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Sec5.5-End of Sec5

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Contents

5.5.1 Classification

Detectors of electromagnetic radiation are generally grouped into three broad groups.

1. **Photon detector**: photons interact with the detector material and release one or more charge carriers such as electrons.

2. **Thermal detector**: the photon energy goes into heat within the material, that finally changes to a measurable property such as device's electric conductivity.

3. **Coherent detector**: the electric field of the wave is sensed directly and phase information can be preserved. The most common form of coherent detection takes advantage of wave interference with a locally produced field, either before or after conversion of the electromagnetic radiation to an electrical signal.

5.5.1 Classification

To distinguish between photon and thermal detectors, consider the following.

Thermal detector … Its response is independent of wavelength of the photons because it depends only on the total power (P) it absorbed.

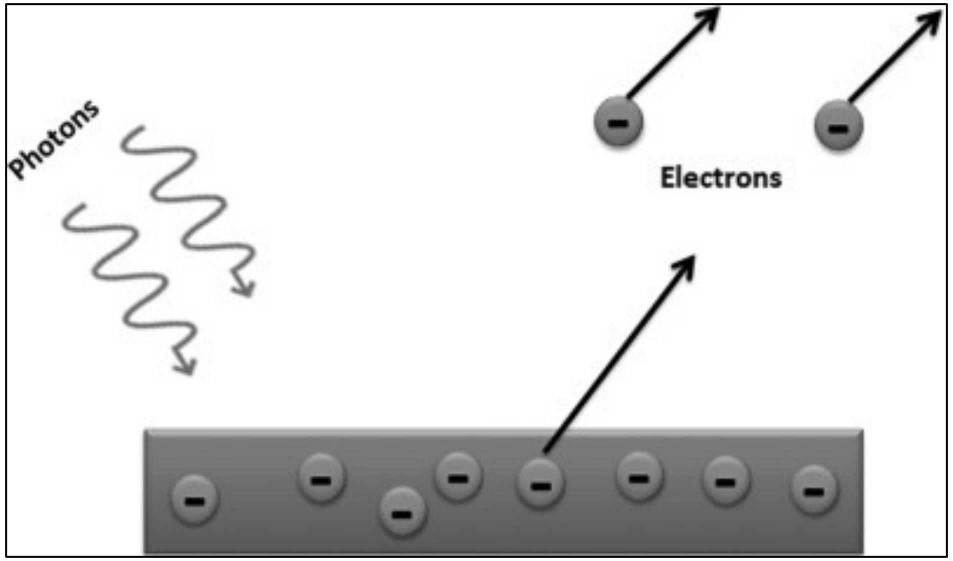
Photon detector … It measures the rate of arrival of photons ($N=P/h\nu$) and the number per second per watt of incident power ($N/P = \lambda/hc$) is proportional to λ, which means its response is also proportional to λ.

5.5.1 Classification

Photon detectors can be subdivided into two types.

(1) Photoemission devices

- This type of device employs the external photoelectric effect in which the photon causes a charge carrier (electron) to be ejected from the material.



https://www.sciencedirect.com/topics/earth-and-planetary-sciences/photoelectric-effect

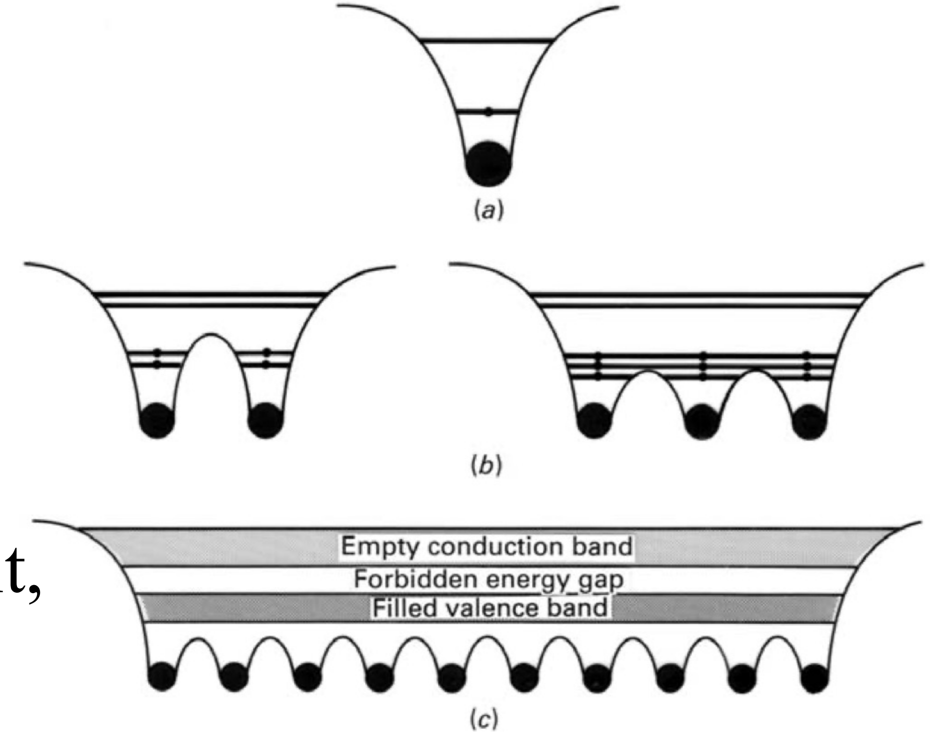
5.5.1 Classification

(2) Photoabsorption devices

- This type of devices use the internal photoelectric effect in a semiconductor to free a charge carrier within the material.
- There are essentially two basic types of interactions: the photoconduction effect and the photodiode effect.
- The photoconductor is composed of a single uniform semiconductor material and there is usually always an external applied electric field.
- The photodiode is composed of multiple different semiconductors which create internal electric fields.

5.5.2 Semiconductors

- When individual atoms come close together, electrons in the outermost orbits of adjacent atoms interact to bind the atoms together.
- These outer or “valence” electrons are shared between the different atomic nuclei.
- A combination of two atoms would have two permitted levels near the core of each atom.
- A combination of three atoms would have three levels near the core because the outer electrons of all three atoms can be shared.
- The higher, unoccupied orbits would also split, indicating that they too can in principle take two or three electrons.

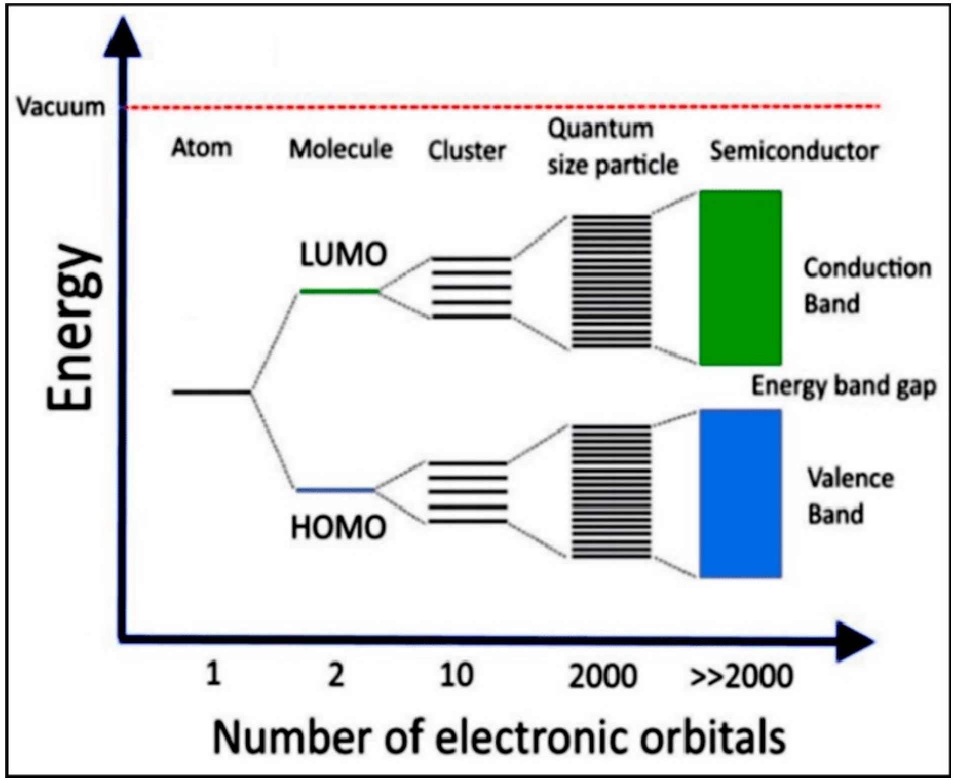


5.5.2 Semiconductors

- Even a sliver of a real crystal contains a large number of atoms, and so there are a huge number of split levels associated with each atom in the crystal because of the sharing of outer electrons.
- In other words, the energy levels or orbits are spread out into a “band.”
- The lowest band of energies is filled with electrons. This band is called the “valence band.”
- Conversely, the upper energy band is empty of electrons because it is composed of the combined unoccupied higher energy levels or orbits of the individual atoms. It is called the “conduction band.”

5.5.2 Semiconductors

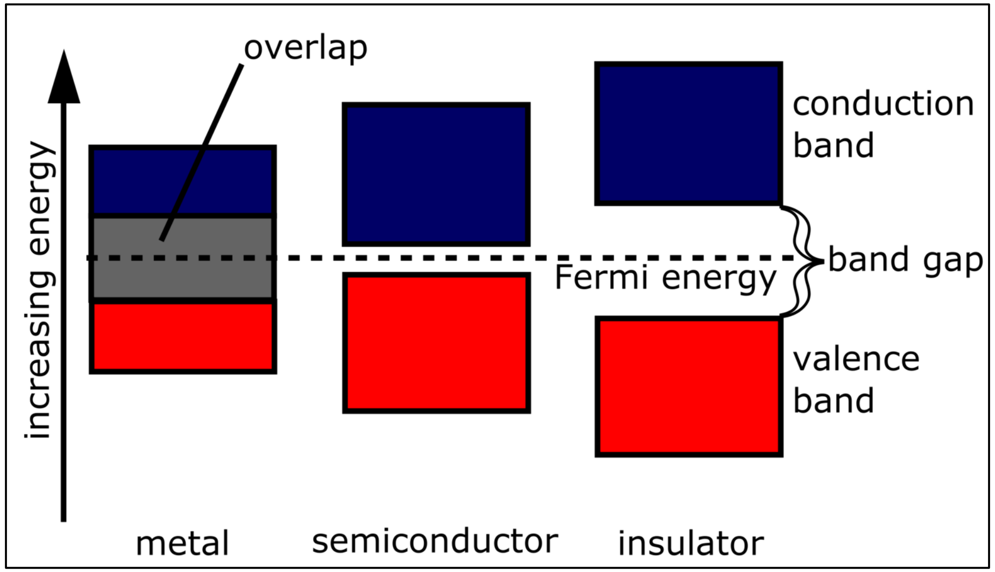
- The individual atoms have a gap between the permitted inner and outer orbits (i.e., a gap in energy between the inner filled levels and the outer unoccupied levels).
- The energy region between the valence band and the conduction band in the crystal must be a “forbidden energy gap” (E_G) .



https://www.researchgate.net/figure/Band-structure-of-a-semiconductor-as-an-interaction-of-atomic-orbitals-adapted-from_fig2_349726510

5.5.2 Semiconductors

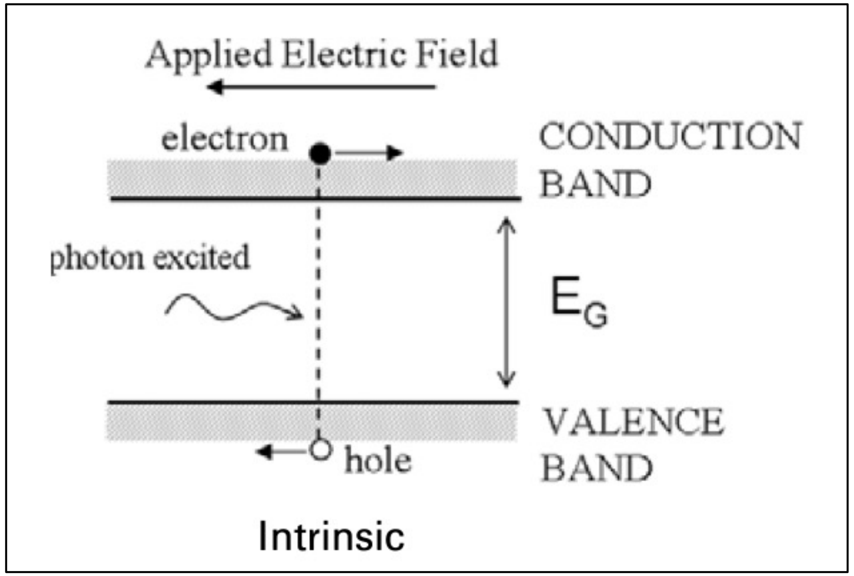
- In metals, the valence and conduction bands overlap, and so any of the many valence electrons can move freely to conduct electricity and heat.
- An insulating material has a highly ordered structure and a very wide forbidden energy gap. The conduction band is totally empty of electrons and so cannot contribute to an electrical current flow.



https://energyeducation.ca/encyclopedia/Band_gap

5.5.2 Semiconductors

- In a semiconductor, a few electrons can be elevated from the valence band to the conduction band across the forbidden energy gap (E_G) merely by absorbing heat energy.
- These electrons promoted to the conduction band and the corresponding vacancies or "holes" left in the valence band allow it to contribute to electrical conductivity.
- Semiconductors are poorer conductors than metals but better than insulators.



5.5.2 Semiconductors

- The number of electrons which can be promoted to the conduction band by absorbing heat will vary with the temperature of the crystal, typically as $\exp(-E_G/2kT)$.
- Those semiconductors with larger bandgaps are preferred because transistors and other devices made from them will be less sensitive to environmental changes.
- For this reason silicon ($E_G = 1.12$eV) is preferred to germanium ($E_G = 0.67$eV) .

5.5.2 Semiconductors

- When a photon is absorbed in the crystalline structure of silicon, its energy is transferred to a negatively charged electron, the photoelectron, which is then displaced from its normal location in the valence band into the conduction band.
- For each semiconductor there is a wavelength of light beyond (redder than) which the material is insensitive to light because the photons are not energetic enough to overcome the forbidden energy gap (E_G) in the crystal. The cutoff wavelength is given by

$$\lambda_c = \frac{hc}{E_G}$$

5.5.2 Semiconductors

- These wavelengths are given in the right table.
- Some of the materials listed are sensitive well into the infrared region and will be discussed again in Chapter 11.
- All of the materials in the table are considered "intrinsic" semiconductors because each has a well-defined bandgap intrinsic to the material.

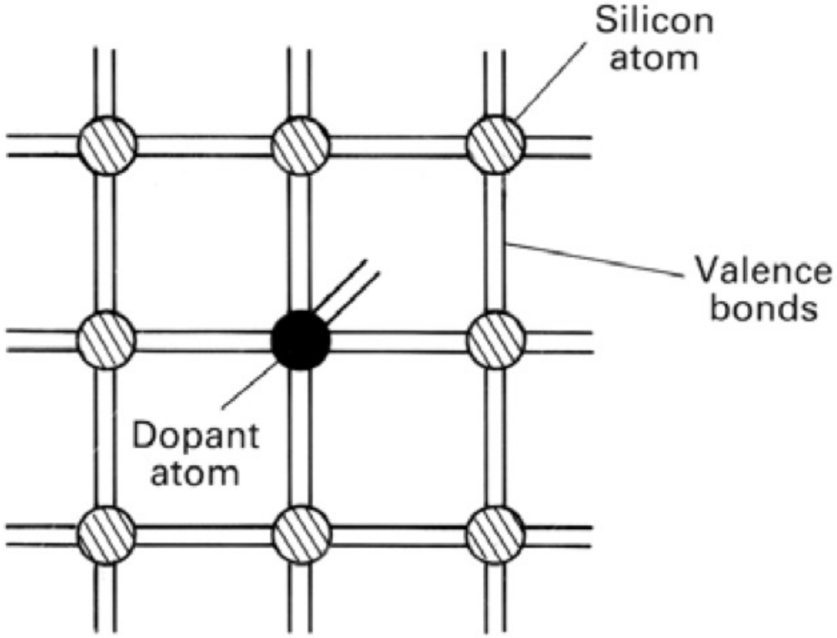
Table 5.2. Forbidden energy gaps for some common semiconductors.

Name	*Symbol*	T (K)	E_G (eV)	λ_c (μm)
Gallium nitride	GaN	295	3.45	0.36
Silicon carbide	SiC	295	2.86	0.43
Cadmium sulfide	CdS	295	2.4	0.5
Cadmium selenide	CdSe	295	1.8	0.7
Gallium arsenide	GaAs	295	1.35	0.92
Silicon	Si	295	1.12	1.11
Germanium	Ge	295	0.67	1.85
Lead sulfide	PbS	295	0.42	2.95
Indium antimonide	InSb	295 77	0.18 0.23	6.9 5.4
Mercury cadmium telluride	$Hg_xCd_{1-x}Te$	77	0.1 ($x = 0.8$) 0.5 ($x = 0.554$)	12.4 2.5

5.5.2 Semiconductors

- It is also possible to create a different kind of semiconductor known as an “extrinsic” semiconductor in which impurity atoms produce intermediate energy levels within the forbidden gap.

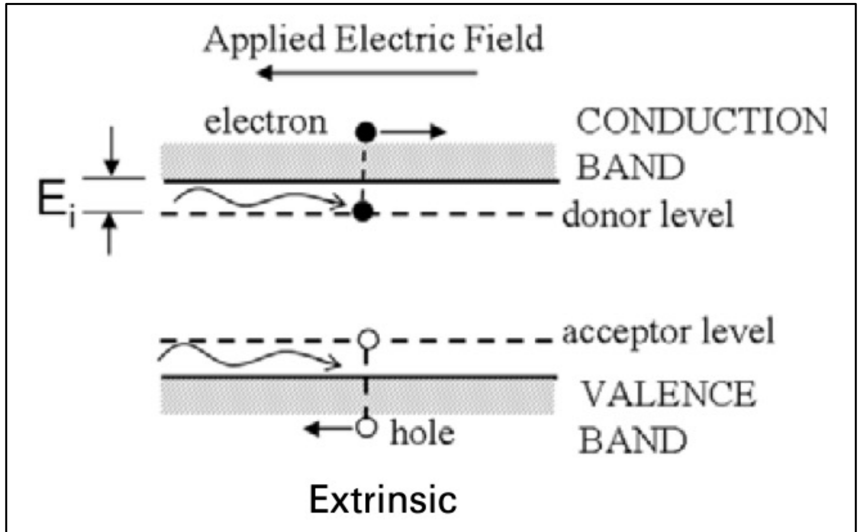
- For example, when silicon atoms in the crystal structure are deliberately replaced with other atoms the semiconductor is said to be “doped.”



Crystal lattice

5.5.2 Semiconductors

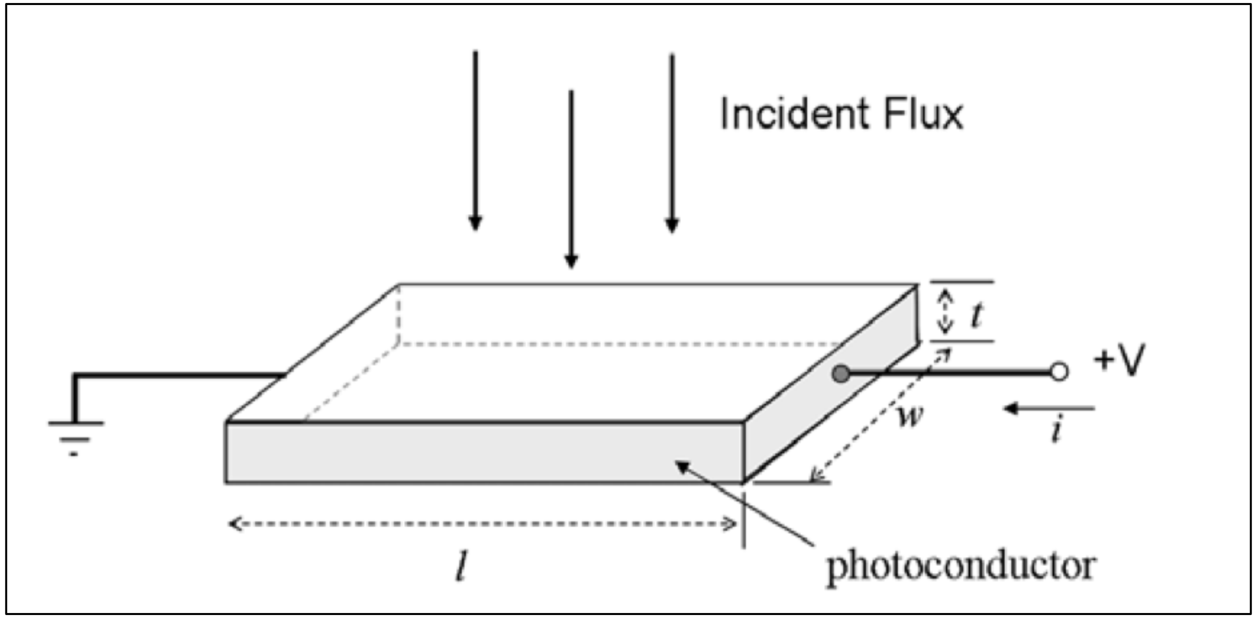
- If the impurity atom has more valence electrons than the semiconductor then it will donate these negative charges to the conduction band; such a material is called n-type.
- If the impurity atom has fewer valence electrons than the semiconductor then a positively charged hole is left in the valence band ready to accept any available electrons; this material is a p-type semiconductor.
- Because of the much lower transition energies (E_i) , extrinsic semiconductors are used in infrared photon detection.



5.5.3 Photoconductors and photodiodes

Photoconductors

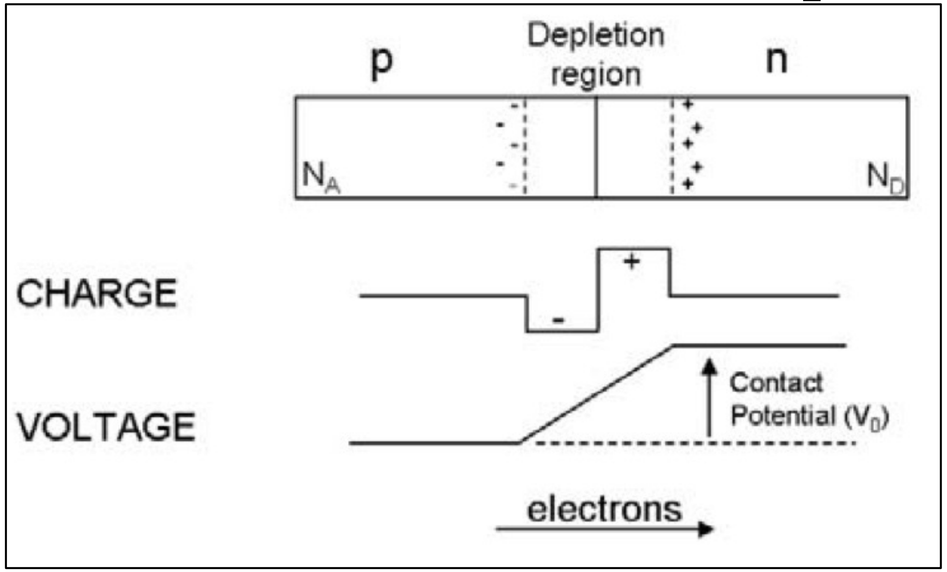
- The simplest application of a semiconductor for detection of photons.
- Photons are absorbed and create electron-hole pairs, both of which contribute to the photocurrent, but it is usually the electrons that dominate.
- Incoming photons are detected by measuring this photocurrent.



5.5.3 Photoconductors and photodiodes

Photodiodes

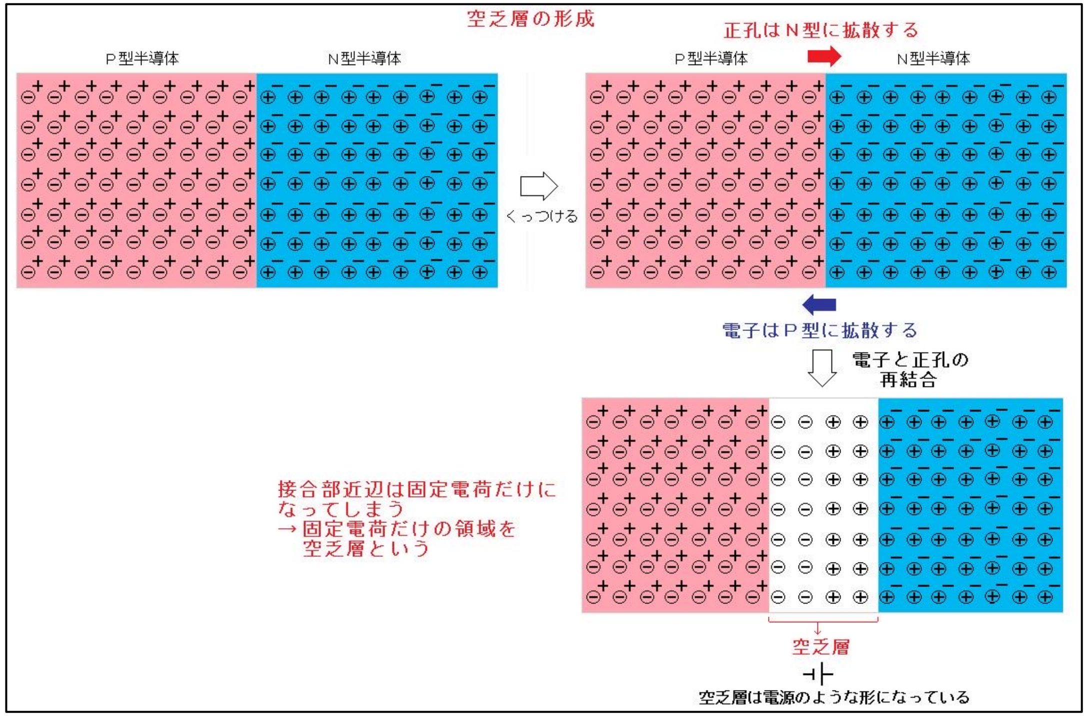
- One of devices using junctions between p-type and n-type regions in semiconductor structures.
- When a p-n junction is formed, electrons from the n region tend to diffuse into the p region near the junction and holes diffuse from the p-side to the n-side.
- A narrow region forms on either side of the junction in which most of electrons and holes are depleted.



5.5.3 Photoconductors and photodiodes

Photodiodes

- In this depletion region, positively charged ions are left on n-side and negatively charged ions are left on p-side. These ions create an internal electric field.
- An electron-hole pair is created within the depletion region by the absorption of a photon.
- Electron and hole are immediately separated by the electric field across the junction and this produces an electric current.



http://imasaracmosanalog.blog111.fc2.com/blog-entry-94.html

5.5.4 Thermal detectors

- In several types of thermal detectors, the "**bolometer**" is the most widely used one in astronomy.
- Semiconductor bolometers, based on silicon or germanium, are well-developed for far-infrared and sub-millimeter astronomy.
- A bolometer consists of a sensitive thermometer and a high cross-section absorber that absorbs almost all of the incident radiation falling on it. The absorber has a heat capacity of C [J/K].
- The radiation energy which a bolometer absorbs (=E [J]) is converted to heat, and this heat raises the bolometer's temperature ($\Delta T = E/C$) .
- The temperature rise causes a change in bolometer resistance, and consequently a change in the voltage across it which can be measured.

5.5.5 Coherent detectors

- The most important form of coherent detectors is the **heterodyne** which mixes two signals of different frequencies (input signal and reference signal) and detects a signal at the "beat" frequency (ν_{IF}) between the two frequencies.
- Input signal is an electrical signal converted from the electric field of the incoming wave, and reference signal is a strong signal produced by Local Oscillator (LO) with a frequency (ν_{LO}) that is close to but different from the input signal frequency (ν_S) . The beat frequency, or intermediate frequency (IF), is $\nu_{IF} = \nu_S - \nu_{LO}$.

5.6 Summary

- To select a suitable spectrometer design, it is necessary to start from understanding astronomical instruments such as prisms, gratings, and grisms.
- The grism can convert a camera into a spectrometer.
- Additional polarization modules can convert vibration information into measurable intensity modulations.
- Most of these concepts are applied to UV and IR instruments.
- There are three types of detectors; photon, thermal, and coherent.
- Photon detectors either use the external photoelectric effect like a photocathode, or the internal photoelectric effect in a semiconductor.