Radiation Detector 2018/19 (SPA6309)

Semiconductor detectors (Leo, Chapter 10)

Semiconductor detectors are used in many situations, mostly for some kind of high precision measurement.

- silicon micro-strip detector
- silicon pixel detector
- charge-coupled device (CCD)
- avalanche photodiode (APD)
- silicon photomultiplier (SiPM)

Basics of semiconductor properties (Leo, 10.1)

The semiconductor material creates a conduction band and a valence gap with an energy gap of ~1eV. If the energy gap is much larger (>5 eV), the material is an insulator, and if there is no energy gap, the material is a metal (conductor). In the ionization detector, the charged particles ionize the gas molecules and electrons are collected as a signal. In semiconductor materials, charged particles create electron-hole pairs and they are collected as a signal of radiation.

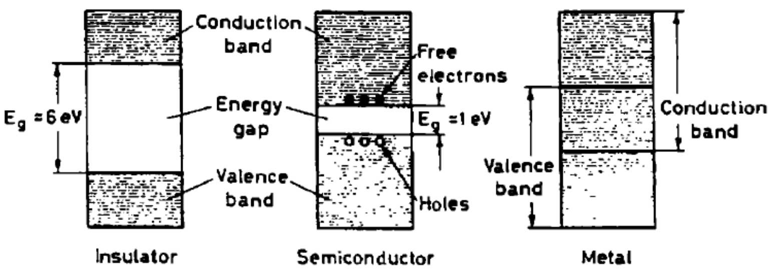


Fig. 10.1. Energy band structure of conductors, insulators and semiconductors

A typical silicon semiconductor can create an electron-hole pair with energy gap 3.6 eV. The density is ~2 g/cm^3, and the thickness is 300μm. Thus, a MIP particle passing through the silicon layer would produce,

2 MeV/cm $\times$ 2 $\times$ 300μm / 3.6 eV ~ 3$\times 10^4$ electron-hole pairs.

Clearly, semiconductors are more sensitive to small energy deposits than a typical gaseous ionization detector (which produces ~70 electrons/cm).

Intrinsic charge carrier (Leo, 10.1.3)

At 0K, all the electrons in the valence band occupy an atom to make the lattice structure. However, at finite temperature, electron-hole pairs are thermally created. The typical density of thermal electron-hole pairs at 300K is 1.5×10^{10}/cm^3 for silicon. This means, in general, a semiconductor has way more thermal electron-hole pairs than electron-hole pairs made by charged particles.

Doped semiconductor (Leo, 10.2)

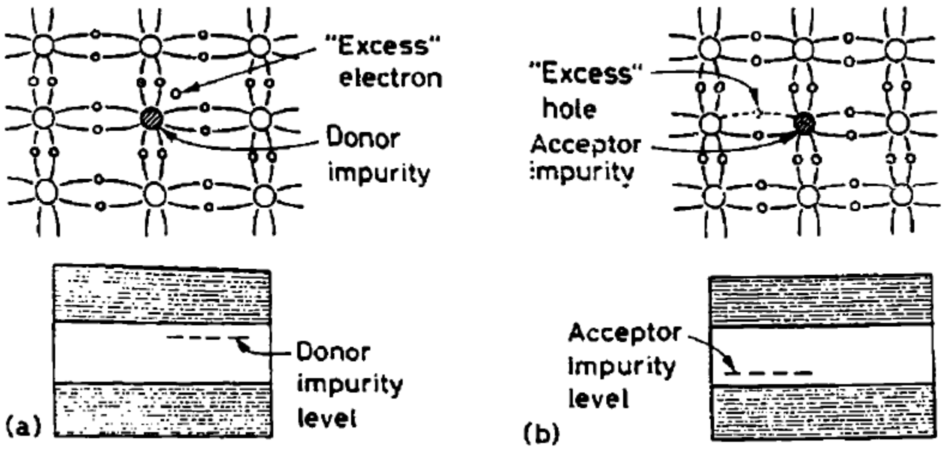


Fig. 10.4. (a) Addition of donor impurities to form n-type semiconductor materials. The impurities add *excess* electrons to the crystal and create donor impurity levels in the energy gap. (b) Addition of acceptor impurities to create p-type material. Acceptor impurities create an *excess* of holes and impurity levels close to the valence band

A pure crystal semiconductor has the same number of electrons and holes. This can be modified by adding a small amount of impurity. For example, a silicon atom has 4 valence electrons which make the lattice structure. By adding a small amount of an element with 5 valence electrons (**donor** element, such as phosphorus, arsenic), there is another energy level just below the conduction band. This means that the presence of extra electrons makes it easier to excite electrons from valence band to the conduction band, and so this enhances the conductivity of the semiconductor. This type of semiconductor is called an **n-type** semiconductor.

On the other hand, one can add a small amount of an element with 3 valence electrons (**acceptor** element, such as gallium, boron), so now there is another energy level just above the valence band. This time, extra electrons make it easier to excite electrons to this level and so it's easier to create hole states in the valence band. This type of semiconductor is called a **p-type** semiconductor.

p-n junction (Leo, 10.3)

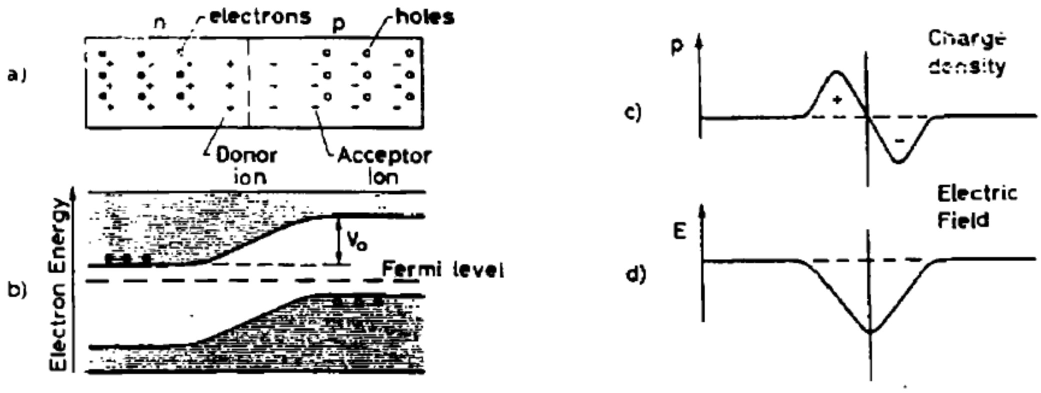


Fig. 10.5. (a) Schematic diagram of an np junction, (b) diagram of *electron* energy levels showing creation of a contact potential V_0, (c) charge density, (d) electric field intensity

In short, n-type semiconductors have extra electrons, and p-type semiconductors have extra holes. The great application of these is to combine them to form a junction, where extra electrons from the n-type semiconductor move to the p-type region. At the junction, the n-type is positively charged, the p-type is negatively charged, and so the junction contains an electric field. The place where there is a change in the potential is called the **depletion zone**, and any electron-hole pairs made in this region will be swept away immediately.

Reverse bias junctions (Leo, 10.3.3)

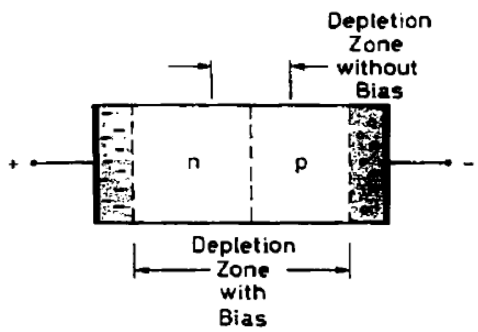
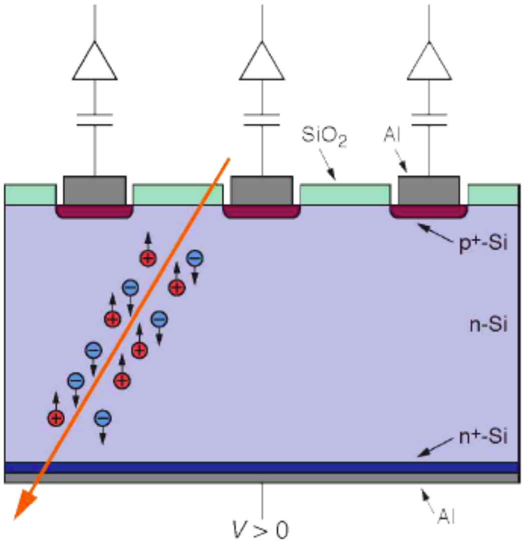


Fig. 10.7. Reversed-bias junction

By applying positive voltage to the n-type side, and negative voltage to the p-type side (**reverse bias junction**), electrons and holes are pulled away, and thus the depletion zone becomes larger. In this way, a greater volume is sensitive to charged particle tracks as it is easier to create electron-hole pairs and so this is the operation condition of semiconductor detector.

Silicon microstrip detector (10.6.2)

The silicon detector lecture is available from the CERN EDIT school 2011, http://indico.cern.ch/event/124392/ (http://indico.cern.ch/event/124392/)



In a typical n-type silicon detector, the doping concentration on the p-type side is ~$10^{15}/cm^3$, and the n-type side is ~$10^{12}/cm^3$. By applying a ~100 V reverse bias voltage, the depletion zone is ~300μm. Here, the p-type region is small but has a higher doping concentration. On the other hand, the n-type region is less doped, but the bulk is formed of an n-type semiconductor and so this region acts as the radiation sensitive region.

The contact between the metals and the semiconductors needs additional care, this requires an additional layer of heavily doped n^+ material (such as n-type semiconductor with gold doping) before the metallic probe.

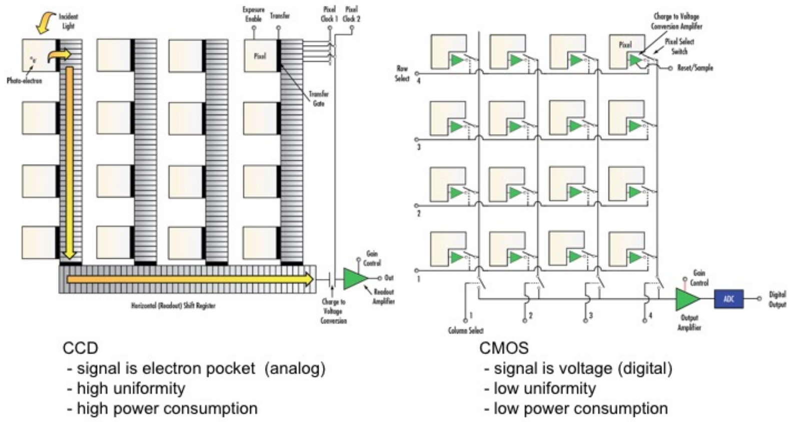
The resolution is striking. The pitch of the p-type semiconductor strip is 50μm, and thus this is the order of the position resolution. In reality, the detector can achieve an even better, few μm position resolution. Because of this reason, microstrip detectors are used in the inner tracker region of collider detectors to differentiate high-density tracks. Since the strip can provide only 1D directional information, if one wants to use this as a tracker, 2 microstrip detectors can be configured in the X and Y direction alternatively.

Silicon pixel detector

It is also possible to configure semiconductor detectors in a pixel so that one layer can resolve both X and Y directions. The problem is this requires a large number of readout channels and has high power consumption.

Charge coupled device (CCD)

Edmunds optics https://www.edmundoptics.com/resources/application-notes/imaging/understanding-camera-sensors-for-machine-vision-applications/ (https://www.edmundoptics.com/resources/application-notes/imaging/understanding-camera-sensors-for-machine-vision-applications/)

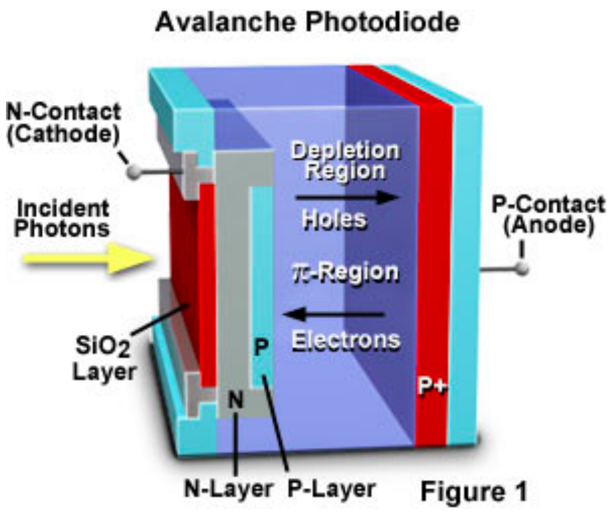


Charge-coupled device (CCD) are probably the most famous silicon detectors for us, due to the CCD camera application. Although it uses pixels, it doesn't read out signals from each pixel by separated into channels, instead, it transfers collected electrons to the next pixel, then the next pixel etc..., and it finally reads the signal at the end. The process takes a finite amount of time and it is not suitable for particle detectors which require few ns speed.

The same job can be done in various ways. Instead of sending electrons, one can send a voltage. **CMOS sensor** converts a signal to a voltage at each pixel, then sends this voltage signal.

Avalanche photodiode (APD)

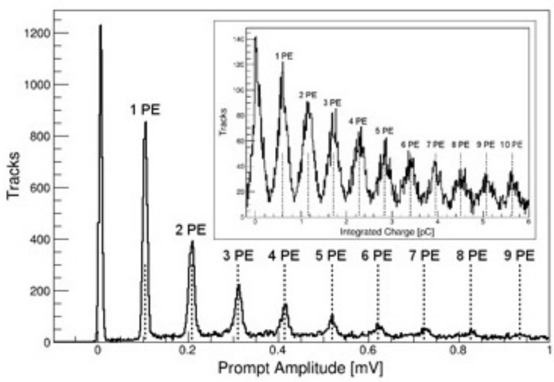
Hamamatsu photonics http://hamamatsu.magnet.fsu.edu/articles/avalanche.html (http://hamamatsu.magnet.fsu.edu/articles/avalanche.html)

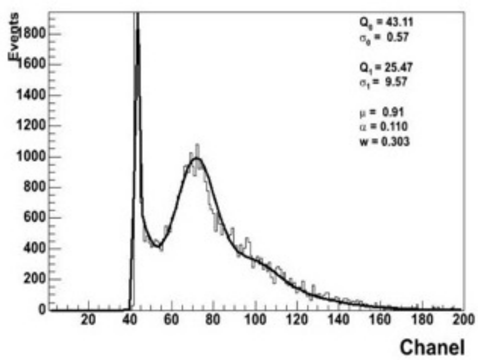


Avalanche photodiode (APD) is a semiconductor photon sensor. Incident photons make electron-hole pairs in the depletion zone. A large reverse bias voltage (~200 V) will pull electrons strongly and their trajectory creates more electron-hole pairs, and in the end, one can get 10^5-10^6 multiplication (gain) for an incident photon signal. Note, the operation voltage is lower than a PMT (~1500 V), but the gain is reasonably high (PMT gain ~10^7). There is a strong temperature dependence, and a stable operation requires a cooling system.

Silicon photomultiplier (SiPM)

"Scintillation light from cosmic-ray muons in liquid argon"
http://iopscience.iop.org/article/10.1088/1748-0221/11/05/P05016
(http://iopscience.iop.org/article/10.1088/1748-0221/11/05/P05016)
"Testing of cryogenic photomultiplier tubes for the MicroBooNE experiment"
http://iopscience.iop.org/article/10.1088/1748-0221/8/07/T07005
(http://iopscience.iop.org/article/10.1088/1748-0221/8/07/T07005)





Silicon photomultiplier (SiPM) or **multi-pixel photon counter (MPPC)**is the next generation photon detector. It is an array of APDs, but each pixel can measure either 1 or 0 because each pixel will be saturated by a single hit of a photon (**Geiger mode**), and the number of photoelectrons is measured by how many pixels are saturated. SiPMs have a much better resolution than PMTs, and many current and future neutrino experiments use them to see signals from optical fibers. Since the sensitive region is small, it is not suitable to cover a large volume (i.g., 20-inch PMTs for Super-Kamiokande), but by combining them with scintillators, SiPMs can also cover a large volume.