

Appendix B: Semiconductor Detectors

Semiconductor devices have been used as radiation detectors in nuclear and high-energy physics for more than 25 years. In the past decade, however, a new technique has been developed (combining ion implantation and photolithography) for the production of large-area detectors requiring readout configurations for complex position measurement or timing applications. The silicon micro-strip detectors used in the CE-06 experiment are examples of this new technology. This appendix considers the principles of semiconductor detectors in general and these relatively new devices in particular.

B.1 General Principles

The general operating principles of semiconductor detectors are fundamentally similar to that of gas detectors (see Appendix A). In order to detect the minute amounts of free charge produced by the incident ionizing radiation, an electric field is set up in a volume of material (the “active region”) in order to “collect” the charge via induction.

There are important differences in the details, however. The stopping power of a semiconductor detector is much greater than any practical gas detector. For example, for 5 MeV α particles, $(dE/dx)_{\text{Si}}/(dE/dx)_{\text{CF}_4} \approx 550 : 1$. This implies the capability to detect ionizing radiation using a small active volume detector (often less than 1 mm in thickness), along with the ability to efficiently detect minimally ionizing particles. Another distinguishing feature of these detectors is the relatively small amount of energy required on the average to produce an electron-ion pair; typically, this is about 3.5 eV for silicon, roughly a factor of ten smaller than that of a typical gas [Lw87]. The intrinsic resolution of these devices is consequently much better than that of gas detectors. The most important difference from gas detectors is, of course, the crystal structure of the solid-state medium. This characteristic is the basis for understanding how these detectors work.

A semiconductor is characterized by a gap of order 1 eV between the highest filled

and lowest unfilled electron energy levels. For pure (“intrinsic”) silicon, the filled levels (the “valence” band) correspond to electrons attached to ions and the unfilled levels (the “conduction” band) to “free” electrons. Since the valence levels are completely filled, no electron in this band can contribute to a current in the silicon. A valence electron may, however, jump the gap into the conduction band via thermal excitations, which implies that near absolute zero a semiconductor becomes a good insulator. A true insulator is different primarily in the size of the energy gap: a large gap can make thermal excitation very improbable even at high temperatures.

An electron which does reach the conduction band leaves behind a vacancy (or “hole”) in one of the valence band energy states. Because of the small separation in energy between the levels in the band, a neighboring electron can easily jump into the available state, itself leaving another empty level. This motion of charge is a current as real as that due to the motion of the electrons in the conduction band, and is called the “hole current.” A model for current in a semiconductor must therefore take into account both the electron and hole contributions.

In practice, it is impossible to construct a completely pure sample of crystalline silicon, and impurities even at the level of one atom in 10^9 can significantly alter [As76] the crystal’s conduction properties. Typically, impurities produce energy levels deep inside the (previously empty) band gap. These levels can remove or capture charge carriers via recombination or trapping into metastable states.

This charge carrier loss is detrimental to good detector performance: high efficiency, good resolution, and fast signal risetimes depend on the rapid and complete charge collection of the ionization event’s charge. Many detectors are produced by purposefully introducing (“doping”) impurities into the silicon, replacing atoms at their lattice sites.

Commonly used dopants for silicon are atomically pentavalent and trivalent, for example, arsenic and boron, respectively. Arsenic has an “extra” electron which does not participate in the covalent bonding with the lattice silicon atoms. This electron is only weakly bound to the impurity atom (since the nucleus is shielded by the other valence electrons) and resides in an energy level just below the conduction band. A trivalent impurity has, on the other hand, an “extra” hole and so produces an energy level located just above the valence band. Arsenic and boron, under these conditions, are referred to as “donor” and “acceptor” atoms, respectively.

Doping with donors or acceptors in concentrations of a few parts in 10^9 produces

n-type or p-type silicon, respectively, named for the sign of the extra charge carrier that is donated. For n-type materials, electrons are called the majority carriers and holes the minority carriers, and vice versa for p-type materials. Dopant concentrations as high as a few parts in 10^4 produce n^+ and p^+ silicon, which is highly conductive and often employed to make electrical contact with n- and p-type silicon.

A “p-n junction” is formed when n-type and p-type materials are placed in close contact. These junctions commonly play a major role in silicon detectors. In the absence of an external field, electrons on the n-side tend to diffuse via thermal motion across the junction to the p-side. Normally, a diffusion of electrons in the opposite direction from the p-side would, on the average, cancel this but there are many fewer conduction electrons on that side (they are the minority carriers) and so a net current of electrons results. Exactly the same argument can be made for the p-side majority holes: a net hole current is set up from the p-side to the n-side. The following discussion only considers the (equivalent) electron motion.

The electrons flow across the junction, leaving bare donor atoms (+1 net charge), and recombine with p-side majority holes, producing bare acceptor atoms (-1 net charge). The bare atoms produce an internal electric field which tends to prevent further electron flow. The section of material in which there exists a non-zero electric field is called the “depletion region,” since any electron-hole pairs generated there (thermally or by ionizing radiation) are swept out by the field. Here, majority carrier current is suppressed whereas minority carrier current (i.e., conduction electrons flowing from the p-side to the n-side) is not. An equilibrium is reached when the normally small minority carrier current equals the suppressed majority carrier current. In silicon, the “contact potential” corresponding to the internal field thus set up is typically $V_0 \approx 1$ volt. The thickness of the depletion region for an intrinsic n-type detector, such as those used in the CE-06 experiment, is

$$d_n = (2\epsilon\rho_n\mu_e V_0)^{\frac{1}{2}}, \quad (\text{B.1})$$

where ρ_n is the n-type resistivity, ϵ is the relative dielectric coefficient, and μ_e is the electron mobility in the silicon. The high resistivity n-type material used in the CE-06 silicon detectors has $\rho_n \approx 2 \times 10^4 \Omega \text{ cm}$, thus with a typical value $V_0 \approx 1$ volt, $d_n \approx 75 \mu\text{m}$.

A p-n junction detector is typically reverse-biased: an external field is applied in the same sense as the internal junction field, i.e., a positive electrode is attached to the n-side, and a negative one to the p-side. The calculation of the depletion region width is the same,

with V_0 replaced by the applied voltage V_{app} . For the particular type of detector used in CE-06, $V_{\text{app}} = 10$ volts creates a depletion depth of $d \approx 240 \mu\text{m}$. For the experiment, the detectors were “over-biased” to approximately 50 volts. Here, the bias level is more than enough to attain a fully-depleted detector, in which the width of the active volume is comparable to the physical detector thickness. The over-biasing further enhances the timing resolution by 10–15% by increasing the field strength in the depletion region.

The increase in the depletion region and the suppression of the majority current are the main reasons for the reverse-biasing of a p-n junction detector. This region is the sensitive volume of the detector: ionizing radiation produces electron-hole pairs which are accelerated out of the region by the field and collected by the electrodes. Electron-hole pairs produced outside the region (in a “dead layer”) are not under the field influence and are free to recombine or become trapped. Fully depleted detectors are those with depletion regions essentially as large as the physical detector depth.

In practice, heavily doped n^+ and p^+ layers are added to the n and p sides respectively, so that metal electrodes can be attached and the induced signals can be read out directly. Without these layers, a depletion zone is formed at the metal-semiconductor interface (a “Schottky barrier”), which would prevent proper charge collection from the actual p-n junction. Such a barrier still forms in the n^+ and p^+ material but the heavy doping causes the width of the depletion region to be essentially zero.

The signal formation in the p-n junction detector is by induction (not actual charge collection) as in Appendix A. In contrast to the gas situation, however, the electron and hole motions contribute roughly equally to the total signal, and no real electron multiplication takes place. The signal on the positive electrode in a standard reverse-biased configuration is negative with a rise-time on the order of $\tau = \epsilon/en_{\text{donor}} = \rho_{\text{donor}}\epsilon$. The high-resistivity silicon used in the CE-06 Si detectors has an “intrinsic” rise-time on the order of 20 nsec.

In a real detector, a “leakage” current exists which induces a signal of the same sign on the electrodes as the desired signal from the incident radiation. The small current due to the motion of thermally generated minority carriers (electrons moving from the p-side to the n-side) is a contribution to this, although the largest factor in the leakage current is often due to surface effects. This can include current on the surface of the detector edge (via a surface contaminant, perhaps) from one contact to the other or current through an epoxy mount, etc. The leakage current provides a limit on the smallest real signal that can be observed: it is caused by essentially random processes and as such can be indistinguishable

from an ionizing event. The method of oxide passivation can greatly reduce the surface component of the current (to levels comparable to the thermal currents) and thus allow the construction of much larger p-n junction detectors, with areas of 10's of cm² compared to 1 cm².

B.2 Passivated, Ion-Implanted Silicon Detectors

The micro-strip detectors such as those used in CE-06 combine the technology of oxide passivation, ion implantation, and photolithography. Typically, a planar sample of high-purity silicon (which is often weakly n-type to begin with due to residual donor impurities) is “passified”: an insulating oxide layer is formed on it [Kn89]. Photolithography, which is essentially a technique for etching patterns in materials using light, is performed on one face^[1] to remove the SiO₂ from specific areas.

At this stage in the construction, the etched silicon wafer is subjected to ion implantation. This is the bombardment of donor atoms on one face and acceptor atoms on the other. For the n-type wafers used in CE-06, acceptors are implanted on the front, etched face to produce a p-n rectifying junction (and a p⁺ surface layer), while donors are implanted on the back to produce a non-rectifying n⁺ surface.

The sample is then baked to anneal the radiation damage produced by the ion implantation, which could otherwise leave lattice defects producing increased leakage current and slow or incomplete charge collection. Finally, aluminum is evaporated on the faces which can then be etched in the desired entrance and/or exit patterns, again by photolithography.

There are several inherent advantages to the ion-implanted passivated detectors over the devices based on Schottky barriers (also called surface-barrier detectors). The leakage current via surface channels can be greatly reduced since the actual p-n junctions are inside the volume of the sample and do not extend to the physical sample edge. For a fully depleted detector, the dead layer thickness is due to the entrance and exit windows and can be made very small (< 1000 Å) since the largest contribution to the layer is from the evaporated aluminum (barring fingerprints!). Furthermore, complex readout electrodes can be etched on the front or back face to suit a wide variety of applications.

The micro-strip detector is a particular example of a readout configuration where electrode “strips” are etched parallel to one another across the detector face, separated by insulating material (typically, SiO₂). Each electrode can be read out separately and

[1] More complex readouts can require etching of more than one face.

independently of the others since the electric field configuration “traps” the ionization trail to the nearest strips in a way similar to that for the MWPC that was used in the CE-06 experiment. If the strips are wide compared to the extent of the ionization trail and the incidence of radiation is essentially normal to the detector face, the signal is confined to a single strip. From this, a measurement of the position of the incident radiation can be made by determining which strip “fired.” The “pitch” of the strips is the distance between the strip centers and can be as small as tens of microns and as large as 1 cm. In the case of the micro-strip detectors used for the CE-06 experiment, the strip pitch was 1 mm, with narrow (50 μm wide) insulating SiO_2 strips between. In the configuration of Fig. 3.31, these dimensions imply a silicon transmission efficiency of 93%.

Since the best position resolution possible is just the strip pitch, small values of this parameter can yield very precise position determination, at the cost of a large number of readouts and complex readout circuitry. If the back face of the detector is unpatterned, a position-independent signal (of the opposite sign) proportional to the deposited energy can also be obtained.