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SEMICONDUCTOR DETECTORS - AN INTRODUCTION* LBL-7282

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I. History

Semiconductor detectors appeared on the scene of Nuclear Physics in about 1960, although McKay of Bell Laboratories had demonstrated the detection of alpha particles by semiconductor diodes several years earlier. The earliest work, just prior to 1960, focused on relatively thin surface barrier germanium detectors, used to detect short-range particles. These detectors, used at low temperature to reduce leakage current, demonstrated the potential of semiconductor detectors to realize energy resolutions substantially better than the ionization (gas) chambers used earlier. Furthermore, the ability of a solid to stop particles in a very short distance and the rugged nature of solid state devices suggested that a small rugged detector might be feasible.

Attention rapidly moved to silicon detectors following this earlier work, largely because silicon, having a considerably larger band-gap than germanium, offered the prospect of good performance at room temperature. Silicon surface barrier detectors and, somewhat later, diffused junction detectors, both used at room temperature, therefore became the first types of semiconductor detectors used in nuclear spectroscopy and they rapidly proved their value as detectors of short-range particles. At this point, a little must be said about the limitations of these detectors - later in the course, the details will be filled in.

Nuclear Spectroscopy is largely a study of the energy levels in the nucleus and the most profitable tool for the study of these levels is to observe the radiation emitted when transistions occur between allowed levels. This radiation, in general, is in the form of gamma rays, so detectors of gamma rays are clearly the most powerful tool in such investigations. NaI scintillation detectors had become important because of this, but their rather poor energy resolution, which results in an inability to separate closely spaced levels, was a major limitation. Silicon is a very poor material for gamma ray detection, since the gamma ray efficiency varies roughly as Z^5 (where Z is the atomic number of the absorber) and Z is only 14 for silicon. Germanium would be a better material (Z = 28), but it was some time before this potential was realized.

The second major limitation in these earlier detectors and still a limitation, although less restrictive now, was the small thickness of the sensitive region of the detectors which limited their use to short-range particle detection. Of course, the small thickness also limits the gamma ray detection efficiency, but in these early days only charged particle detection was seriously considered. In the next part of this introduction, I will discuss detector physics in a little more detail; for the moment, two points should be noted:

(i) To first order charge collection in a detector only occurs from regions where an electric field exists. Diffusion does occur from field-free regions, but it is slow and its effects are usually undesirable. In junction or surface-barrier (sometimes called Schottky-barrier) detectors, this means that the "depletion layer" is the sensitive region of a detector.

(ii) The thickness of a depletion layer i a semiconductor diode is proportional to

$$\sqrt{\frac{V}{N}} \text{ or } \sqrt{V \cdot \rho}$$

where V is the applied voltage, N is the concentration of the dominant impurity in the semiconductor and ρ is its resistivity. Thus, in the case of a detector made from p-type silicon having a resistivity of 2000 Ωcm, (which is very pure by normal commercial silicon standards), an applied voltage of 200 V yields a depletion layer thickness of only 200 μm (0.2 mm). This i: barely adequate to stop 15 MeV alpha particles or 4 MeV protons, so the use of such detectors is very limited even for particle experiments.

Fortunately, this limitation was rapidly circumvented due to the work of Pell at General Electric, who (for entirely unrelated purposes) demonstrated that lithium, an interstitial donor, could be drifted in an electric field at moderate temperatures to virtually completely compensate the acceptors in p-type silicon (and germanium). This work was rapidly exploited in semiconductor detectors to produce lithium-drifted detectors with sensitive regions up to several millimeters thick. By 1961, such detectors had become the primary spectroscopy tool in charged particle experiments.

The next major step was obvious, but was delayed by the feeling on the part of many of us working in the field that large-scale use of liquid nitrogen was not acceptable. It was clear that lithium-drifted germanium would provide the potential for high-resolution gamma-ray detection (albeit with much smaller efficiencies than NaI scintillation detectors). It was equally clear that the small band-gap of germanium would require low temperature operation. Therefore, it took some time for lithium-drifted germanium gamma-ray detectors to appear (1964) but when they did, they were exploited very rapidly and they must be regarded as the dominant tool in the intensive period of nuclear spectroscopy in the mid to late 1960's.

In 1965, the first non-nuclear application of semiconductor detectors started to develop. The availability of low-noise field effect transistors and their use with silicon detectors at low temperatures realized adequate energy resolution to resolve the characteristic K x-rays of most elements. This made development of the field of energy-dispersive x-ray fluorescence possible and has led to a large commerical business which impacts on many areas of research far outside the nuclear area.

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The final detector development I want to discuss is the development of very pure germanium which makes possible thick germanium detectors without the need for lithium drifting. This work was initiated by R. N. Hall of General Electric in the early 1970's, and it is having a major impact at the present time. Its value rests mainly on the fact that lithium is very mobile in germanium at room temperature. Consequently, the processing and handling of lithium-drifted germanium detectors is rendered quite difficult and multi-detector systems are hardly feasible. High-purity germanium avoids these problems, so detector arrays and telescopes of many detectors are feasible. Furthermore, with some reservations caused by potential surface contamination, high-purity germanium detectors can be cooled when required but warmed up to room temperature for storage. While this fact should be used with caution due to the potential problem of surface contamination, it does make possible the in-situ annealing of radiation damage which is a key factor in some very long-range particle telescope applications.

In this rapid review, I have not discussed materials other than silicon and germanium. Part of the course will deal with this topic, but its impact on the field is only small at the present time and the prospects for any major impact are not good.

Before closing this historical review, I should perhaps draw your attention to the fact that the nuclear research aspects of the use of detectors have become less predominant in recent years. Partly, this is because x-ray fluorescence analysis, environmental survey work and space applications have all become important, but it is because there has been a real shift of interest in nuclear physics. Much of the interest in nuclear physics now centers on heavy ion physics and the particular characteristics of heavy ions have led to a resurgence of gas ionization detectors. Therefore, although semiconductor detectors still are used where their special advantages are important, they are not so dominant in nuclear sicience as they were for the decade 1965-1975.

II. Physics of Detectors

The simple-minded approach to semiconductor detectors is to regard them as an analog of the gas ionization chamber. In a brief review like this, it is tempting to assume such a simple approach. However, to provide a real introduction to the remaining talks, a little more detail is necessary.

The first point to appreciate is that a much smaller amount of energy is required to release electrons (and thereby holes) in a semiconductor (or all solids) than in gases. Thus, on the average, only 3 eV (approximately) is required to produce a hole electron pair in germanium and 3.7 eV in silicon, while approximately 30 eV is required in gas. The relatively easy production of free holes and electrons in solids results from the close proximity of atoms which causes many electrons to exist at energy levels just below the conduction band. In gases, the atoms are isolated for practical purposes and electrons are relatively tightly bound. The important result is that a given amount of energy absorbed from incident radiation produces more free charges in the solid than in the gas and the statistical fluctuations become a smaller fraction of the total released charge. This is the basic reason for semiconductor detectors yielding better energy

resolution than gas detectors, at least at higher energies. At low energies, the fact that the signal is 10 times larger means that electronic noise in the electronic preamplifier is effectively smaller in relation to the signal.

Next, it is necessary to understand the importance of semiconductor junctions. If we consider a slice of silicon 1 cm^2 in area and 1 mm thick and 2000 Ωcm resistivity with ohmic contacts on each side, it is easy to see that we have a 200 Ω resistor. If 100 V is applied across such a resistor, a current of 0.5 A will flow. Radiation incident on the slice would produce free holes and electrons, but any change in current resulting from this would be infinitesimally small compared with the large steady current flowing through the device. This is in great contrast to the gas ionization chamber whose leakage current is minute. Semiconductor junctions provide the mechanism for overcoming this problem.

Semiconductor junctions are discussed in all courses on semiconductor physics and electronics, but the emphasis is slightly different in semiconductor detectors and matters are, in some respects, simpler. The operation of junctions depends on the fact that a mass action law compels the product of electron and hole concentrations to be constant for a given semiconductor at a fixed temperature. Therefore, heavy doping with a donor not only increases the free electron concentration, but also depresses the hole concentration to satisfy the requirement that the product must have a value dependent only on the semiconductor. For example, for silicon at room temperature $n \cdot p = 10^{16}$; therefore, a region doped with donors to a concentration of 10^{18} will only contain a concentration of $\sim 10^2$ holes.

Figure 1 shows diagrammatically the behavior of a junction in a semiconductor. We have shown a heavily doped n layer on top of a more lightly doped p layer. With no applied bias, as in Fig. 1(a), a few free electrons diffuse across the junction into the p region and holes diffuse into the n region to produce the charge dipole layer shown in Fig. 1(b). This charge distribution results in the potential distribution shown. Therefore, in equilibrium, a self-adjusting potential barrier is created. If reverse bias is now applied to the junction (i.e., positive to the n side as in Fig. 1 (c), the effect is to drive free holes away from the junction on the p side and electrons away from it on the n side. The exposed donor (+) and the acceptor (-) charges which are fixed in the lattice, then produce the charge distribution shown, resulting in the field and potential distributions shown. A region is produced which is free of holes or electrons (to a first approximation) known as the depletion layer. However, a field exists in this region and pairs of holes and electrons produced by radiation are collected to produce a current in the external circuit - this is the basis of a semiconductor detector. Of course, any pairs of electrons and holes produced by thermal processes are also collected - this is the source of bulk leakage current.

The important point is that the leakage current is no longer that of a piece of the raw semiconductor. Instead, it is almost completely the small current caused by thermal generation of carriers in the depletion layer (although surface effects usually are dominant in practical devices). The simple explanation of this result is that the upper contact contains virtually no holes to be pushed downward by the electric field, while the lower contact contains almost no electrons to be dragged up. Therefore, the junction doping almost eliminates leakage for the reverse bias direction.
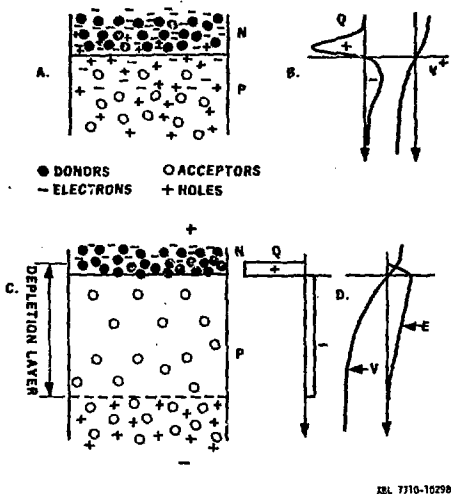
● DONORS   O ACCEPTORS
~ ELECTRONS   + HOLES

XBL 7710-10298

Fig. 1 A. Junction in equil
        B. Charge and potential profiles
        C. Reverse bias
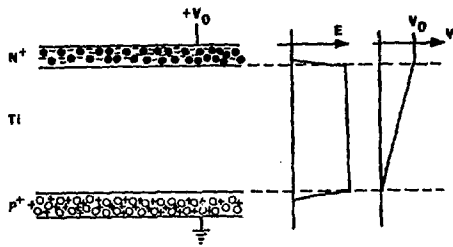   D. Charge, field (E) four potential profiles

XBL 7710-10299

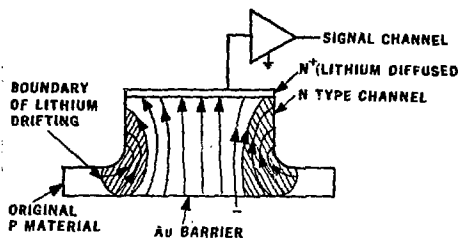Fig. 2 Totally Depleted Detector

Fig. 3 Effect of surface channels
        A. Internal fields in a detector
        B. Effect on background

XBL 7710-10300

A word should be added about totally depleted detectors - that is detectors where the depletion layer exhausts the entire thickness of the detector wafer and penetrates through to the back contact. Such detectors are used frequently as ΔE detectors (i.e., to sample the ionization in a portion of a particle's track) or sometimes as energy detectors (e.g., Li-drifted and high-purity detectors). They range in thickness from a few microns (Si ΔE detectors) to 1.5 cm (Ge detectors used in particle telescopes). From the discussion of the previous paragraph, it is clear that a ΔE or totally depleted detector must consist of two contacts oppositely (heavily) doped with a relatively lightly doped bulk region between, as shown in Fig. 2. Such a detector is sometimes referred to as a p-i-n detector and the contacts are termed blocking contacts. The type of each contact must be such that the bulk electric field drives the contact majority carriers into the contact and away from the bulk. Thus, positive bias is applied to the n^+ contact and negative to the p^+ contact.

In this brief introduction, I can only devote a few words to the subject of surface problems, a factor that has occupied much of the time of detector-makers through the years. It is well known that the electrical behavior of the surface, where the lattice abruptly terminates, can be dominant in determining the leakage current of devices, but the other effects are not so well-known. Depending on the contaminants, surfaces can behave as lightly doped n- or p-type channels. Being lightly doped, they act as very poor junctions to the bulk and are therefore the source of poor leakage characteristics in many diodes. However, they may also produce electric field dis-tortions in the bulk material. Figure 3(a) illus-trates one example of the effect of surface causing background counts in x-ray spectra. Here, the n-type channel on the side of a detector acts as an

extension of the n^+ lithium contact, distorting the field so that charges produced by x rays in the shaded regions are partially collected in the surface where they couple only slowly into the external circuit. This produces partial pulses causing a rather flat background below x-ray peaks in spectra, as shown in Fig. 3(b). The background may constitute as much as 40 percent of the total counts in some x-ray detectors. Analogous effects occur in germanium gamma-ray detec-tors where surface channels can cause loss of efficiency,

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and if the surface conditions change with time, drifts occur in efficiency. Surface channels also constitute an unknown and variable dead layer if charged particles enter through the side surface of a detector, so such a mode of operation should be used with great caution.

Incidentally, we use the guard-ring arrangement shown in Fig. 4 to overcome the background problem in low background x-ray systems. Here the boundaries of the sensitive region which produces external signals are defined by electric field lines in the bulk and surface effects are avoided.
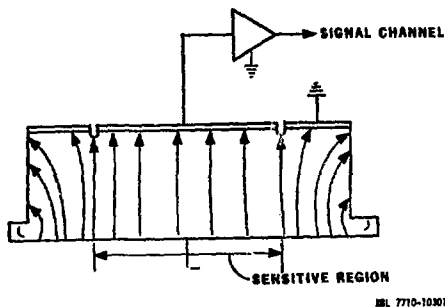

Fig. 4 Guard-ring detector

A final word must be said about coaxial detectors. The coaxial geometry is a very convenient technique for making large volume detectors with relatively small exposed surfaces and with reasonably short carrier collection distances. Therefore, this geometry is dominant in the gamma-ray detection area. In the case of lithium-drifted detectors, the bulk starting material is p-type and drifting is carried out from a lithium diffused layer on the outside surface. Drifting is stopped at a point where a small core of the original p-type material remains; this acts as one electrical contact, while the outer lithium-diffused layer is the other. The core does contribute some slow pulses in the final detector which can be objectionable under some experimental conditions (e.g., very high counting rates). High-purity germanium coax detectors, of necessity, must be fabricated by first removing a core of the material, then making contacts to the inner and outer surfaces. Therefore, no core of "dead" material is present in thr final detector and no slow pulses should occur. Furthermore, we have freedom to choose whether the n^+ or p^+ contact is on the inside. This proves to be useful since radiation damage tends to cause hole trapping and such trapping is less objectionable if electrons are collected at the central contact (i.e., an n^+ central contact). To avoid very high fields near this contact, it is preferable to use n-type bulk material. Therefore, from the point of view of radiation damage, the ideal high-purity coaxial detectors are the inverse of lithium-drifted Ge coaxes. They are made from n-type material and the n^+ contact is on the inner surface. Practically speaking, however, present commercial high-purity coax detectors are not made this way.

III. Material Requirements

The semiconductor detector area imposes some very stringent requirements on the materials that can be used. Later talks will deal with material properties and problems in some detail, since this has been a major factor in detector work. Here, I want to give a brief summary of the required material character-istics and to stress the severity of the material requirements.

One gross comparison can be made to emphasize our problems. Silicon and germanium crystals were de-veloped primarily for use in transistors, most of the development taking place in the late 1940's and until 1960. The active linear size of a modern transistor is in the 20 μm range, so the active volume must be in the range of 10^{-8} cm^3. Even large-scale inte-grated circuits (LSI) contain only a thousand or so active elements so the volume of material actually employed is ~10^{-5} cm^3. Faults in the material that miss the active elements do not affect the performance of such circuits. On the other hand, semiconductor detectors may have volumes as large as 100 cm^3 - a factor of 10^7 greater than an LSI - and any faults in this volume can be catastrophic to the operation of the detector. Furthermore, almost perfect collection of carriers over a distance as big as 2 cm may be required in detectors, while the base layer of a transistor may be only a few μm thick (a ratio of ~10^4). These requirements place very stringent demands on the quality (i.e., crystal perfection, purity, uniformity), compared with materials used for more conventional electronic devices.

More subtle problems are also important. For example, only very minute traces of oxygen can be present in germanium to be used for lithium drifting, since oxygen virtually stops the drift process. Even if lithium drifting is not to be used (as in high-purity detectors), oxygen cannot be tolerated due to the severe carrier trapping it causes. We also know that dislocation-free crystals produce useless germanium detectors - this is believed to be due to traps caused by the divacancies that exist in large quantities in such material. Therefore, germanium crystals grown for use in detectors must contain a uniform, moderate level of dislocations to provide sinks for the vacancies. Also, it has now become evident that hydrogen, included in the germanium be-cause virtually all high-purity germanium crystals are grown in a pure hydrogen atmosphere, plays a major role in the behavior of the germanium. Details of the effects of hydrogen are not yet fully worked out and this is an active area of study at the present time.

In view of these subtle effects in well-charac-terized and relatively simple materials, such as germanium and silicon, it is not surprising that the more complex 3-5 and 2-6 compound semiconductors present very difficult problems. Indeed, it is perhaps surprising that detectors (albeit not good spectrometers) have been made from several of these materials (e.g., GaAs, HgI2, CdTe). In practically all cases, serious trapping of one carrier occurs so the usefulness of the detectors is quite limited.

A final comment on materials must be registered. High-purity germanium (electrically active impurity concentrations ~10^{10}/cm^3) is the purest material ever produced (~1 part in 10^{13}). Despite this, its electrical behavior and detector performance are totally dominated by the minute concentration of impurities - both electrically active ones and others, such as oxygen which causes trapping.

IV. Signal Processing

The development of detectors has been accompanied
by the development of low-noise electronics and
signal processing techniques. These developments have
played a big part in the applications of detectors.
At the end of this course, we will give a brief
review of the electronic parts of detector systems.
For the present, I would like to emphasize that the
right type of electronics is an essential part of a
good detector system and that the design of such
electronics is not black magic, as so many physicists
believe. It is a well understood subject and an
intelligent detector user should be familiar with the
salient features of the signal processing system.