentrations of electrons and holes respectively.

When the photon of frequency v_1 strikes the crystal, its energy is high enough to separate the electron from its site in the valence band and push it through the forbidden energy gap into a conduction band at a higher energy level. In that band, the electron is free to serve as a current carrier. The deficiency of an electron in the valence band creates a hole that also serves as a current carrier that can move within the valence band. This is manifested in reduction of the specific resistivity of the material.

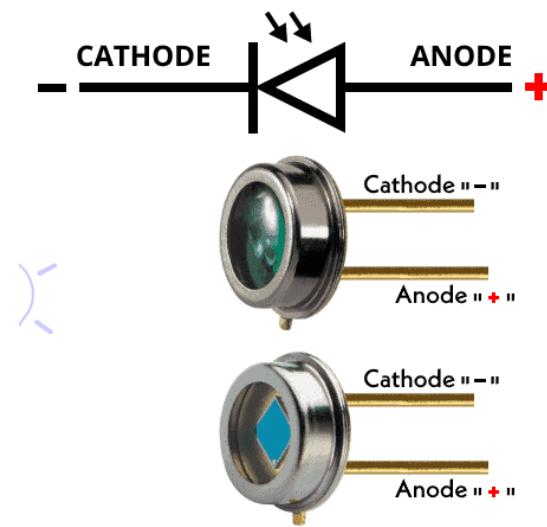
On the other hand, Fig. b shows that a photon of lower frequency v_2 does not have sufficient energy to push the electron through the forbidden energy gap. The photon energy is released as heat without creating current carriers. The forbidden energy gap serves as a threshold below which the material is not light sensitive.

All devices that directly convert photons of EMR into charge carriers are the quantum detectors that are generally produced in forms of Photodiodes, Phototransistors, and Photoresistors.



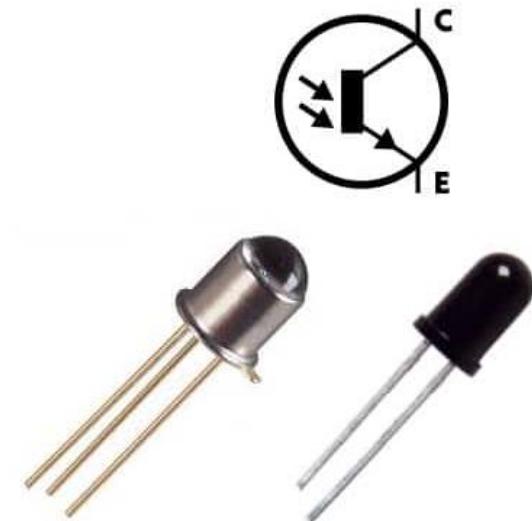
Photoresistor

WWW.FIFR



Photodiode

IOLOGY.ORG



Phototransistor

When comparing the characteristics of different photodetectors, the following specifications usually should be considered:

NEP (noise equivalent power) is the amount of light equivalent to the intrinsic noise level of the detector. The NEP is expressed in units of W/Hz^{-2}

D* (D-star) refers to the detectivity of a detector's sensitive area of 1 cm^2 and a noise bandwidth of 1 Hz . Detectivity is another way to measure the sensor's signal-to-noise ratio. The detectivity is expressed in units of Hz^2/W .

IR cutoff wavelength (λ_c) represents the long wavelength limit of spectral response and often is listed as the wavelength at which the detectivity drops by 10 % of the peak value.

Maximum current is specified for photoconductive detectors (such as HgCdTe) which operate at constant currents. The operating current never should exceed the maximum limit.

Maximum reverse voltage is specified for Ge and Si photodiodes and photoconductive cells. Exceeding this voltage can cause the breakdown and severe deterioration of the sensor's performance.

Radiant responsivity is the ratio of the output photocurrent (or output voltage) divided by the incident radiant power at a given wavelength, expressed in A/W or V/W .

Dark current ID for photodiodes is a leakage current at a reverse voltage when the diode is in complete darkness. This current generally is temperature-dependent and may vary from pA to μA . It approximately doubles for every 10°C in temperature increase.

Field of view (FOV) is the angular measure of the volume of space where the sensor can respond to the source of radiation.

Junction capacitance (C_j) is similar to the capacitance of a parallel plate capacitor. It should be considered whenever a high-speed response is required. The value of C_j drops with reverse bias and is higher for the larger diode areas.

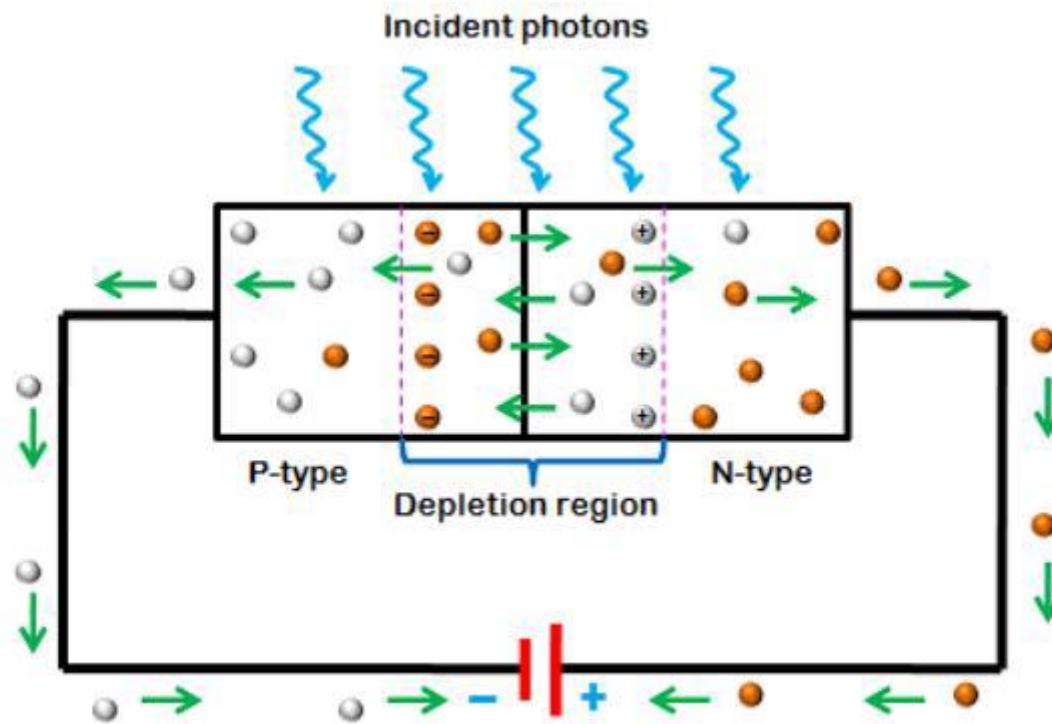
Photodiodes

Photodiodes are semiconducting optical sensors, which if broadly defined may even include solar batteries. However, here we consider only the information aspect of these devices rather than the power conversion.

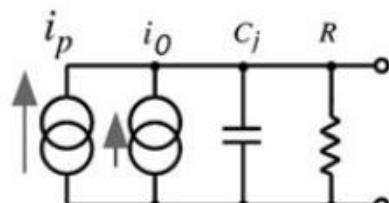
In a simple way, the operation of a photodiode can be described as follows. If a pn-junction is forward biased (positive side of a battery is connected to the p side) and is exposed to light of proper frequency, the current increase will be very small with respect to a dark current. In other words, the bias current is much greater than the current generated by light, and the diode is just a diode, not really useful for sensing light.

If the junction is reverse biased , when light strikes the semiconductor, the current will increase quite noticeably. Impinging photons create electron– hole pairs on both sides of the junction. When electrons enter the conduction band, they start flowing toward the positive side of the battery. Correspondingly, the created holes flow to the negative terminal, meaning that photocurrent ***ip flows in*** the network.

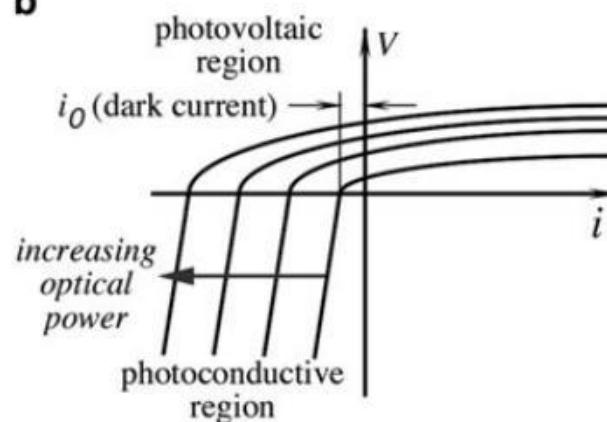
Under dark conditions, dark current i_0 is independent of applied voltage and mainly is the result of thermal generation of charge carriers. Thus, a reverse-biased photodiode electrical equivalent circuit contains two current sources and a RC network.



a



b



4 An equivalent circuit of a photodiode (a) and its volt-ampere characteristic (b)

The process of optical detection involves the direct conversion of optical energy (in form of photons) into an electrical signal (in form of electrons). If a probability that a photon of energy $h\nu$ will produce an electron in a detection is η , then the average rate of production of electrons $\langle r \rangle$ for an incident beam of optical power P is given by [1]:

$$\langle r \rangle = \frac{\eta P}{h\nu}$$

the electrical current is proportional to the optical power incident on the detector:

$$i = \langle r \rangle e = \frac{\eta e P}{h\nu},$$

where e is the charge of an electron. A change in input power ΔP (due to intensity modulation in a sensor, for instance) results in the output current Δi . Since power is proportional to squared current, the detector's electrical power output varies quadratically with input optical power, making it a "square-law" optical power detector.

The voltage-to-current response of a typical photodiode is shown in Fig. 15.4b. If we attach a high-input impedance voltmeter to the diode (corresponds to the case when $I = 0$, that is along the y-axis), we will observe that with increasing optical power, the voltage changes in a quite nonlinear fashion. In fact, variations are logarithmic. However, for the short circuit conditions ($V = 0$, that is along the x-axis), that is when the diode is connected to a current-to-voltage converter, current varies linearly with the optical power. The current to- voltage response of the photodiode is given by [2]:

where i_0 is a reverse “dark current” which is attributed to the thermal generation of electron–hole pairs, i_s is the current due to the detected optical signal, k_b is Boltzmann constant and T is the absolute temperature.

$$i = i_0 \left(e^{eV/k_b T} - 1 \right) - i_s,$$

$$i = i_0 \left(e^{eV/k_b T} - 1 \right) - \frac{\eta e P}{h\nu},$$

which is the overall characteristic of a photodiode. Efficiency of the direct conversion of optical power into electric power is quite low. Typically, it is in the range of 5–10 %; however, it was reported that some experimental photocells were able to reach efficiency as high as 90 %. In the sensor technologies, however, photocells are generally not used.

Photoresistor

A photoresistor, just as a photodiode, is a photoelectric device. It is a resistor whose resistance is called a photoresistance R_p that depends on incident light. The most common materials for its fabrication are cadmium sulfide (CdS) and cadmium selenide (CdSe) that are semiconductors whose resistances change upon light entering the surface. For its operation, a photoresistor requires a power source (excitation signal) because unlike a photodiode or phototransistor, it does not generate photocurrent—a photoeffect is manifested in change in the material's electrical resistance.

An electrode is set at each end of the photoconductor. In darkness, the resistance of the material is high. Hence, applied voltage V results in small dark current which is attributed to temperature effects. When light is incident on the surface, photocurrent current i_p flows between its electrodes and through the battery.

The reason for the current increase is the following. Directly beneath the conduction band of the crystal is a donor level and there is an acceptor level above the valence band. In darkness, the electrons and holes in each level are almost crammed in place in the crystal, resulting in a high resistance of the semiconductor. When light illuminates the photoconductive crystal, photons are absorbed which result in the added-up energy in the valence-band electrons.

This moves them into the conduction band, creating free holes in the valence band, increasing the conductivity of the material. Since near the valence band is a separate acceptor level that can capture free electrons not as easily as free holes, the recombination probability of the electrons and holes is reduced and the number of free electrons in the conduction band is high. Since CdS has a band gap of 2.41 eV, the absorption edge wavelength is $\lambda = c/v$ 515 nm, which is in the visible spectral range. Hence, the CdS detects light shorter than 515 nm wavelengths (violet, blue, and green). Other photoconductors have different absorption edge wavelengths. For instance, while CdS is most sensitive at shorter wavelengths range, Si and Ge are most efficient in the near infrared. The conductance of a semiconductor is given by:

$$\Delta\sigma = ef(\mu_n\tau_n + \mu_p\tau_p).$$

where μ_n and μ_p are the free electron and hole movements ($\text{cm}/\text{V s}$), τ_n and τ_p are the free electron and hole lives (sec), e is the charge of an electron, and f is the number of generated carriers per second per unit of volume. For a CdS sell $\mu_n\tau_n > \mu_p\tau_p$, hence, conductance by free holes can be ignored. Then the sensor becomes an n-type semiconductor. Thus:

$$\Delta\sigma = ef\mu_n\tau_n, \quad (15.15)$$

We can define sensitivity b of a photoresistor through a number of electrons generated by one photon (until the carrier lifespan ends):

$$b = \frac{\tau_n}{t_t}, \quad (15.16)$$

where $t_t = l^2/V\mu_n$ is the transit time for the electron between the sensor's electrodes, l is distance between the electrodes, and V is applied voltage. Then, we arrive at:

$$b = \frac{\mu_n\tau_n V}{l^2}. \quad (15.17)$$

For example, if $\mu_n = 300 \text{ cm}^2/\text{V s}$, $\tau_n = 10^{-3} \text{ s}$, $l = 0.2 \text{ mm}$, and $V = 1.2 \text{ V}$, then the sensitivity is 900, which means that a single photon releases 900 electrons, making a photoresistor to work as a photomultiplier. Indeed, a photoresistor is a very sensitive device!

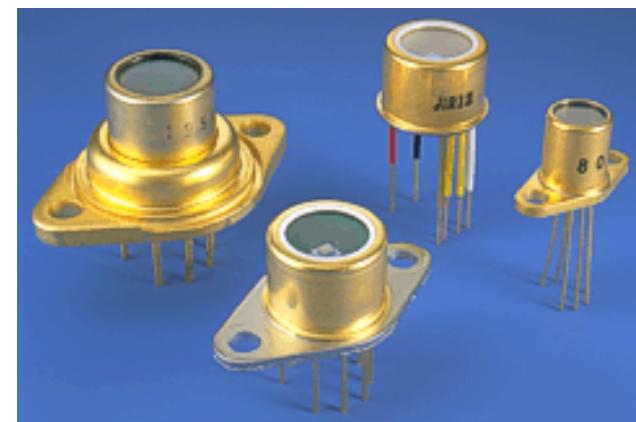
It can be shown that for better sensitivity and lower cell resistance, a distance l between the electrodes should be reduced, while width of the sensor d should be increased. This suggests that the sensor should be very short and very wide. For practical purposes, this is accomplished by fabricating a sensor in a serpentine shape as shown in Fig. 15.11b).

HgCdTe(MCT) infrared sensors

At present, HgCdTe is the most widely used variable gap semiconductor for infrared (IR) photodetectors. Over the last forty years it has successfully fought off major challenges from extrinsic silicon and lead-tin telluride devices, but despite that it has more competitors today than ever before.

Progress in IR detector technology is connected with semiconductor IR detectors, which are included in the class of photon detectors. In this class of detectors the radiation is absorbed within the material by interaction with electrons either bound to lattice atoms or to impurity atoms or with free electrons. The observed electrical output signal results from the changed electronic energy distribution. The photon detectors show a selective wavelength dependence of response per unit incident radiation power. They exhibit both perfect signal-to-noise performance and a very fast response.

But to achieve this, the photon detectors require cryogenic cooling. This is necessary to prevent the thermal generation of charge carriers. The thermal transitions compete with the optical ones, making non-cooled devices very noisy. Cooling requirements are the main obstacle to the more widespread use of IR systems based on semiconductor photodetectors, making them bulky, heavy, expensive and inconvenient to use. Current **cooled IR detector systems use material such as HgCdTe, InSb, PtSi, and doped Si.**



HgCdTe has inspired the development of three –generations of detector devices. The first generation, linear arrays of photoconductive detectors, has been produced in large quantities and is in widespread use today.

The second generation, two-dimensional arrays of photovoltaic detectors, is now in high-rate production – thousands of arrays annually.

Third generation devices, defined here to encompass the more exotic device structures embodied in two-colour detectors, avalanche photodiodes, and hyperspectral arrays, are now fielded in demonstration programs.

Several properties of HgCdTe qualify it as highly useful for infrared detection. These are:

- Adjustable bandgap from 0.7 to 25 μm .
- Direct bandgap with high absorption coefficient.
- Moderate dielectric constant/index of refraction.
- Moderate thermal coefficient of expansion.
- Availability of wide bandgap lattice-matched substrates for epitaxial growth.

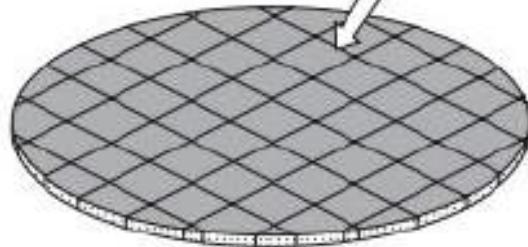
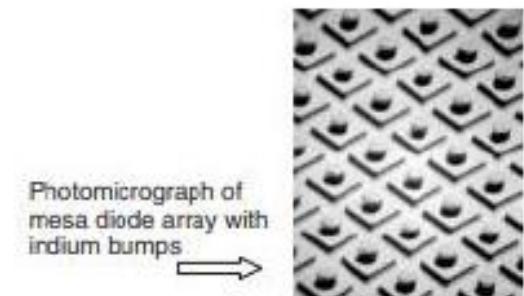
Three principal methods have been developed to synthesis :

- Bulk.
- Liquid phase epitaxy – LPE.
- Vapour phase epitaxy – VPE.
- Metal organic chemical vapour deposition – MOCVD.
- Molecular beam epitaxy – MBE.

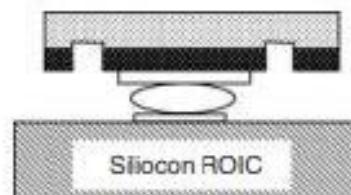
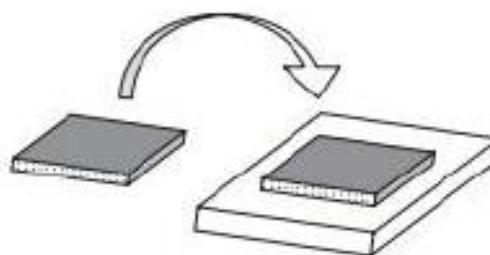
Photocurrent and quantum efficiency

MCT has a strong optical absorption coefficient and only thin layers are needed to produce high quantum efficiency. Typically in MW detectors the absorber need only be 4–5 μm thick and about twice this in LW detectors. Ideally, the absorption should occur well within a diffusion length of the p–n junction to avoid signal loss due to recombination.

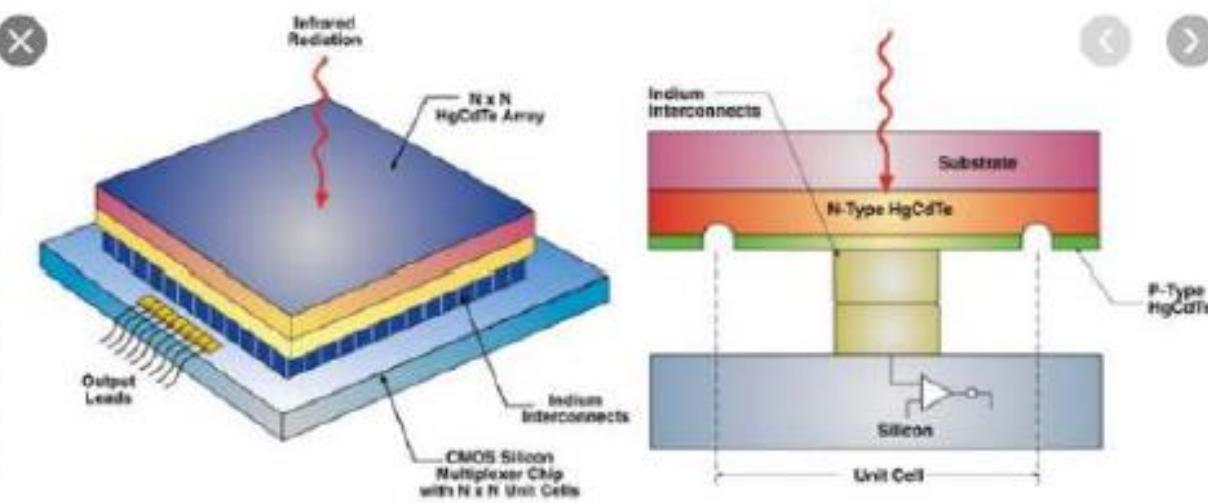
A long carrier lifetime is nearly always observed in n-type material with low carrier concentration. Device engineers tend to favor using n-type absorbers for the best quantum efficiency and try to minimize the volume of the p-region for lower thermal leakage currents.



HgCdTe layer grown on large area substrate (Si, GaAs or sapphire) using VPE growth method. Processed into arrays with indium bumps and sawn up into array blocks.



The main commercial drive though is to cost reduce the manufacture of large-area arrays and avoid expensive CdZnTe substrates. Silicon, gallium arsenide and sapphire are the commonest substrates used because they are available commercially in large area wafers at relatively low cost



Wafer-scale processing using VPE MCT material, mesa diodes, and indium bump interconnect technology

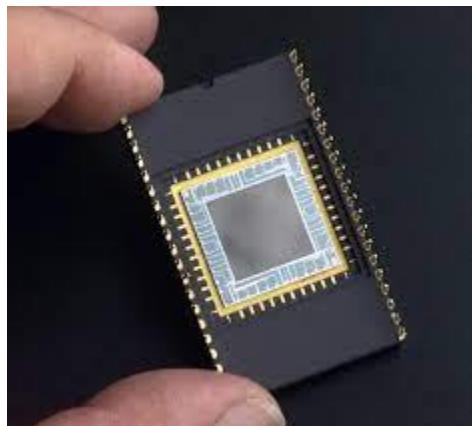
Visible-light color sensors

The CCD (Charge Coupled Device) and CMOS (Complementary Metal Oxide Semiconductor) imaging sensors are two different technologies presently used for digitally capturing images in the visible spectral range.

Both types of the imagers convert light into electric charge and process it into electronic signals.

In a CCD sensor, every pixel's charge is transferred through a very limited number of output nodes (often just one) to be converted to voltage, buffered, and sent off-chip as an analog signal. Then, the analog signal is digitized by an external ADC. All of the pixel can be devoted to light capture, and the output's uniformity (a key factor in image quality) is high.

In a CMOS sensor, each pixel has its own charge-to-voltage conversion, and often the sensor also includes amplifiers, noise-correction, and digitization circuits, so that the chip outputs digital bits. These additional functions increase the design complexity and reduce the area available for light capture. With each pixel doing its own conversion, uniformity is lower. But the chip can be built to require less off-chip circuitry for basic operation.



CCD detectors



What is CMOS!!

complementary metal oxide semiconductor

[SUBSCRIBE NOW](#)

Engineer's Academy



CCD Sensor

A CCD chip is divided into pixels. Each pixel has a potential well that collects the electrons produced by the photoelectric effect. At the end of an exposure (frame), each pixel has collected an amount of electrons (i.e., charge) proportional to the amount of light that fell onto it. The CCD is then read out by cycling the voltages applied to the chip in a process called “clocking.” Due to the structure of a CCD, clocking causes the charge in one pixel to be transferred to an adjacent pixel.

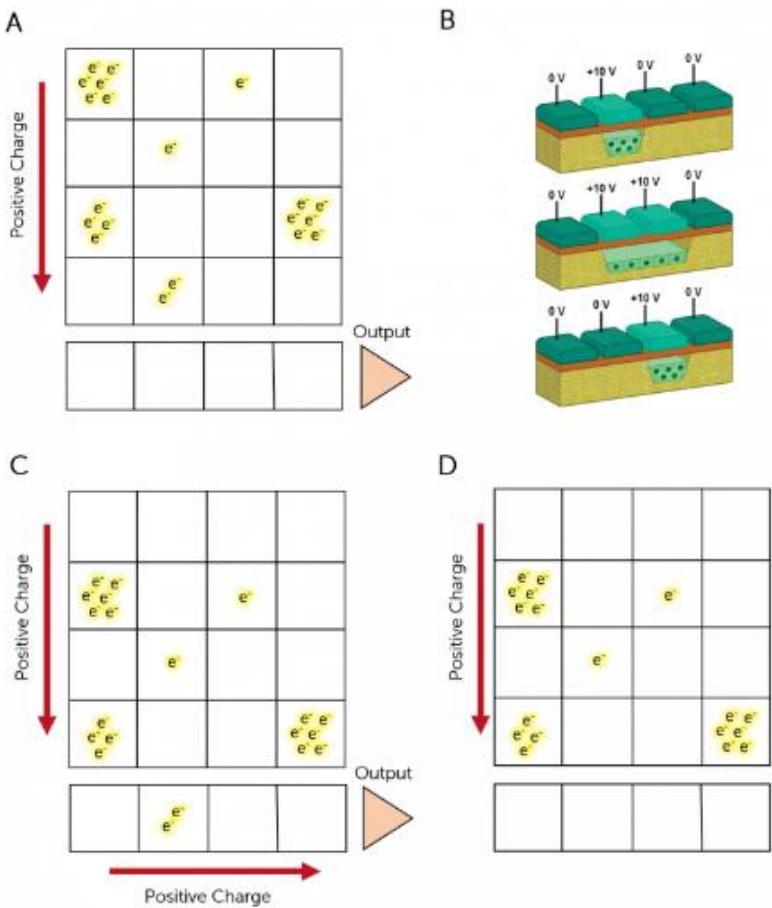
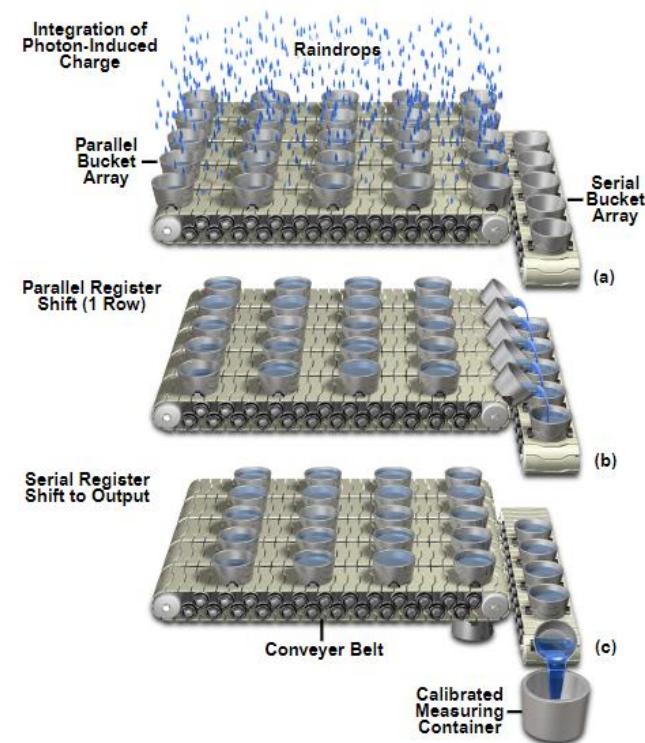
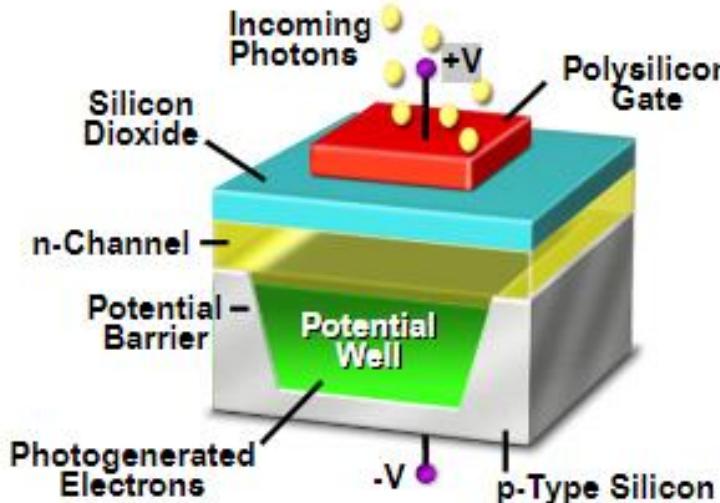


Figure 1: Schematic depicting charge transfer on a CCD. (A) Different numbers of photoelectrons accumulate on pixels within the sensor when it is exposed to light. Each row of electrons is shifted down a row using a positive voltage. (B) The electrons are shifted by spreading the positive voltage over neighboring pixels (in the same column) to transfer them to a new pixel. This will continue all the way down the sensor until they are transferred to the readout register. (C) Those electrons that are on the bottom row are transferred into the readout register. (D) Once on the readout register, the electrons are shifted horizontally, column by column, via a positive charge until they reach the output node, where they are amplified and digitized. This process is repeated until the whole sensor is clear of electrons. Then the sensor can be exposed to light again to acquire a new image.

Bucket brigade – The incoming photons are represented by the raindrops, and the CCD chip is a 2D array of buckets. Each bucket represents a pixel, and the water it collects is the combined charge accumulation due to photoelectrons. Once the rain has stopped (the shutter is closed), conveyor belts move the columns of buckets down one row (the gates are clocked). The water in the buckets at the edge of the array pours into more buckets on a horizontal conveyor belt. This conveyor belt then pours these buckets one at a time into a container on a scale, that is a graduated cylinder (the readout electronics). The volume of water from each bucket is measured and rounded to the nearest milliliter (corresponding to the digital output of a CCD, which reports the counts, or analog-to-digital units—ADUs, from each pixel). Then the image is formed by reconstructing the distribution of rainfall on the array.

Figure 2 - Metal Oxide Semiconductor (MOS) Capacitor



CMOS Sensor

A CMOS sensor or complementary metal-oxide-semiconductor sensor is one kind of electronic chip, used to change the photons into electrons for digital processing. These sensors are mainly used for creating images within digital cameras, digital CCTV cameras & digital video cameras. These electronic chips can also be found in scanners, barcode readers & astronomical telescopes. The low-cost manufacturing of CMOS makes it achievable to generate low-cost consumer devices.

The CMOS sensor works on the principle of the photoelectric effect to change the photons into electrical energy. Not like CCD sensors, CMOS sensors will change electric charge into voltage directly within the pixels. At present CMOS sensors are available with outstanding image quality & high frame rates, so used in high-performance-based industrial cameras.

Like CCDs, CMOS imagers include an array of photosensitive diodes (PD), one diode within each pixel. Unlike CCDs, however, each pixel in a CMOS imager has its own individual amplifier integrated inside . Since each pixel has its own amplifier, the pixel is referred to as an “active pixel”.

In addition, each pixel in a CMOS imager can be read directly on an x-y coordinate system, rather than through the “bucket-brigade” process of a CCD. This means that while a CCD pixel always transfers a charge, a CMOS pixel always detects a photon directly, converts it to a voltage, and transfers the information directly to the output. Since CMOS pixel has an additional circuitry located next to it, the light sensitivity of a CMOS chip tends to be lower. Many of the photons arriving at the chip hit the circuitry instead of the photodiode.

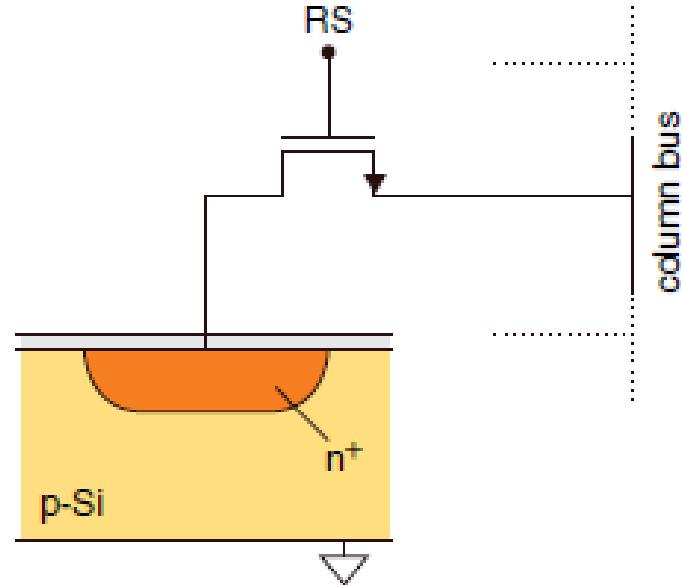
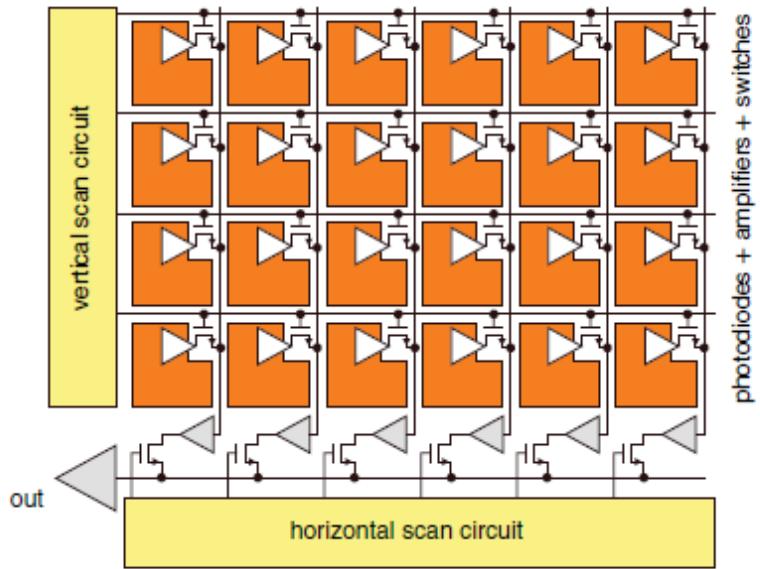


Figure 7.2 Schematic architecture of a 2-dimensional CMOS image sensor

The working principle of CMOS are

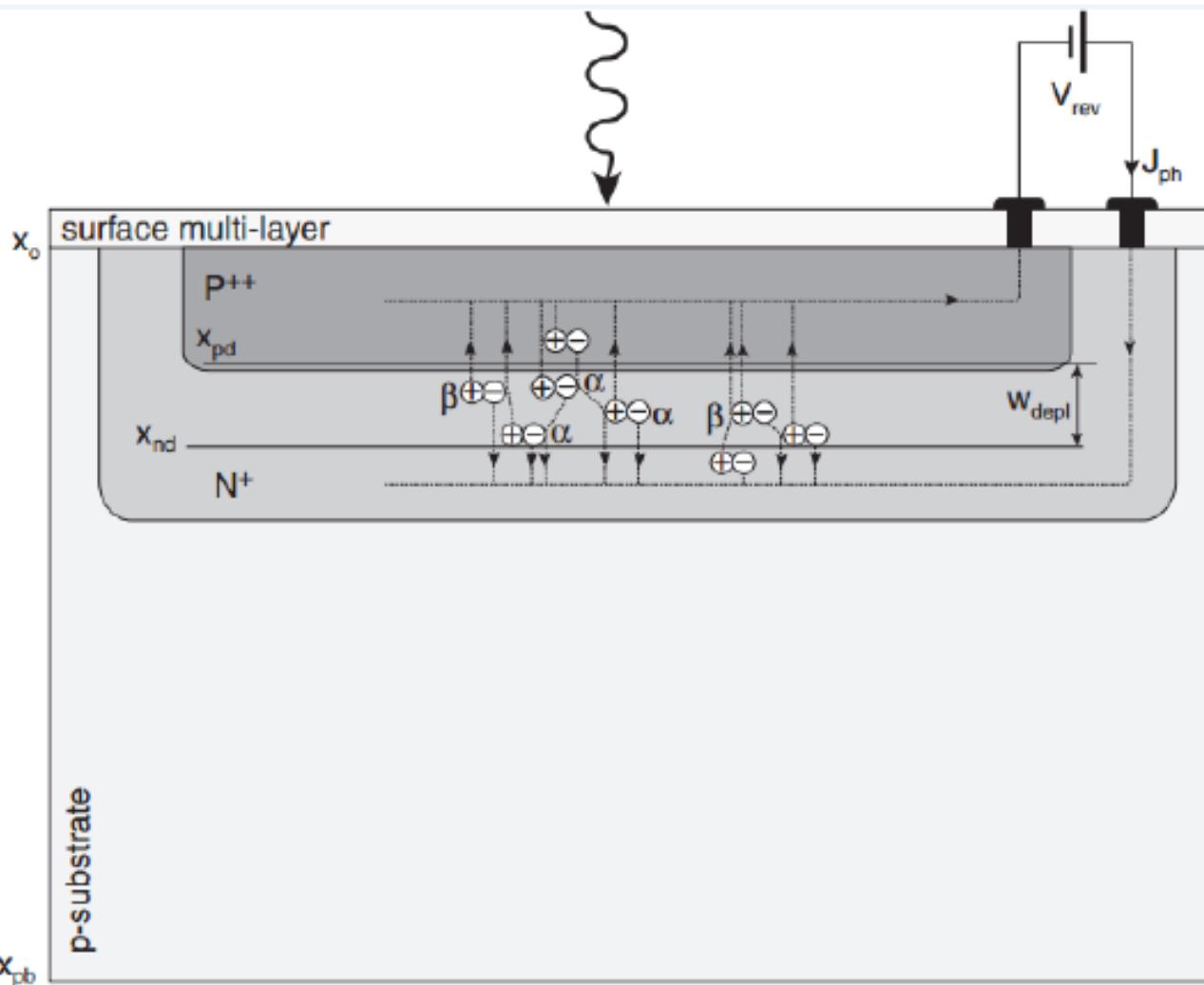
- At the start of an exposure the photodiode is reverse biased to a high voltage (e.g. 3.3 V). This reset action is performed by means of circuitry present on the column bus (not shown in the figure). To allow the pixel to be reset, the row select (RS) needs to be active such that the pixel is connected to the column bus. Once the pixel is reset, the exposure can start and the RS switch will become inactive.
- During the exposure time, the n+-region (cathode) of the photodiode is left floating. Impinging photons might get absorbed in the silicon and as a result of this action, electron-hole pairs can be generated. The present electrical field across the junction of the photodiode will separate the two charge carriers. Electrons will move to the n+ side of the photodiode and the hole will move to the p-substrate side of the photodiode. In this way, the reverse voltage across the photodiode will decrease.

- At the end of the exposure time the remaining voltage across the diode is measured, and its drop from the original value is a measure for the amount of photons falling on the photodiode during the exposure time. It should be clear that the measurement of the voltage across the diode requires an activation of the RS switch.
- To allow a new exposure cycle, the photodiode is reset again.

CMOS Sensor	CCD Sensor
CMOS sensor is a metal oxide semiconductor chip, used to change light into an electrical signal.	It is a charge-coupled device, used to transmit electrically charged signals.
CMOS sensors are available in two types active pixel and passive pixel.	CCD sensors are available in three types like Full-Frame, Frame-Transfer & Interline-Transfer.
Low power consumption	Moderate to high power consumption
Moderate complexity	Low complexity
CMOS resolution is low to high	CCD resolution is low to high
Low uniformity	High uniformity
It has a moderate dynamic range	It has a low dynamic range
Moderate to the high noise level	Low noise level
The fill factor is moderate	The fill factor is high
Chip signal is digital	Chip signal is analog
These sensors are not expensive to design because these sensors are designed on most typical Si production lines.	These are expensive to generate.
CMOS sensors are used from automation in industries to traffic control-based applications.	CCD sensors are used in hand-held, surveillance, video cameras of desktop computers, etc.

Avalanche photodiode

The avalanche photodiode is similar to the conventional pn junction, apart from the fact that the doping levels are relatively high. The operation of the avalanche photodiode is based on impact ionization within the depletion layer. The basic device structure is shown in Figure



The doping concentration of the p⁺⁺ layer exceeds 10¹⁹ cm⁻³ and n⁺ is in the order of 2 × 10¹⁸ cm⁻³ (this is generally referred to as the single-sided abrupt junction). Under these conditions and $V_{\text{rev}} \gg 10$ V,

$$w_{\text{depl}} \approx \sqrt{\frac{2\epsilon}{qN_D}V_{\text{rev}}} \approx 0.1 \mu\text{m}$$

$$E_{\text{max}} = E(x_j) \approx \sqrt{\frac{2qN_D}{\epsilon}V_{\text{rev}}} \approx 10^7 \text{ V/m}$$

The avalanche photodiodes are named so because if a reverse bias is applied to the p-n junction and a high-intensity field is formed with the depletion layer, photon carriers will be accelerated by the field and collide with the atoms, producing the secondary carriers. In turn, the new carriers are accelerated again, resulting in the extremely fast avalanche-type increase in current. There-fore, these diodes work as amplifiers, making them useful for detecting extremely low levels of light.

The device is operated fully depleted and has two field regions: i) a light absorption region followed by the π region which is about (30–150) μm wide with a relatively low field ($\sim 2 \times 10^4$ V cm⁻¹) wherein charge carriers are drifting; ii) a narrow (a few micrometers) high field region ($\sim 10^5$ V cm⁻¹) wherein the multiplication takes place.

The principle of operation of an APD is based on the conversion of the energy of incoming photons into electron–holes pairs in silicon as in PIN and their further multiplication through an avalanche process in the depleted region by application of a very high reverse bias voltage to a p – n junction. The charge carriers created in the depleted region of the junction by the incident radiation, will drift in the π region towards the corresponding electrodes under the electric field applied across the junction: the holes will drift toward the p + side in a low electric field, while the electrons will drift toward the narrow n + side in a high electric field where an avalanche process will eventually take place, i.e., the electrons will be accelerated and acquire a kinetic energy large enough so that they can create additional electron-hole pairs via ionization through their collisions with atoms in the crystal lattice. At sufficiently high voltage, i.e., high electric field values, holes can also produce electron-hole pairs and therefore produce additional electrons. This electron multiplication generates avalanche breakdown that occurs at the so-called breakdown voltage which is the maximum reverse bias voltage which can be applied to an APD (when an APD operates close to avalanche breakdown, its gain is a very rapidly increasing function of the applied reverse bias voltage). The value of the breakdown voltage varies with the type of APD. Then, the operating voltage of an APD has to be kept lower than this breakdown voltage. In practice, this avalanche multiplication process - referred to as avalanche multiplication of photocurrent - occurs beyond a value of the applied voltage corresponding to an internal electric field

Radiation detectors

In EMR, there is a region of the γ -radiation. Then, there are the X-rays that, depending on the wavelengths, are divided into hard, soft, and ultrasoft rays. However, a spontaneous radiation from the matter not necessarily should be electromagnetic: there is the so-called nuclear radiation, which is emission of particles from the atomic nuclei. A spontaneous atomic decay can be of two types: the charged particles (α and β particles, and protons), and uncharged particles, which are the neutrons. Some particles are complex like the α -particles, which are the nuclei of helium atoms consisting of two neutrons, while other particles are generally simpler, like the β -particles which are either electrons or positrons. Ionizing radiations are given that name because as they pass through various media that absorbs their energy, additional ions, photons, or free radicals are created.

A radiation detector is a sensor that upon interaction with radiation produces a signal that can preferably be processed electronically to give the requested information.

Charged particles, such as α particles, transfer their energy directly by ionization and excitation. In all cases, the ionization results either in the production of charge carriers, viz. electrons and ions in a gaseous detection medium, and electrons and holes in a semiconductor detector material, or in the emission of light quanta in a scintillator.

These processes represent the three major groups of radiation detectors, i.e. gas filled, semiconductor and scintillation detectors.

Scintillation detectors

The operating principle of these detectors is based on the ability of certain materials to convert nuclear radiation into light. Thus, an optical photon detector in a combination with a scintillating material can form a radiation detector.

Certain materials, when struck by radiation, emit a small flash of light, a scintillation.

The light intensity resulting from the radiation is extremely small. This demands photomultipliers to magnify signals to a detectable level.

Scintillator materials show property called luminescence. When hit by radiation, an ionizing particle, they absorbed and re-emit energy in form of visible light.

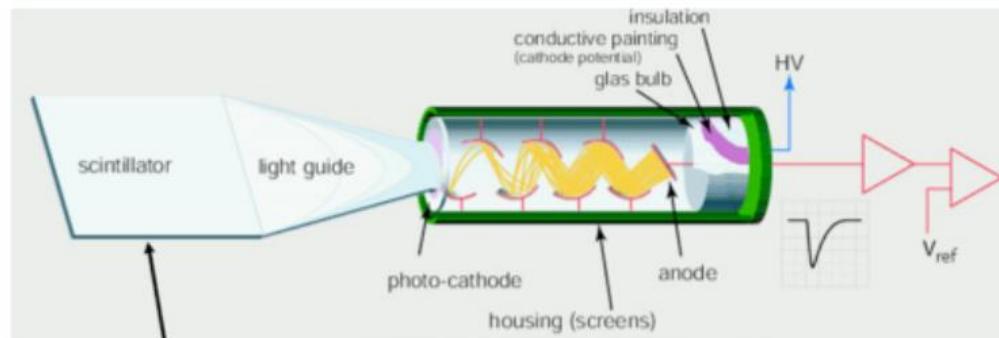
If re-emission is fast (10^{-6} sec) the phenomenon is called **fluorescence** and If re-emission is slower ($>10^{-6}$ sec) the phenomenon is called **Phosphorescence**

The ideal scintillation material should possess the following properties:

1. It should convert the kinetic energy of charged particles into detectable light with a high efficiency.
2. The conversion should be linear. That is, the light produced should be proportional to the input energy over a wide dynamic range.
3. The post luminescence (the light decay time) should be short to allow fast detection.
4. The index of refraction of the material should be near that of glass to allow efficient optical coupling of the light to the photomultiplier tube.

The most widely used scintillators include the inorganic alkali halide crystals (of which sodium iodine is the favorite), and organic-based liquids and plastics. The inorganics are more sensitive, but generally slow, while organics are faster, but yield less light.

One of the major limitations of the scintillation counters is their relatively poor energy resolution.



Cathode of photosensitive material. Light guided into PhotoMultiplier Tube (PMT) cathode and by photoelectric effect will produce electrons.

An electron multiplier system, made of dynodes, follows. Avalanche is created.

The final signal of electrons is collected on the anode.

SEMICONDUCTOR DETECTORS

semiconductor detector is a capacitor. If upon interaction with radiation, electrons are lifted from the valence band into the conduction band, the transport of the charge carriers in an applied electric field is observed.

In these materials, the basic information carriers are electron–hole pairs created along the path taken by the charged particle through the detector. The charged particle can be either primary radiation, or a secondary particle. When an external electric field is applied to the semiconductive material, the created carriers form a measurable electric current. The detectors operating on this principle are called solid-state or semiconductor diode detectors. The operating principle of these radiation detectors is the same as that of the semiconductor light detectors.

When a charged particle passes through a semiconductor with the band structure, the overall significant effect is the production of many electron– hole pairs along the track of the particle. The production process may be either direct or indirect, in that the particle produces high-energy electrons (or Δ rays) which subsequently lose their energy in production more electron–hole pairs. Regardless of the actual mechanism involved, what is of interest to our subject is the average energy expended by the primary charged particle produces one electron–hole pair. This quantity is often called the “ionization energy.” The major advantage of semiconductor detectors lies in the smallness of the ionization energy. The value of it for silicon or germanium is about 3 eV, compared with 30 eV required to create an ion pair in typical gas-filled detectors. Thus, the number of charge carriers is about ten times greater for the solid-state detectors for a given energy of a measured radiation.

To fabricate a solid-state detector, at least two contacts must be formed across a semiconductor material. For detection, the contacts are connected to the voltage source which enables carrier movement. The use of a homogeneous Ge or Si, however, would be totally impractical. The reason for that is in an excessively high leakage current caused by the material's relatively low resistivity (50 k Ω cm for silicon).

Thus, the detectors are fabricated with the blocking junctions, which are reverse biased to dramatically reduce leakage current.

Several configurations of silicon diodes are currently produced. Among them diffused junction diodes, surface barrier diodes, ion implanted detectors, epitaxial layer detectors, and others. The diffused junction and surface barrier detectors find widespread applications for detection of α particles and other short-range radiation.

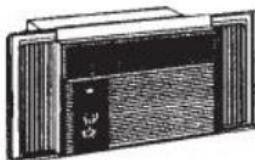
A good solid-state radiation detector should possess the following properties:

1. Excellent charge transport.
2. Linearity between the energy of the incident radiation and number of electron–hole pairs.
3. Absence of free charges (low leakage current).
4. Production of a maximum number of electron–hole pairs per unit of radiation.
5. High detection efficiency.
6. Fast response speed.
7. Large collection area.
8. Low cost.

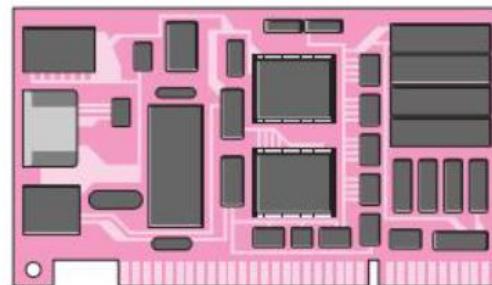
Application Areas of Heat Transfer



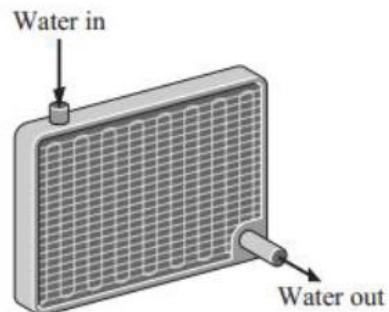
The human body



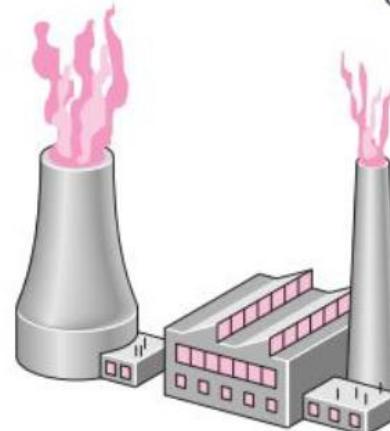
Air-conditioning systems



Circuit boards



Car radiators



Power plants



Refrigeration systems

Heat transfer equipment such as heat exchangers, boilers, condensers, radiators, heaters, furnaces, refrigerators, and solar collectors are designed primarily on the basis of heat transfer analysis.

Keeping in line with current practice, we will refer to the thermal energy as *heat* and the transfer of thermal energy as *heat transfer*. The amount of heat transferred during the process is denoted by Q . The amount of heat transferred per unit time is called **heat transfer rate**, and is denoted by \dot{Q} . The overdot stands for the time derivative, or “per unit time.” The heat transfer rate \dot{Q} has the unit J/s, which is equivalent to W.

The rate of heat transfer per unit area normal to the direction of heat transfer is called **heat flux**, and the average heat flux is expressed as (Fig. 1–11)

$$\dot{q} = \frac{\dot{Q}}{A} \quad (\text{W/m}^2) \quad (1-8)$$

where A is the heat transfer area. The unit of heat flux in English units is Btu/h · ft². Note that heat flux may vary with time as well as position on a surface.

Heat flux is heat transfer *per unit time* and *per unit area*, and is equal to $\dot{q} = \dot{Q}/A$ when \dot{Q} is uniform over the area A .

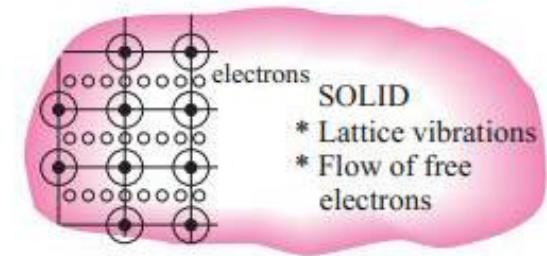
The transfer of energy as heat is always from the higher-temperature medium to the lower-temperature one, and heat transfer stops when the two mediums reach the same temperature.

There are three modes of heat transfer: conduction, convection and radiation.

Conduction is the transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interactions between the particles. Conduction can take place in solids.

In solids, it is due to the combination of vibrations of the molecules in a lattice and the energy transport by free electrons.

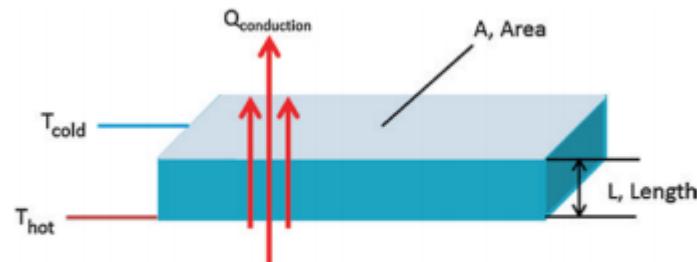
Conduction is the heat transfer through solids. It can also occur with stagnant fluids. The one-dimensional rate of conductive heat transfer is determined by Eq. below:



Consider steady heat conduction through a large plane wall of thickness $\Delta x = L$ and area A , as shown in Fig. 1–21. The temperature difference across the wall is $\Delta T = T_2 - T_1$. Experiments have shown that the rate of heat transfer \dot{Q} through the wall is *doubled* when the temperature difference ΔT across the wall or the area A normal to the direction of heat transfer is doubled, but is *halved* when the wall thickness L is doubled. Thus we conclude that *the rate of heat conduction through a plane layer is proportional to the temperature difference across the layer and the heat transfer area, but is inversely proportional to the thickness of the layer*. That is,

$$\text{Rate of heat conduction} \propto \frac{(\text{Area})(\text{Temperature difference})}{\text{Thickness}}$$

$$Q_{\text{conduction}} = \frac{kA(T_{\text{hot}} - T_{\text{cold}})}{L}$$



1.3 Heat transfer through an object by conduction

where $Q_{\text{conduction}}$ is heat flow, k is the thermal conductivity of the material, A is the cross-sectional area of heat flow, T_{hot} is the temperature of the hot surface, T_{cold} is the temperature of the cold surface and L is the length of the material through which heat is conducting.

The conduction resistance is defined by

$$R_{conduction} = \frac{L}{kA}$$

As shown in, in order to minimize the conduction resistance, conductivity of the material and cross-sectional area of material is maximized while the through-path (length) of the material is minimized.

Convection is the mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion, and it involves the combined effects of *conduction* and *fluid motion*. The faster the fluid motion, the greater the convection heat transfer. In the absence of any bulk fluid motion, heat transfer between a solid surface and the adjacent fluid is by pure conduction. The presence of bulk motion of the fluid enhances the heat transfer between the solid surface and the fluid, but it also complicates the determination of heat transfer rates.

Convection: Convection is the heat transfer from a surface to a fluid. Some common fluids include air and water. Other fluids such as alcohol and oil can also be mentioned in cooling electronics. The rate of convection heat transfer is determined by below

$$Q_{\text{convection}} = h_c A (T_{\text{ambient}} - T_{\text{surface}}) \quad (2.3)$$

where $Q_{\text{convection}}$ is heat flow, h_c is the convection heat transfer coefficient, A is the surface area, T_{ambient} is the ambient temperature of the fluid, and T_{surface} is the temperature of the surface of the material.

The convection resistance is described by $R_{\text{convection}} = \frac{1}{h_c A}$ (2.4)

Radiation is the energy emitted by matter in the form of electromagnetic waves (or photons) as a result of the changes in the electronic configurations of the atoms or molecules. Unlike conduction and convection, the transfer of energy by radiation does not require the presence of an intervening medium.

In fact, energy transfer by radiation is fastest (at the speed of light) and it suffers no attenuation in a vacuum. This is how the energy of the sun reaches the earth. In heat transfer studies we are interested in thermal radiation, which is the form of radiation emitted by bodies because of their temperature. It differs from other forms of electromagnetic radiation such as x-rays, gamma rays, microwaves, radio waves, and television waves that are not related to temperature.

All bodies at a temperature above absolute zero emit thermal radiation. Radiation is a volumetric phenomenon, and all solids, liquids, and gases emit, absorb, or transmit radiation to varying degrees.

However, radiation is usually considered to be a surface phenomenon for solids that are opaque to thermal radiation such as metals, wood, and rocks since the radiation emitted by the interior regions of such material can never reach the surface, and the radiation incident on such bodies is usually absorbed within a few microns from the surface.

The maximum rate of radiation that can be emitted from a surface at an absolute temperature T_s (in K or R) is given by the **Stefan–Boltzmann law** as

$$\dot{Q}_{\text{emit, max}} = \sigma A_s T_s^4 \quad (\text{W}) \quad (1-25)$$

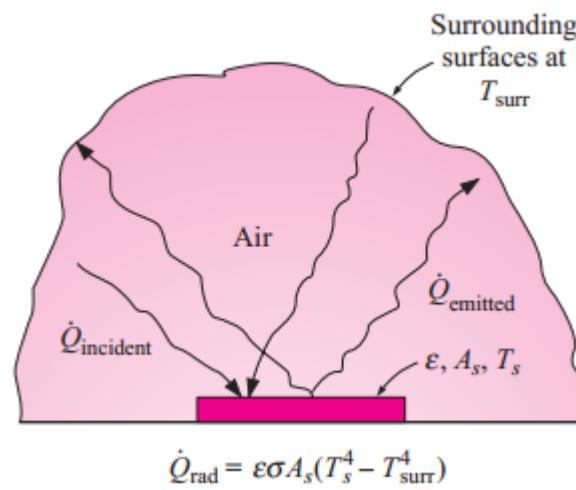
where $\sigma = 5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$ or $0.1714 \times 10^{-8} \text{ Btu/h} \cdot \text{ft}^2 \cdot \text{R}^4$ is the *Stefan–Boltzmann constant*. The idealized surface that emits radiation at this maximum rate is called a **blackbody**, and the radiation emitted by a blackbody is called **blackbody radiation** (Fig. 1–34). The radiation emitted by all real surfaces is less than the radiation emitted by a blackbody at the same temperature, and is expressed as

$$\dot{Q}_{\text{emit}} = \varepsilon \sigma A_s T_s^4 \quad (\text{W}) \quad (1-26)$$

where ε is the **emissivity** of the surface. The property emissivity, whose value is in the range $0 \leq \varepsilon \leq 1$, is a measure of how closely a surface approximates a blackbody for which $\varepsilon = 1$. The emissivities of some surfaces are given in Table 1–6.

When a surface of emissivity ε and surface area A_s at an *absolute temperature* T_s is *completely enclosed* by a much larger (or black) surface at absolute temperature T_{surr} separated by a gas (such as air) that does not intervene with radiation, the net rate of radiation heat transfer between these two surfaces is given by (Fig. 1-36)

$$\dot{Q}_{\text{rad}} = \varepsilon \sigma A_s (T_s^4 - T_{\text{surr}}^4) \quad (\text{W}) \quad (1-28)$$



What Is a Thermal Sensor?

- Temperature is the measure of the average kinetic energy of the molecules of a gas, liquid, or solid.

- A thermal sensor is a device that is specifically used to measure temperature.

The most popular sensor in terms of market surveys and sales is the temperature sensor.

This sensor is used in a wide range of applications critical to the medical, agricultural, industrial, and automotive communities, to name just a few.

Sensor Structure

A typical contact temperature sensor consists of the following components, 1. A sensing element—a device whose electrical properties vary in response to changes in temperature. A good sensing element should have low specific heat, small mass, strong and predictable sensitivity to temperature, and good long-term stability.

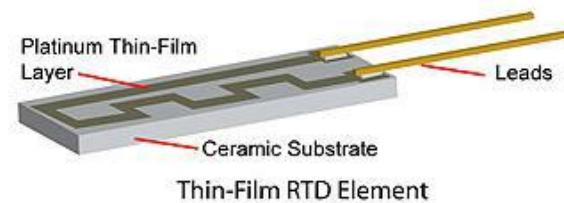
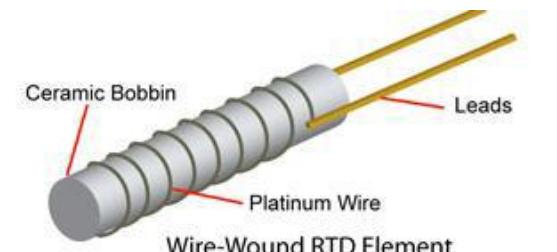
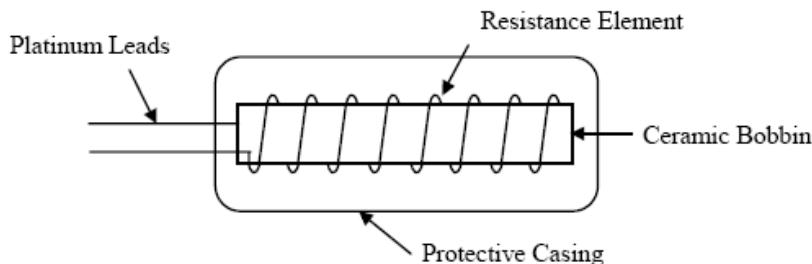
2. Terminals are the conductive pads or wires for interfacing between the sensing element and external electronic circuit. The terminals should have the lowest possible thermal conductivity and low electrical resistance (platinum is often the best compromise, yet expensive). Also, the terminals may be used for supporting the sensing element so they should have a reasonable mechanical strength and stability.

3. A protective envelope is either a housing or coating which physically separates the sensing element from the environment, yet couples thermally. The envelope should have a low thermal resistance (high thermal conductivity), low thermal capacity, high electrical isolation properties, and be mechanically strong. It must be environmentally stable and impermeable to moisture and other compounds that may spuriously affect the sensing element.

All such sensors can be divided into three groups: RTDs, semiconductors and thermistors. They belong to class of the absolute temperature sensors, that is, they can measure temperatures which are referenced to an absolute temperature scale.

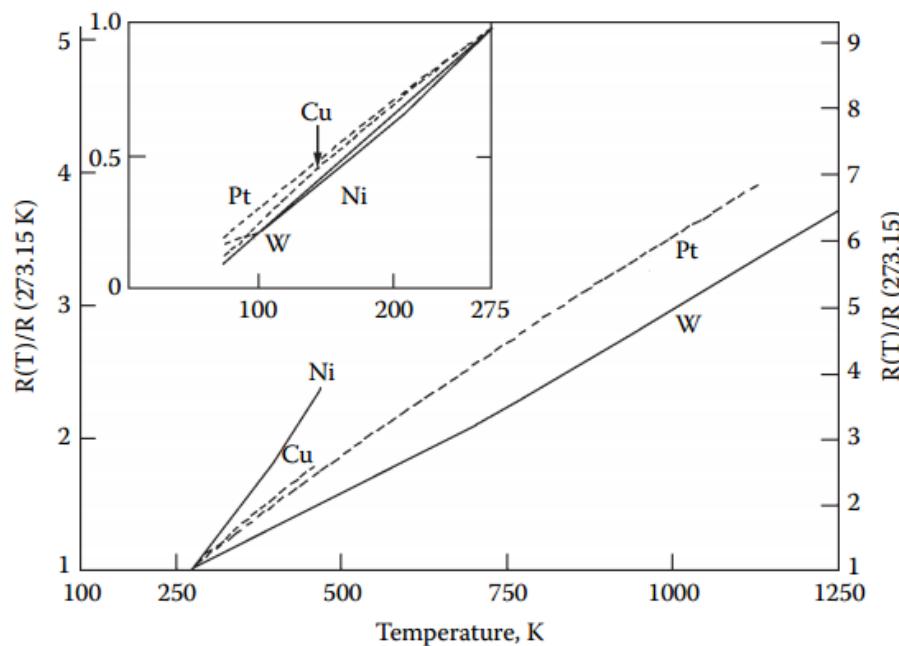
Resistance Thermometers

Resistance thermometers are also known as resistance temperature detectors, or RTDs. They are typically made of a single pure metal . Each metal has a material property of electrical resistance that is a function of temperature. The most accurate resistance thermometers are ones that use metals that have a very linear relationship with temperature, such as platinum. By using the relationship curves between electrical resistance and temperature, when the resistance of the metal is measured, a temperature can be calculated . Figure depicts the construction of one type of resistance thermometer



Type	Temperature Range (°K)	Resistance Ω	Medium
Platinum: Ceramic encased	250–350	100 (0°C)	Still air
Platinum (SPRT): Long stem	250–350	25.5 (0°C)	Still air
Thermistor: Glass enclosed	220–550	104 (25°C)	Still air
Thermistor: Glass enclosed	220–550	104 (25°C)	Still water
Germanium: Copper encased	10–30		Metal block
Germanium: Copper encased	<2		Metal block

Experimental measurements clearly show that the resistance thermometers that use metals display an increase in resistance as temperature increases.



Basically the metal consists of ion cores immersed in a sea of electrons. The number of free electrons in the metal does not vary with temperature and is a constant. The only parameters that can vary with temperature are the motion of the electrons and the vibrations of the ion cores. As temperature increases, the electron motion increases and the electrons collide with themselves and the vibrating ion cores. Since the electrons are much smaller than the ion cores, one can neglect electron-electron collisions. The major contribution is therefore due to the electrons colliding with the vibrating ion cores.

Electrical conductivity of a metal sample may be expressed as follows:

$$\sigma = ne\mu$$

where n = electron density, e = electronic charge, and μ = electron mobility.

The electron mobility is defined as follows:

$$\mu = \frac{e\tau}{m} \quad (5.3)$$

where τ = average time between collisions, and m = electron mass.

Noting that the resistivity, ρ , of a metal is the inverse of the conductivity, one obtains, using Equations 5.2 and 5.3, the following relation:

$$\rho = \frac{1}{\sigma} = \frac{m}{ne^2} \left(\frac{1}{\tau} \right) \quad (5.4)$$

The most common material used in metal thermometers is platinum. PRTs typically have a resistance range between .1 Ω and 1 KΩ.

Other, less popular metal resistance thermometers use copper (Cu), iridium (Ir), or combinations of rhodium and cobalt (Rh-Co) or platinum and cobalt (Pt-Co). The Cu thermometer is the most linear, but it has a limited temperature range (0 to 100°C). The Ir thermometer provides an excellent match to aluminum substrates and is normally used as a thin film in surface temperature measurements. Rh-Co and Pt-Co are used primarily for low-temperature (.5 to 30 K) applications.

Thermometers that use semiconductors as the sensing element differ from metal-based thermometers in that the resistance decreases with increasing temperature.

Also, in contrast to metals, the free electron density in semiconductors is not constant but increases with temperature

The conductivity is given by the following equation

$$\sigma = e(n\mu_n + p\mu_p)$$

where μ_n and μ_p are the mobilities of the electrons and holes, respectively.

$$\sigma = e^2 \left(\frac{n\tau_n}{m_n} + \frac{p\tau_p}{m_p} \right)$$

where τ_n and τ_p are the average time between collisions for electrons and holes, respectively. In an intrinsic semiconductor the number of electrons is equal to the number of holes, and hence

$$n = p = n_i \quad (5.10)$$

where n_i = intrinsic carrier density.

Thermometers that use semiconductors are thermally sensitive resistors, or what is commonly called thermistors.

The semiconductors used in thermistors are not the common semiconductors such as silicon or gallium arsenide.

Typically thermistors use metal oxides or combinations of metal oxides.

Examples of metal oxides that are used in thermistors are the oxides of tungsten manganese, nickel, cobalt, iron, copper, lithium, magnesium, and chromium. The most stable mixed metal oxides are Mn-Ni and Mn-Ni-Co.

Thermistors typically have resistance between $10\ \Omega$ and $100\ M\Omega$. Due to the large resistance range, thermistors provide excellent sensitivity and are also very stable, particularly between 100 and 300°C. Thermistors can also be manufactured very cheaply

For applications greater than 1,000°C thermistors made with zirconium oxide are the most popular. Zirconium is unique in its ability to withstand high temperatures.

Thermistor

The term thermistor is a contraction of the words **thermal** and **resistor**.

A thermistor belongs to class of the absolute temperature sensors, that is, it can measure temperature that is referenced to an absolute temperature scale.

The **Thermistor** is a special type of variable resistive element that changes its physical resistance when exposed to temperature changes.

Basically, it is a two-terminal solid state thermally sensitive transducer constructed using sensitive semiconductor-based metal oxides with metallized or sintered connecting leads formed into a ceramic disc or bead.

This allows the thermistor to vary its resistive value in proportion to small changes in the temperature. In other words, as its temperature changes, so does its resistance. Hence the name, “Thermistor”, a combination of the words thermally sensitive resistor.

All thermistors are divided into two groups:

NTC (negative temperature coefficient)

PTC (positive temperature coefficient)

NTC (negative temperature coefficient)

NTC or negative temperature coefficient thermistor is a device whose resistance decreases with an increase in temperature. These types of resistors usually exhibit a large, precise, and predictable decrease in resistance with an increase in temperature.

A conventional metal-oxide (ceramic) thermistor has a negative temperature coefficient, that is, its resistance decreases with increase in temperature. The NTC thermistor's resistance, as of any resistor, is determined by its physical dimensions and the material-specific resistivity. The relationship between the resistance and temperature is highly nonlinear.

A ceramic thermistor (thermo-resistor) is fabricated of a crystalline material that essentially is a semiconductor.

In case of NTC thermistor, cobalt, nickel, iron and copper oxides are preferred

High-quality NTC thermistors can be successfully fabricated from monocrystalline or polycrystalline germanium or silicon.

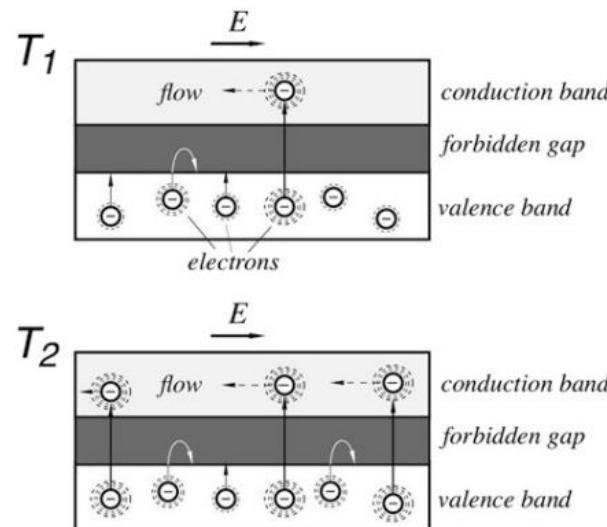
NTC (negative temperature coefficient) – working principle

In a semiconductive crystalline material, most of the electrons have lower energies in the valence energy band, with a smaller number being in the conduction band. The valence band electrons are mostly bound in the crystal, while the conduction electrons are free to move through the material, creating an electric current.

Thus, resistivity of the material depends on a number of electrons in the conduction band. When external electric field E is applied, electrons flow, making a current.

If the temperature of the material is low (T_1), the probability of an electron having a sufficient energy for jumping the gap of forbidden energies is low. A low number of charge carriers (negative and positive) defines a low conductivity (higher material resistance).

At a higher temperature T_2 , more electrons are “hotter” and thus the probability of them to cross the energy gap is higher. As a result, a larger number of electrons participate in the flow, resulting in a higher current and correspondingly— in lower resistance of the material.



Remembering that the electrical resistance of a material is reciprocal of its conductance, the thermally related probability of crossing the energy gap defines the material resistance, the normalized resistance of a Ge or Si thermistor can be expressed as:

$$r = \frac{R(T)}{R_0} = e^{\frac{E_a}{k_B} \left(\frac{1}{T} - \frac{1}{T_0} \right)} = e^{\beta \left(\frac{1}{T} - \frac{1}{T_0} \right)},$$

where β is the characteristic temperature of the semiconductor and R_0 is the nominal resistance at a selected temperature T_0 . The nominal resistance depends on the semiconductor type, its processing impurities, and the sensor geometry.

PTC Thermistors

PTC thermistors increase their resistance as the temperature rises.

All metals possess positive temperature coefficients (PTC). Their temperature coefficients of resistivity (TCR) are quite low.

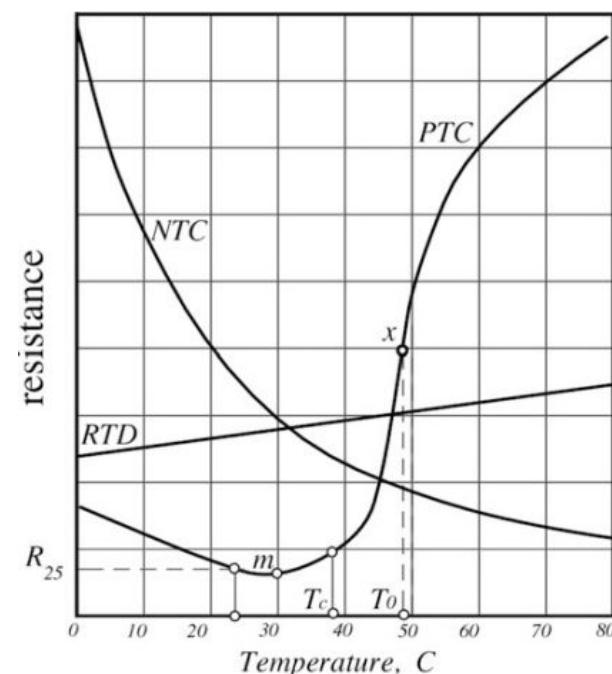
Thus many of them are not very useful for temperature sensing that requires high sensitivity. RTDs have small positive temperature coefficients.

Ceramic PTR thermistors

A PTC thermistor is fabricated of polycrystalline ceramic substances, where the base compounds, usually barium titanate or solid solutions of barium and strontium titanate (highly resistive materials), are made semiconductive by the addition of dopants.

Above the Curie temperature of a composite material, the ferroelectric properties change rapidly resulting in a rise in resistance, often several orders of magnitude.

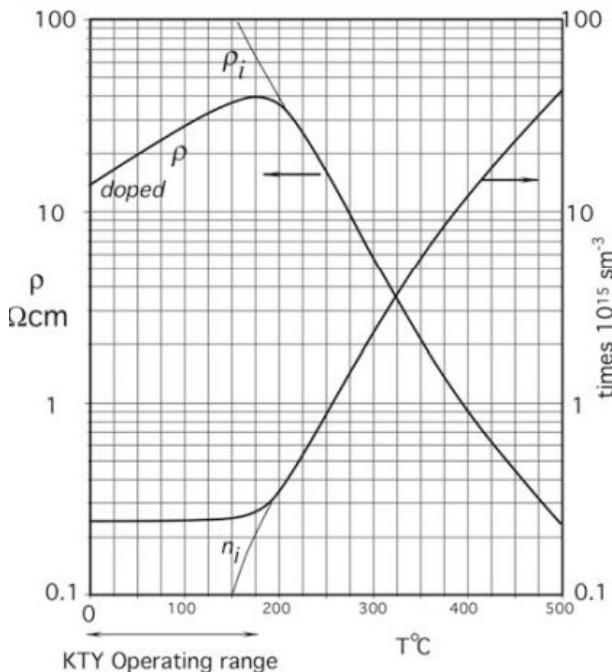
This Thermistor has a non-linear characteristic curve. As the switching type PTC Thermistor gets heated, initially the resistance starts to decrease, up to a certain critical temperature, after which as the heat is increased, the resistance increases dramatically.



Silicon PTC thermistors

Conductive properties of bulk silicon have been successfully implemented for the fabrication of temperature sensors with the positive temperature coefficient (PTC).

Pure silicon, either polysilicon or single-crystal silicon, intrinsically has a negative temperature coefficient of resistance. However, when it's doped with an n-type impurity, in a certain temperature range, its temperature coefficient becomes positive. This is the result of reducing charge carrier mobility at lower temperatures. At higher temperatures, the number n of free charge carriers increases due to the number n_i of spontaneously generated charge carriers, and the intrinsic semiconductor properties of silicon predominate. Thus, at temperatures below 200 C resistivity ρ has a positive temperature coefficient while over 200 C it becomes negative.



The relationship between resistance and temperature is linear, as expressed in the following equation: $\Delta R = k(\Delta T)$ where ΔR is the change in resistance, ΔT is the change in temperature and k is the temperature coefficient. When k is positive, it causes a linear increase in resistance as the temperature rises.

The Si PTC sensors have reasonably good linearity, and a high long-term stability (typically 0.05 K per year).

Thermistors:

Advantages

- 1) Small size and low cost.
- 2) Fast temperature response.
- 3) High sensitivity.
- 4) Suitable for precise temperature measurement and control.
- 5) Need simple electric circuitry.
- 6) No need for a reference junction.

Disadvantages

- 1) Response is non-linear.
- 2) Not suitable for measurement of high temperature.
- 3) Required external power source and bridge circuit.
- 4) Temperature span is limited.

Thermistor Applications:

- PTC thermistors were used as timers in the degaussing coil circuit of most CRT displays. A degaussing circuit using a PTC thermistor is simple, reliable (for its simplicity), and inexpensive.
- We can also use PTC thermistors as heater in automotive industry to provide additional heat inside cabin with a diesel engine or to heat diesel in cold climatic conditions before engine injection.
- We can use PTC thermistors as current-limiting devices for circuit protection, as replacements for fuses.
- We can also use NTC thermistors to monitor the temperature of an incubator.
- Thermistors are also commonly used in modern digital thermostats and to monitor the temperature of battery packs while charging. We regularly use NTC thermistors in automotive applications.
- NTC thermistors are used in the Food Handling and Processing industry, especially for food storage systems and food preparation. Maintaining the correct temperature is critical to prevent food-borne illness.
- NTC thermistors are used throughout the Consumer Appliance industry for measuring temperature. Toasters, coffee makers, refrigerators, freezers, hair dryers, etc. all rely on thermistors for proper temperature control.

Thermoelectric Sensors - thermocouple

A thermoelectric contact sensor is called a thermocouple because at least two dissimilar conductors (a couple) are joined to form a junction.

A thermocouple is a passive sensor, meaning it generates a voltage in response to temperature and does not require any external excitation power.

In other words, a thermocouple is a direct converter of thermal energy into electrical energy and because it's a voltage generating sensor, sometimes a thermocouple is called a "thermal battery."

The thermoelectric sensors belong to the class of relative sensors, because the voltage produced depends on a temperature difference between two thermocouple junctions, in large part regardless of the absolute temperature of each junction.

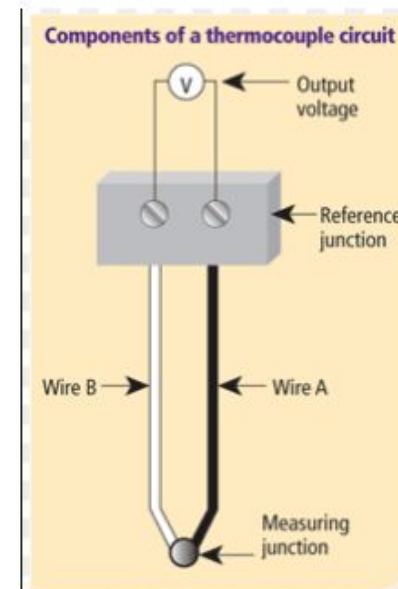
To measure temperature with a thermocouple, one junction will serve as a reference and its absolute temperature must be measured by a separate absolute sensor, such a thermistor or RTD, or be thermally coupled to a material that is in a state of a known reference temperature

The metals that are used to make thermocouples are:

Copper (Cu), Constantan (55 % Cu + 45%Ni), Iron (Fe), Chromel (90 % Ni + 10 % Cr), Alumel® (95 % Ni + 2 % Mn, 2 % Al), Nicrosil® (84.6 % Ni + 14.2 % Cr + 1.4 Si), Nisil® (95.5 % Ni + 4.4 % Si + 1 % Mg), Platinum (Pt), and Rhodium (Rh).

Thermocouples

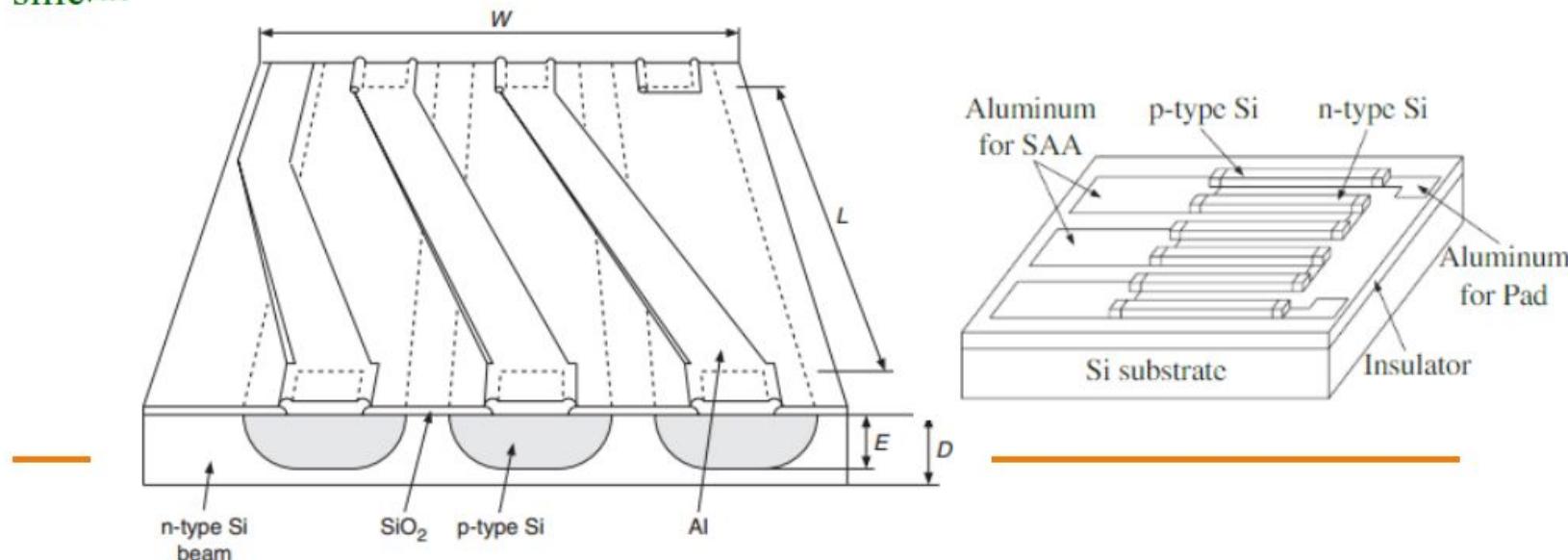
Thermocouples are sensors composed of two different metals at their sensing end. A voltage is created when there is a temperature gradient between the hot sensor element and the cold reference junction. The change in voltage can be reported as a temperature through the Seebeck effect . **The Seebeck effect says that the change in voltage is linearly proportional to the change in temperature and the two variables are related to each other through a coefficient that is determined by the materials used in the thermocouple .** Figure depicts the construction of a thermocouple.



Thermocouples are two-lead elements that measure the temperature difference between the ends of the wires. The operating principle is based on the thermoelectric Seebeck effect, which says that a temperature difference ΔT in a (semi)conductor also creates an electrical voltage ΔV :

$$\Delta V = \alpha_s \Delta T \quad (6.29)$$

where α_s is the Seebeck coefficient expressed in V/K. The Seebeck coefficient α_s is a material constant. By taking two wires of materials with different α_s , we get different electrical voltages across the wires, even when the wires experience the same temperature gradients. With a junction of the wires at the hot point, the voltages are subtracted, and an effective Seebeck coefficient will remain. Thermocouples or thermopiles (several thermocouples in series) in thermal sensors are made of thin-film metals or polysilicon, or monocrystalline silicon



Seebeck coefficients for metals are much smaller than those for silicon and that the influence of aluminum interconnections on chips is negligible compared to the Seebeck coefficient for silicon. The electrical resistance and also the thermal conductivity play a part in determining how efficiently a thermopile functions in a thermal sensor. These parameters are much more favorable for bismuth telluride compounds or silicon–germanium compounds than for mono- or polysilicon [8]. However, the advantage of these compounds largely lies in their low thermal conductivity, compared with that of silicon, and in many microsensors the thermal resistance of the sensors is determined more by conduction through air or membranes than through the thermopile. In these, a silicon thermopile will lead to almost the same performance as thermopiles made of other compounds but has the big advantage that it can be produced in standard IC technology.

Table 6.3 Seebeck coefficients ($\mu\text{V/K}$) of some selected materials and standard thermocouples

Material	273 K ($\mu\text{V/K}$)	300 K ($\mu\text{V/K}$)
Antimony (Sb)		43 ^a
Chromium (Cr)	18.8	17
Gold (Au)	1.79	1.94
Copper (Cu)	1.70	1.83
Silver (Ag)	1.38	1.51
Rhodium (Rh)	0.48	0.40
Lead (Pb)	-0.995	-1.047
Aluminum (Al)		-1.7
Platinum (Pt)	-4.45	-5.28
Nickel (Ni)	-18.0	
Bismuth (Bi)		-79 ^a
J-type thermocouple Fe–CuNi	50	51
T-type thermocouple Cu–CuNi	39	41
E-type thermocouple NiCr–CuNi	59	
K-type thermocouple NiCr–NiAl	39	41
S-type thermocouple Pt–Pt/10%Rh	5	7
T-type thermocouple Pt–Pt/13%Rh	5	6
Monocrystalline silicon (typical)	500	500
Polycrystalline silicon (typical)	150	150

^aAveraged over 0 °C to 100 °C.

we summarize the most important recommendations for the use of these standard thermocouples.

Type T: Copper (+) versus Constantan (-) is resistant to corrosion in moist atmosphere and suitable for subzero temperature measurements. Its use in air oxidizing environment is restricted to 370 C (700 F) due to the oxidation of the copper thermoelement.

Type J: Iron (+) versus Constantan (-) is suitable in vacuum and in oxidizing, reducing, or inert atmospheres, over the temperature range of 0–760 C (32– 1400 F). The rate of oxidation in the iron thermoelement is rapid above 540 C (1000 F), and the use of heavy-gage wires is recommended when long life is required at the higher temperatures. This thermocouple is not recommended for use below the ice point because rusting and embrittlement of the iron thermoelement make its use less desirable than Type T.

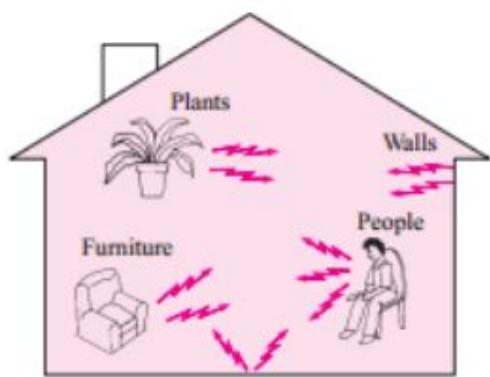
Type E: Chromel® (+) versus Constantan (-) is recommended for use over the temperature range of 200 to 900 C (330 to 1600 F) in oxidizing or inert atmospheres. These thermocouples are suitable to subzero measurements since they are not subject to corrosion in atmospheres with high moisture content. Type E develops the highest e.m.f. per degree of all the commonly used types and is often used primarily because of this feature.

Type K: Chromel® (+) versus Alumel® () is recommended for use in an oxidizing or completely inert atmosphere over a temperature range of 200 to 1260 C (330 to 2300 F). Due to the resistance to oxidation, type K is often used at temperatures above 540 C. However, it should not be used in reducing atmospheres, in sulfurous atmospheres, and in a vacuum

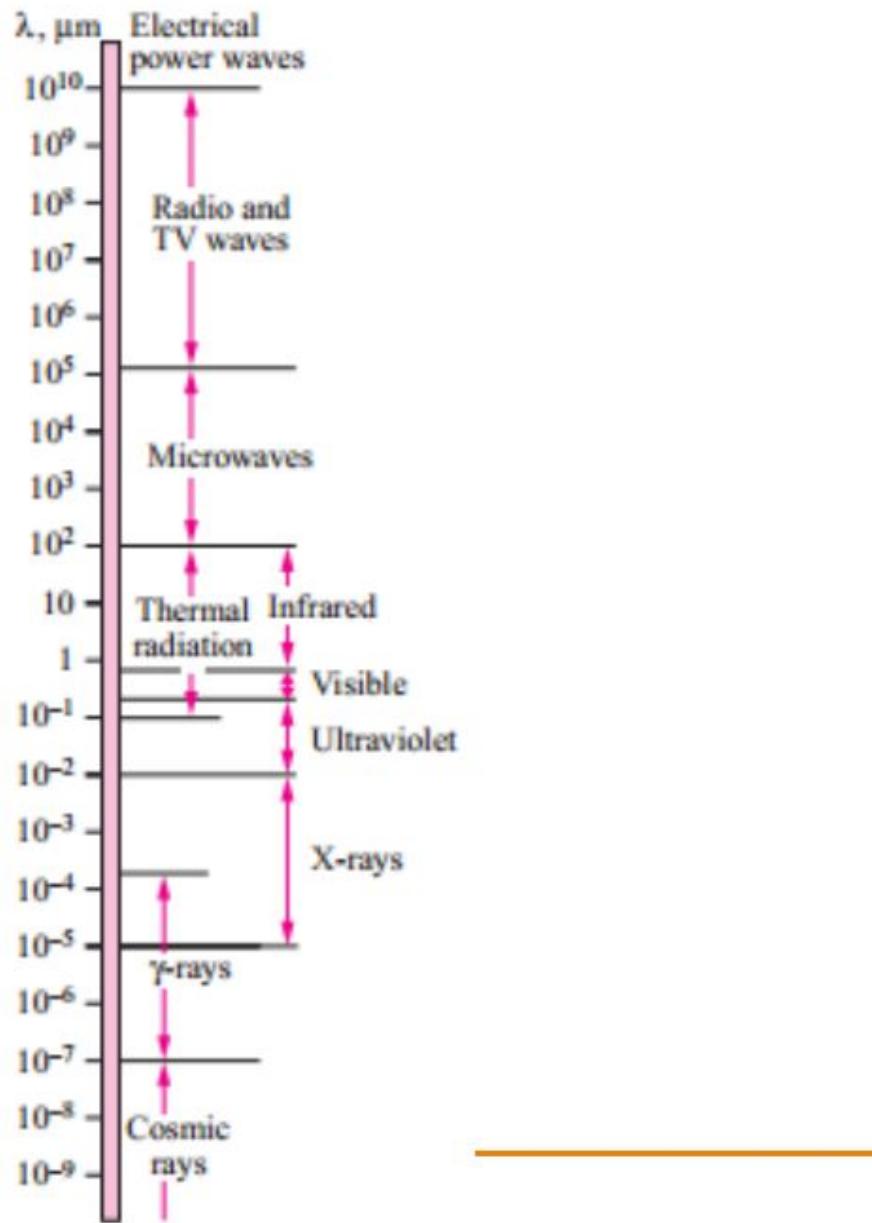
Types R and S: Pt/Rh (+) versus Pt () is recommended for continuous use in oxidizing or inert atmospheres over a temperature range of 0–1480 C (32–2700 F).

Type B: 30 % Pt/Rh (+) versus 6%Pt/Rh () is recommended for continuous use in oxidizing or inert atmospheres over the range of 870–1700 C (1000–3100 F). It is also suitable for short term use in a vacuum, but should not be used in reducing atmospheres, nor those containing metallic or nonmetallic vapors. It should never be directly inserted into a metallic primary protecting tube or well.

The electromagnetic wave spectrum



Everything around us constantly emits thermal radiation



Thermal radiation is also defined as the portion of the electro-magnetic spectrum that extends from about 0.1 to 100 μm , since the radiation emitted by bodies due to their temperature falls almost entirely into this wave-length range. Thus, **thermal radiation includes the entire visible and infrared (IR) radiation as well as a portion of the ultraviolet (UV) radiation**

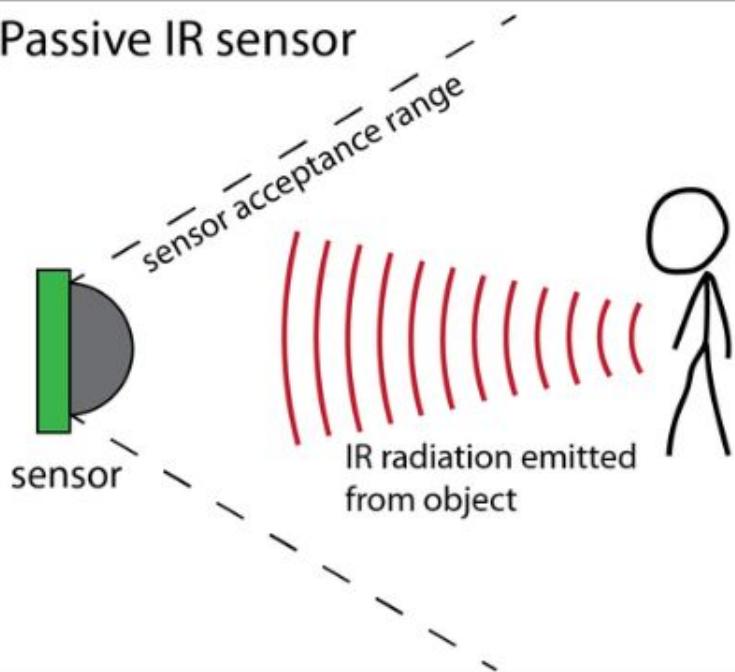
What we call light is simply the visible portion of the electromagnetic spec-trum that lies between 0.40 and 0.76 μm . Light is characteristically no different than other electromagnetic radiation, except that it happens to trigger the sensation of seeing in the human eye.
Light, or the visible spectrum, consists of narrow bands of color from violet (0.40–0.44 μm) to red (0.63–0.76 μm)

Radiation Thermometers

All substances and objects emit thermal radiation when it is at a temperature higher than absolute zero (0 K or -273.15°C). There is a **relationship between temperature and radiation energy emitted that can be used to calculate the temperature of the object surface**. Unlike other sensors discussed above, radiation thermometers are primarily used at a distance from the object of interest and can be used for hard-to-reach objects. An **example of a radiation thermometer is an infrared camera**, which measures infrared wavelengths that emit from an object.



Passive IR sensor



Active IR sensor

Legend:
■ IR receiver
□ IR LED



no object, no reflected
IR radiation



object present, IR
radiation gets reflected

Active infrared sensor

The transmitter of the **active infrared sensor** emits a modulated infrared beam, which is received by the infrared receiver, thereby forming a warning line composed of infrared beams. When it is blocked by leaves, rain, small animals, snow, sand, and fog, the alarm should not be reported, and the alarm will be issued when people or objects of considerable size are blocked.

Active infrared detector technology mainly adopts one transmitter and one receiver, which belongs to linear prevention. Now it has developed from the original single beam to multi beams, and it can also double transmitter and receiver to minimize the false alarm rate, thereby enhancing the stability and reliability of the product.

Passive infrared sensor

Passive infrared sensors work by detecting infrared rays emitted by the human body. The sensor collects the infrared radiation from the outside world and concentrates it on the infrared sensor. Infrared sensors usually use pyroelectric elements, which will release charges when receiving infrared radiation temperature changes, and generate an alarm after detection and processing.

This sensor is aimed at detecting human radiation. Therefore, the radiation-sensitive element must be very sensitive to infrared radiation with a wavelength of around 10 μm . In order to be sensitive to the infrared radiation of the human body, its radiation surface is usually covered with a special filter, so that the interference of the environment is obviously controlled.

Infrared Sensor

From the transduction point of view, the infrared sensor is fairly simple. The transduction from radiation to heat is carried out by a black absorber, which can have an efficiency up to 99 %. The first transduction step from incident radiation density P''_{inc} (in W/m^2) to thermal power P is

$$P = Q P_{\text{inc}}$$

$$Q = \alpha A_D \tau_{\text{filter}}$$

where A_D is the sensitive area of the sensor (usually the area that is coated black), α is the absorptivity of the black coating of the sensitive area, and τ_{filter} is the transmittance of an infrared filter, which can be applied to select specific radiation wavelengths or simply for mechanical protection. The absorptivity α is between 0 and 1 and denotes the fraction of infrared radiation power which is absorbed by the black coating. Various types of black coatings are used for silicon infrared sensors.

Infrared sensors have many applications. Burglary alarms use infrared sensors of the pyroelectric type, which respond to changes in the infrared image. This is particularly useful in security applications, where an image without any movements is the proper one and a sudden movement indicates an intruder. For gas analysis, such as CO and CO₂, infrared sensors

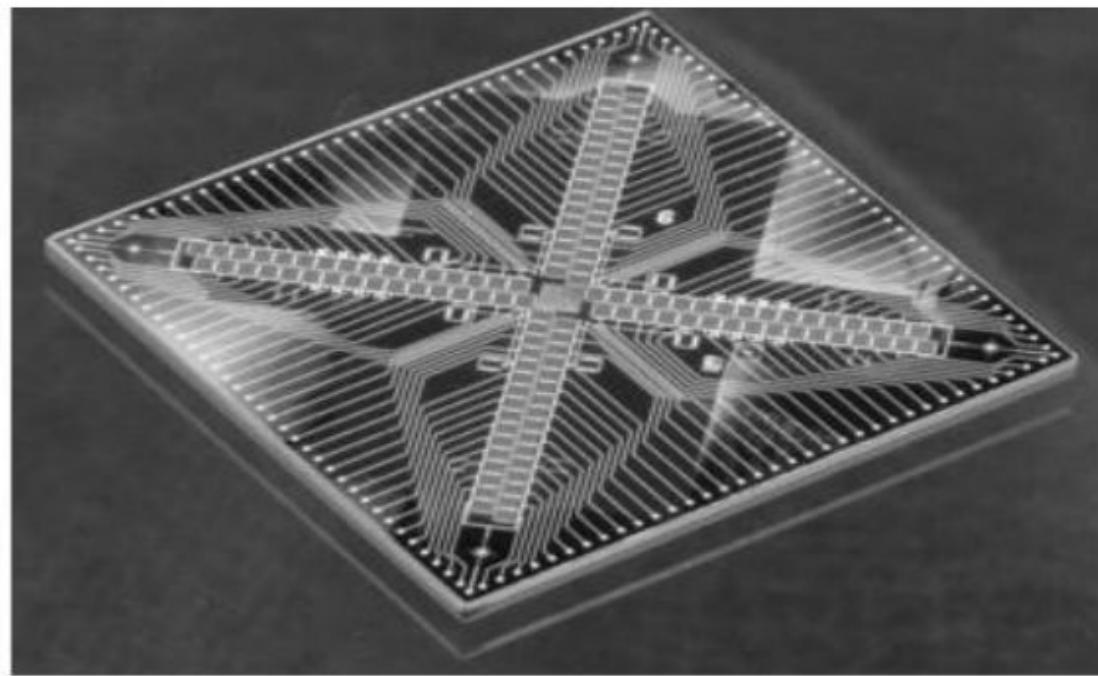


Figure 6.11 Focal plane array of 4×32 infrared detectors for satellite attitude control instrument, chip size $20.5 \text{ mm} \times 20.5 \text{ mm}$ (Xensor Integration)

based on thermopiles and thin membranes are used. Other applications include temperature measurement, where, for instance, the toasting of bread can be monitored using an infrared sensor. For space applications, EADS Sodern developed a focal plane array (FPA) of infrared detectors for a so-called Earth sensor, where the image of the Earth is projected onto the FPA chip using a germanium lens. The Earth sensor uses the image in the (14 to 16) μm band, emitted by the CO₂ of the atmosphere. This image of Earth is nicely round and is dependent neither on day or night nor on the seasons. In this way, the attitude of the satellite with respect to the Earth can be measured, and if necessary, corrected; as a result, for instance, a weather satellite will monitor the weather in the required region, instead of that of the North Pole or space. The FPA chip contains 132 infrared pixels (each with its own thermopile and black area) and measures $20.5 \text{ mm} \times 20.5 \text{ mm}$ (Figure 6.11) [17].

Interaction of gaseous species at semiconductor Surfaces-Catalysis

4.3.4.1 Adsorption/Desorption Mechanism

During the gas molecule–solid-state surface interaction, the gas species initially gets physisorbed and chemisorbed at the semiconductor surface. There is no charge transfer in case of physisorption. A molecule is considered to be chemisorbed when there is an electronic transfer between the gas and the solid, and the conductivity of the material gets affected.

As an illustrative example, the different oxygen species formed as the oxygen molecules interact with a solid-state surface are shown in Figure 4.12 (Kohl 1989, Liu et al. 2007). Oxygen can be adsorbed in the form of O_2^- , O^- , or O^{2-} . Due to energy considerations, near room temperature, the O^{2-} specie dominates the surface coverage, whereas at higher temperatures, O^- is the dominating specie. The adsorption of these species on the surface extracts electrons from the donor levels of the material. The extraction of electrons creates an electron-depleted or positive space charge region near the surface (Figure 4.12). This results in an increase in the resistance of an n-type material.

The adsorbed oxygen ions are present in large concentrations at any semiconductor surface. The gas-sensing mechanism depends on the decrease or increase in the concentration of the adsorbed oxygen ion at the semiconductor surface. It is clear that on interaction with a reducing gas, the number of adsorbed oxygen species will be reduced and a number of electrons will be released back to the semiconductor surface (conduction band of the semiconductor). The O_2^- and O^- species preferentially interact with the C–C bond of the incoming reducing gas. Increase in the concentration of electrons in the conduction band results in an increase in the conductivity of the n-type semiconductor. The large increase in the conductivity of the oxide semiconductor in the presence of a reducing gas is because of a decrease in the adsorbed oxygen species at the oxide surface. It is clear that the effect of an oxidizing gas will be reverse (increase in absorbed oxygen sites and decrease in the conductivity of the semiconductor).

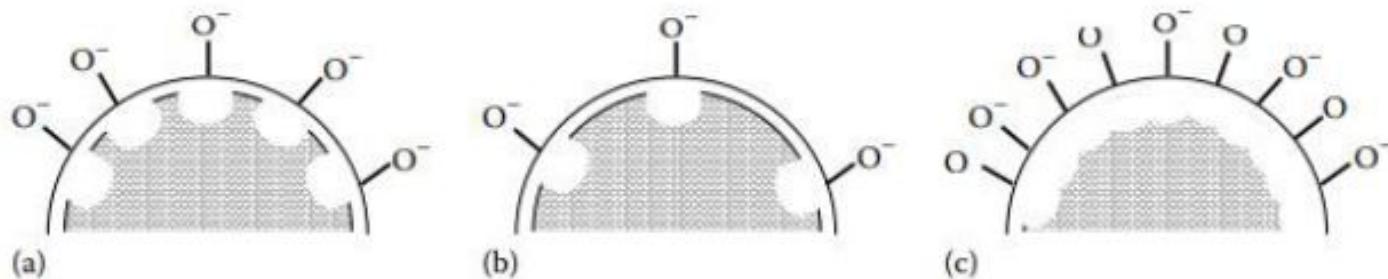
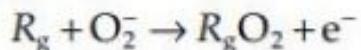
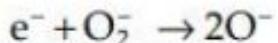
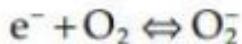


FIGURE 4.13

Effect of (a) air, (b) reducing gas, and (c) oxidizing gas on an n-type semiconductor material. Depletion region is shown as white region, and shadowed region shows the conducting regions of the oxide nanoparticles.

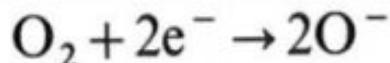
The reaction steps (Kohl 1989) are given below:



Here R_g represents the reducing gas.

If a p-type semiconductor is used in place of an n-type semiconductor, the reducing gas will decrease the adsorbed oxygen sites, take away electrons from the semiconductor surface, and create more holes in the semiconductor. This is also illustrated in Figure 4.13. The conductivity of the p-type semiconductor due to increase in the concentration of holes will thus increase.

- Typical operation principle “one explanation”
 - Resistive sensor, resistance decrease when a layer of powdered SnO_2 is exposed to combustible gas in present of ambient air.
 - Oxygen in air adsorbs at semiconductor surface, oxygen dissociates to form O^- . The electron is picked up from the semiconductor, which increases its resistance.



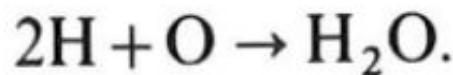
- O^- is highly reactive and easily react with combustible gases which contain hydrogen.



- Hydrogen react and form water, as a result an electron is released which lowers the resistance in the semiconductor.
- To increase the reaction rate a catalyst is often included.

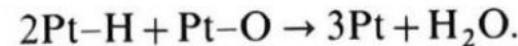
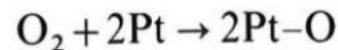
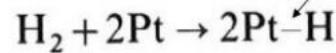
Catalysis, the acceleration of chemical reactions

- Catalyst is needed to increase the sensitivity and accelerate the reaction in metal-oxide gas sensor
 - A catalyst is not consumed and lower the activation energy for the reactions
 - Without the catalyst, the reaction have a high activation energy:



chemical reactions

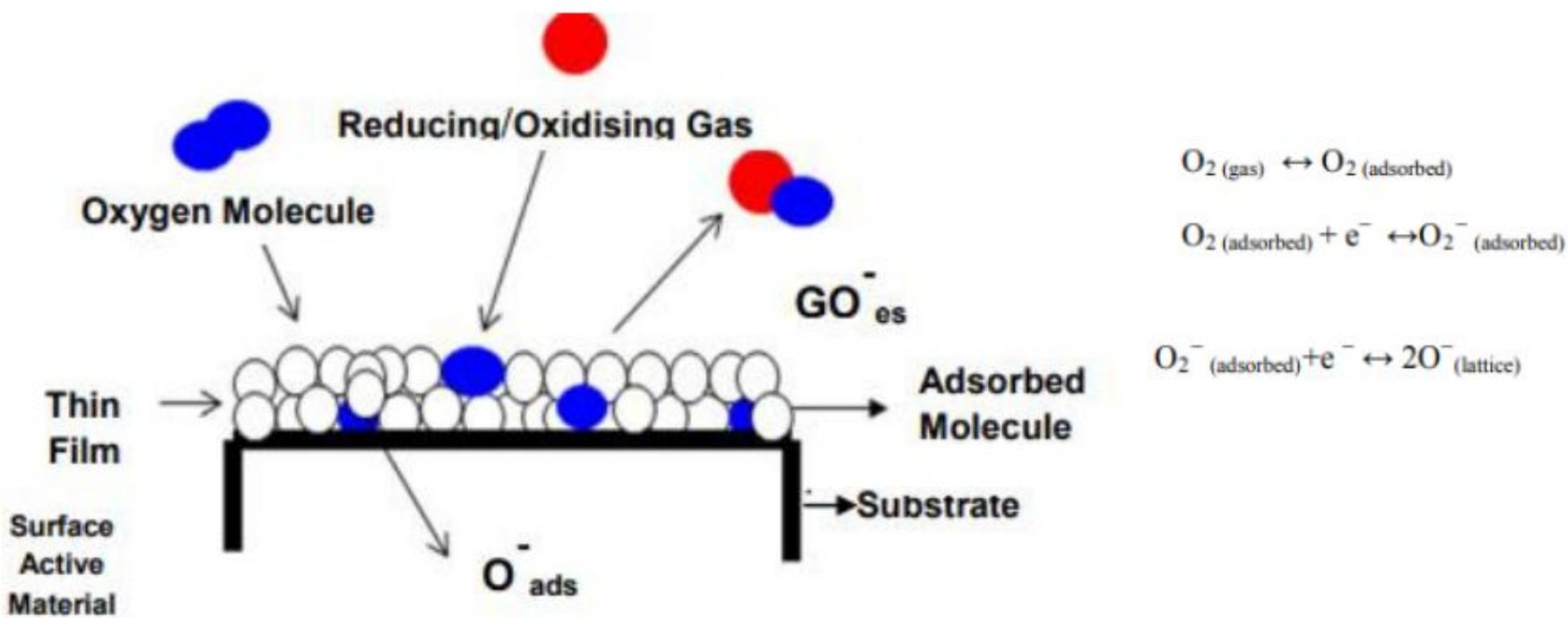
With Platinum as a catalyst



Hydrogen is adsorbed on a platinum surface ("group of")

The activation energy is drastic reduced

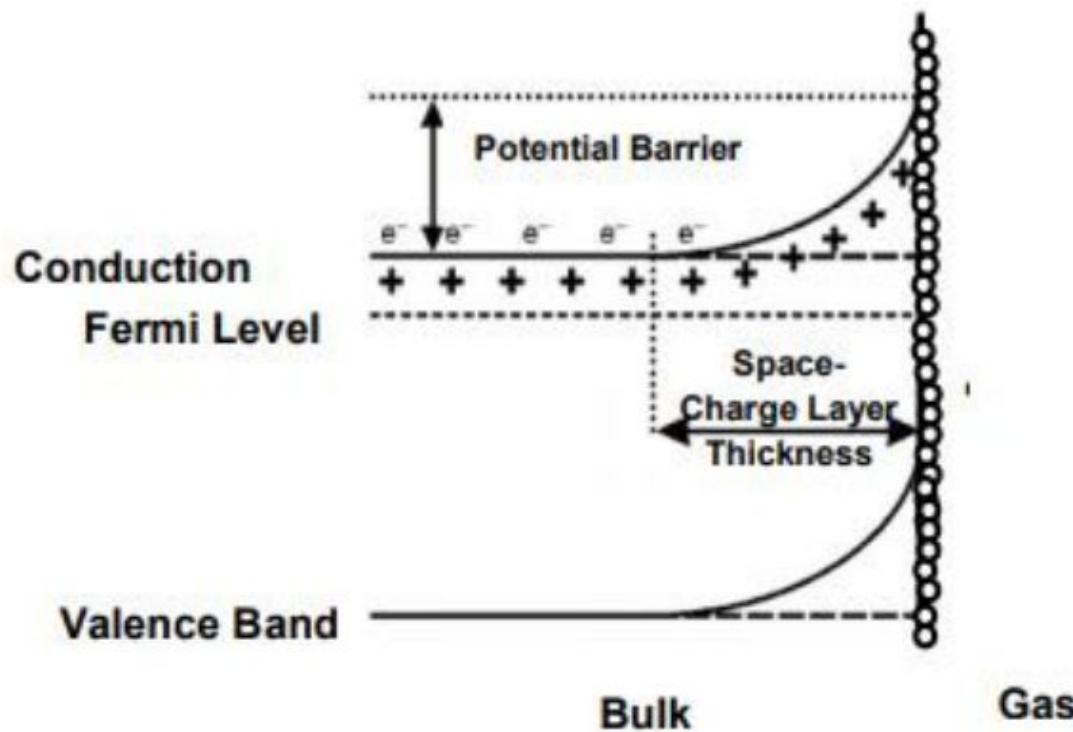
At elevated temperatures, reactive oxygen species such as O_2^- , O^{2-} and O^- are adsorbed on the surface of metal oxide semiconductor.



Schematic representation of metal oxide semiconductor as gas sensors

The sensing element of chemiresistive type sensors normally comprises of a semiconducting material with high surface-to-volume ratio on a ceramic (glass) substrate with ohmic contacts to measure the change in resistance/conductance. When, gas/volatile organic compounds (VOC) samples interact on the surface of metal oxide semiconductor, due to the combustion reaction that occurs with the oxygen species on the surface of metal oxide particles leads to change in resistance and forms the basic principle of detection.

As shown in Fig. when O₂ molecules are adsorbed on the surface of metal oxides, they would extract electrons from the conduction band E_c. This will lead to band bending and an electron depleted region (space charge region). The thickness of this space charge region is equivalent to the length of band bending region



Schematic representation of band bending after chemisorption of charged species

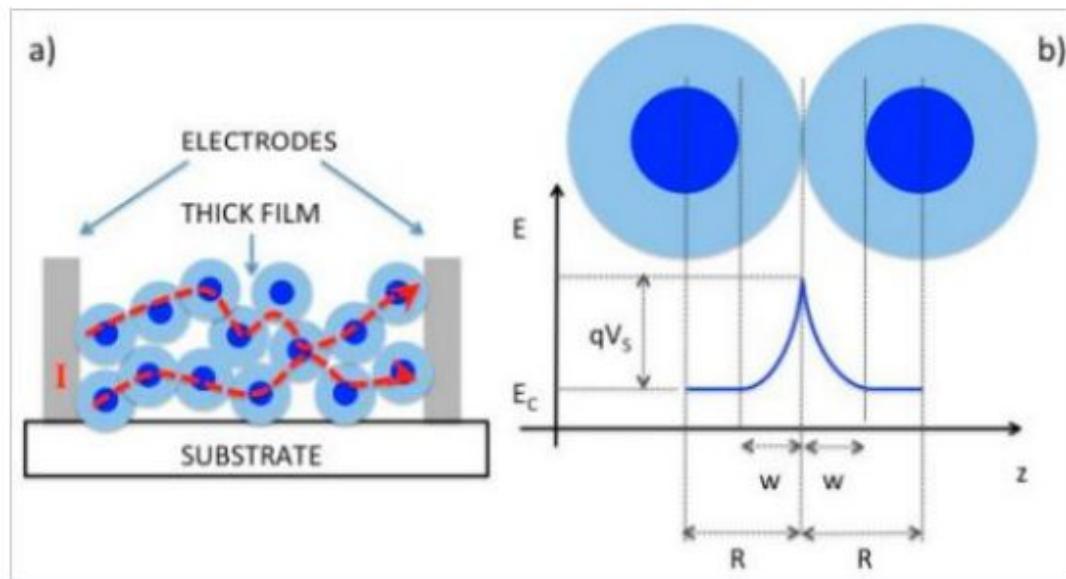
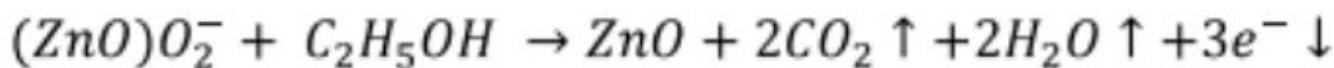
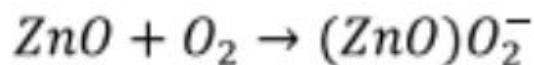
Table 1: Classification according to the changes in the response of sensing element

Classification	Oxidising Gases	Reducing Gases
n-type	Resistance increase	Resistance decrease
p-type	Resistance decrease	Resistance increase

Table 2: Classification of metal oxides based on the conductivity type

Type of Conductivity	Metal oxides
n – type	ZnO, MgO, CaO, TiO ₂ , WO ₃ , SnO ₂ , In ₂ O ₃ , Al ₂ O ₃ , Ga ₂ O ₃ , V ₂ O ₅ , Nb ₂ O ₅ , ZrO ₂
p – type	Y ₂ O ₃ , La ₂ O ₃ , CeO ₂ , Mn ₂ O ₃ , NiO, PdO, Ag ₂ O, Bi ₂ O ₃ , Sb ₂ O ₃ , TeO ₂

When the reducing gas like ethanol interacts with n-type semiconductor, then the surface conductivity increases based on the following reaction:



$$\frac{R_{\text{Gas}}}{R_{\text{Air}}} = \exp \frac{eV_{\text{Air}} - eV_{\text{Gas}}}{k_B T}$$