In many radiation detection applications, the use of a solid detection medium is of great advantage. For the measurement of high-energy electrons or gamma rays, detector dimensions can be kept much smaller than the equivalent gas-filled detector because solid densities are some 1000 times greater than that for a gas. Scintillation detectors offer one possibility of providing a solid detection medium, and their application to the detection and measurement of various radiations has been described in Chapter 10.

One of the major limitations of scintillation counters is their relatively poor energy resolution. The chain of events which must take place in converting the incident radiation energy to light and the subsequent generation of an electrical signal involves many inefficient steps. Therefore, the energy required to produce one information carrier (a photoelectron) is of the order of 1000 eV or more, and the number of carriers created in a typical radiation interaction is usually no more than a few thousand. The statistical fluctuations in so small a number place an inherent limitation on the energy resolution that can be achieved under the best of circumstances, and nothing can be done about improving the energy resolution beyond this point. As detailed in Chapter 10, the energy resolution for sodium iodide scintillators is limited to about 6 percent when detecting 0.662 MeV gamma rays, and is largely determined by the photoelectron statistical fluctuations.

The only way to reduce the statistical limit on energy resolution is to increase the number of information carriers per pulse. As we will show in this chapter, the use of semiconductor materials as radiation detectors can result in a much larger number of carriers for a given incident radiation event than is possible with any other detector type. Consequently, the best energy resolution achievable today is realized through the use of such detectors. The basic information carriers are electron-hole pairs created along the path taken by the charged particle (primary radiation or secondary particle) through the detector. The
electron-hole pair is somewhat analogous to the ion pair created in gas-filled detectors. Their motion in an applied electric field generates the basic electrical signal from the detector.

Devices employing semiconductors as the basic detection medium became practically available in the early 1960s. Early versions were called crystal counters, but modern detectors are referred to as semiconductor diode detectors or simply solid-state detectors. Although the latter term is somewhat ambiguous in the sense that technically scintillation counters can also be thought of as solid detectors, it has come into widespread use to characterize only those devices that are based on electron-hole pair collection from semiconductor media.

In addition to superior energy resolution, solid-state detectors can also have a number of other desirable features. Among these are compact size, relatively fast timing characteristics, and an effective thickness which can be varied to match the requirements of the application. Drawbacks may include the limitation to small sizes and the relatively high susceptibility of these devices to performance degradation from radiation-induced damage.

Of the available semiconductor materials, silicon predominates in the diode detectors used primarily for charged particle spectroscopy, which is discussed in this chapter. Germanium is more widely used in ion-drifted detectors for gamma ray measurements described in Chapter 12, whereas devices that use other semiconductor materials are covered in Chapter 13.

Several comprehensive books are available on the topic of solid-state detectors, including Refs. 1-6. Each of these contains a rather complete citation of the literature up to the time of publication, and the references in these chapters will largely be limited to those which have appeared more recently.

I. SEMICONDUCTOR PROPERTIES

A. Band Structure in Solids

The periodic lattice of crystalline materials establishes allowed energy bands for electrons that exist within that solid. The energy of any electron within the pure material must be confined to one of these energy bands which may be separated by gaps or ranges of forbidden energies. A simplified representation of the bands of interest in insulators or semiconductors is shown in Fig. 11-1. The lower band, called the valence band, corresponds to those electrons that are bound to specific lattice sites within the crystal. In the case of silicon or germanium, they are parts of the covalent bonding which constitute the interatomic forces within the crystal. The next higher-lying band is called the conduction band and represents electrons that are free to migrate through the crystal. Electrons in this band contribute to the electrical conductivity of the material. The two bands are separated by the band gap, the size of which determines whether the material is classified as a semiconductor or an insulator. The number of electrons within the crystal is just adequate to completely fill all
available sites within the valence band. In the absence of thermal excitation, both insulators and semiconductors would therefore have a configuration in which the valence band is completely full, and the conduction band completely empty. Under these circumstances, neither would theoretically show any electrical conductivity.

In a metal, the highest occupied energy band is not completely full. Therefore, electrons can easily migrate throughout the material because they need achieve only small incremental energy to be above the occupied states. Metals, therefore, are always characterized by very high electrical conductivity. In insulators or semiconductors, on the other hand, the electron must first cross the band gap in order to reach the conduction band and the conductivity is therefore many orders of magnitude lower. For insulators, the band gap is usually 5 eV or more, whereas for semiconductors, the gap is considerably less.

B. Charge Carriers

At any nonzero temperature, some thermal energy is shared by the electrons in the crystal. It is possible for a valence electron to gain sufficient thermal energy to be elevated across the band gap into the conduction band. Physically, this process simply represents the excitation of an electron which is normally part of a covalent bond such that it can leave the specific bonding site and drift throughout the crystal. The excitation process not only creates an electron in the otherwise empty conduction band, but it also leaves a vacancy (called a hole) in the otherwise full valence band. The combination of the two is called an electron-hole pair and is roughly the solid-state analog of the ion pair in gases. The electron in the conduction band can be made to move under the influence of an applied electric field. The hole, representing a net positive charge, will also tend to move in an electric field, but in a direction opposite that of the electron. The motion of both of these charges contributes to the observed conductivity of the material.
The probability per unit time that an electron-hole pair is thermally generated is given by

\[ p(T) = C T^{3/2} \exp\left( - \frac{E_g}{2kT} \right) \]  

(11-1)

where

\[ T = \text{absolute temperature} \]
\[ E_g = \text{bandgap energy} \]
\[ k = \text{Boltzmann constant} \]
\[ C = \text{proportionality constant characteristic of the material} \]

As reflected in the exponential term, the probability of thermal excitation is critically dependent on the ratio of the band gap energy to the absolute temperature. Materials with a large band gap will have a low probability of thermal excitation, and consequently will show the very low electrical conductivity characteristic of insulators. If the band gap is as low as several electron volts, sufficient thermal excitation will cause a conductivity high enough for the material to be classified as a semiconductor. In the absence of an applied electric field, the thermally created electron-hole pairs ultimately recombine, and an equilibrium is established in which the concentration of electron-hole pairs observed at any given time is proportional to the rate of formation. From Eq. 11-1, this equilibrium concentration is a strong function of temperature and will decrease drastically if the material is cooled.*

C. Migration of Charge Carriers in an Electric Field

If an electric field is applied to the semiconductor material, both the electrons and holes will undergo a net migration. The motion will be the combination of a random thermal velocity and a net drift velocity parallel to the direction of the applied field. The motion of the conduction electrons is a relatively easy process to visualize, but the fact that holes also contribute to conductivity is less obvious. A hole moves from one position to another if an electron leaves a normal valence site to fill an existing hole. The vacancy left behind by the electron then represents the new position of the hole. Because electrons will always be drawn preferentially in an opposite direction to the electric field vector, holes move in the same direction as the electric field. This behavior is consistent with that expected of a point positive charge, because the hole actually represents the absence of a negatively charged electron.

At low-to-moderate values of the electric field intensity, the drift velocity \( v \) is proportional to the applied field. Then a mobility \( \mu \) for both electrons and holes

*Because the ionization potential for gases is typically 15 eV or more, the probability of a thermally generated ion pair is negligibly small in gas ionization chambers, even at room temperature.
can be defined by

\[ v_h = \mu_h \mathcal{E} \]  

\[ v_e = \mu_e \mathcal{E} \]

where \( \mathcal{E} \) is the electric field magnitude. In gases, the mobility of the free electron is much larger than that of the positive ion, but in semiconductor materials the mobility of the electron and hole are roughly of the same order. Numerical values for common semiconductor materials are given in Table 11-1.

At higher electric field values, the drift velocity increases more slowly with the field. Eventually, a saturation velocity is reached which becomes independent of further increases in the electric field. Figures 11-2a to 11-2d show the dependence of the drift velocity on field magnitude for silicon and germanium.

<table>
<thead>
<tr>
<th>TABLE 11-1. Properties of Intrinsic Silicon and Germanium</th>
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<tbody>
<tr>
<td><strong>Si</strong></td>
</tr>
<tr>
<td><strong>Atomic number</strong></td>
</tr>
<tr>
<td><strong>Atomic weight</strong></td>
</tr>
<tr>
<td><strong>Stable isotope mass numbers</strong></td>
</tr>
<tr>
<td><strong>Density (300 K); g cm(^{-3})</strong></td>
</tr>
<tr>
<td><strong>Atoms cm(^{-3})</strong></td>
</tr>
<tr>
<td><strong>Dielectric constant</strong></td>
</tr>
<tr>
<td><strong>Forbidden energy gap (300 K); eV</strong></td>
</tr>
<tr>
<td><strong>Forbidden energy gap (0 K); eV</strong></td>
</tr>
<tr>
<td><strong>Intrinsic carrier density (300 K); cm(^{-3})</strong></td>
</tr>
<tr>
<td><strong>Intrinsic resistivity (300 K); (\Omega\text{cm})</strong></td>
</tr>
<tr>
<td><strong>Electron mobility (300 K); cm(^2)/V-s</strong></td>
</tr>
<tr>
<td><strong>Hole mobility (300 K); cm(^2)/V-s</strong></td>
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<tr>
<td><strong>Electron mobility (77 K); cm(^2)/V-s</strong></td>
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<tr>
<td><strong>Hole mobility (77 K); cm(^2)/V-s</strong></td>
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<tr>
<td><strong>Energy per hole-electron pair (300 K); eV</strong></td>
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<td><strong>Energy per hole-electron pair (77 K); eV</strong></td>
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<tr>
<td><strong>Fano factor (77 K)</strong></td>
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<td><strong>Energy per hole-electron pair (77 K); eV</strong></td>
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<td><strong>Energy per hole-electron pair (77 K); eV</strong></td>
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<td><strong>Energy per hole-electron pair (77 K); eV</strong></td>
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<td><strong>Energy per hole-electron pair (77 K); eV</strong></td>
</tr>
</tbody>
</table>

Many semiconductor detectors are operated with electric field values sufficiently high to result in saturated drift velocity for the charge carriers. Because these saturated velocities are of the order of $10^7$ cm/s, the time required to collect the carriers over typical dimensions of 0.1 cm or less will be under 10 nanoseconds. Semiconductor detectors can therefore be among the fastest-responding of all radiation detector types.
D. Effect of Impurities or Dopants

1. INTRINSIC SEMICONDUCTORS
In a completely pure semiconductor, all the electrons in the conduction band and all the holes in the valence band would be caused by thermal excitation (in the absence of ionizing radiation). Because under these conditions each electron
must leave a hole behind, the number of electrons in the conduction band must exactly equal the number of holes in the valence band. Such material is called an *intrinsic* semiconductor. Its properties can be described theoretically, but in practice it is virtually impossible to achieve. The electrical properties of real materials tend to be dominated by the very small levels of residual impurities; this is true even for silicon and germanium, which are the semiconductors available in the highest practical purities.

In the discussions that follow, we will let \( n \) represent the concentration (number per unit volume) of electrons in the conduction band. Also \( p \) will represent the concentration of holes in the valence band. In the intrinsic material (subscript \( i \)), the equilibrium which is established by the thermal excitation of electrons from the valence to conduction band and their subsequent recombination leads to equal numbers of electrons and holes, or

\[
n_i = p_i \tag{11-4}
\]

The quantities \( n_i \) and \( p_i \) are known as the intrinsic carrier densities. From Eq. 11-1, it is clear that these densities will be lowest for materials with large bandgap energy, and when the material is used at low temperature. Intrinsic hole or electron densities at room temperature are \( 1.5 \times 10^{10} \text{ cm}^{-3} \) in silicon, and \( 2.4 \times 10^{13} \text{ cm}^{-3} \) in germanium.

2. *n*-TYPE SEMICONDUCTORS

To illustrate the effect of doping on semiconductor properties, we will use crystalline silicon as an example. Germanium and other semiconductor materials behave in a similar way. Silicon is tetravalent and in the normal crystalline structure forms covalent bonds with the four nearest silicon neighbor atoms. A sketch of this situation is shown in Fig. 11-3a where each of the dashes represents a normal valence electron involved in a covalent bond. Thermal excitation in the intrinsic material consists of breaking loose one of these covalent electrons, leaving behind an unsaturated bond or hole.

We now consider the effect of the small concentration of impurity which may be present in the semiconductor either as a residual amount after the best purification processes, or as a small amount intentionally added to the material to tailor its properties. We first assume that the impurity is pentavalent, or is found in Group V of the periodic table. When present in small concentrations (of the order of a few parts per million or less) the impurity atom will occupy a substitutional site within the lattice, taking the place of a normal silicon atom. Because there are five valence electrons surrounding the impurity atom, there is one left over after all covalent bonds have been formed. This extra electron is somewhat of an orphan and remains only very lightly bound to the original impurity site. It therefore takes very little energy to dislodge it to form a conduction electron without a corresponding hole. Impurities of this type are referred to as *donor impurities* because they readily contribute electrons to the
conduction band. Because they are not part of the regular lattice, the extra electrons associated with donor impurities can occupy a position within the normally forbidden gap. These very loosely bound electrons will have an energy near the top of the gap as shown in Fig. 11-3b. The energy spacing between these donor levels and the bottom of the conduction band is sufficiently small so that the probability of thermal excitation given by Eq. 11-1 is high enough to ensure that a large fraction of all the donor impurities are ionized. In nearly all cases, the concentration of impurity $N_D$ is large compared with the concentration of electrons expected in the conduction band for the intrinsic material.
Therefore, the number of conduction electrons becomes completely dominated by the contribution from the donor impurities, and we can write

\[ n \approx N_D \]  

(11-5)

The added concentration of electrons in the conduction band compared with the intrinsic value increases the rate of recombination, shifting the equilibrium between electrons and holes. As a result, the equilibrium concentration of holes is decreased by an amount such that the equilibrium constant given by the product of \( n \) and \( p \) is the same as for the intrinsic material

\[ np = n_i p_i \]  

(11-6)

For example, in room temperature silicon, the intrinsic carrier densities are about \( 10^{10} \) cm\(^{-3} \). If a donor impurity is present at a concentration of \( 10^{17} \) atoms per cm\(^3 \) (about 2 parts per million), the density of conduction electrons \( n \) will be \( 10^{17} \) cm\(^{-3} \) and the concentration of holes \( p \) will be \( 10^3 \) cm\(^{-3} \).

Even though conduction electrons now greatly outnumber the holes, charge neutrality is maintained because of the presence of ionized donor impurities. These sites represent net positive charges which exactly balance the excess electron charges. They are not, however, to be confused with holes because the ionized donors are fixed in the lattice and cannot migrate.

The net effect in n-type material is therefore to create a situation in which the number of conduction electrons is much greater and the number of holes much smaller than in the pure material. The electrical conductivity is then determined almost exclusively by the flow of electrons, and holes play a very small role. In this case, the electrons are called the majority carriers and holes the minority carriers.

3. p-TYPE SEMICONDUCTORS

The addition of a trivalent impurity such as an element from Group III of the periodic table to a silicon lattice results in a situation sketched in Fig. 11-4a. If the impurity occupies a substitutional site, it has one fewer valence electron than the surrounding silicon atoms and therefore one covalent bond is left unsaturated. This vacancy represents a hole similar to that left behind when a normal valence electron is excited to the conduction band, but its energy characteristics are slightly different. If an electron is captured to fill this vacancy, it participates in a covalent bond that is not identical to the bulk of the crystal because one of the two participating atoms is a trivalent impurity. An electron filling this hole, although still bound to a specific location, is slightly less firmly attached than a typical valence electron. Therefore, these acceptor impurities also create electron sites within the normally forbidden energy gap. In this case, the acceptor levels lie near the bottom of the gap because their properties are quite close to sites occupied by normal valence electrons.
Normal thermal excitation in the crystal assures that there will always be some electrons available to fill the vacancies created by the acceptor impurities, or to occupy the acceptor sites shown in Fig. 11-4b. Because the energy difference between typical acceptor sites and the top of the valence band is small, a large fraction of all the acceptor sites are filled by such thermally excited electrons. These electrons come from other normal covalent bonds throughout the crystal and therefore leave holes behind in the valence band. To a good approximation, an extra hole is created in the valence band for every acceptor impurity which is added. If the concentration $N_A$ of acceptor impurities is made to be large compared with the intrinsic concentration of holes $p_i$, then
the number of holes is completely dominated by the concentration of acceptors, or

\[ p \approx N_A \]  

(11-7)

The increased availability of holes enhances the recombination probability between conduction electrons and holes, and therefore decreases the equilibrium number of conduction electrons. Again, the same equilibrium constant discussed earlier holds, and \( np = n_p n_p \). In \( p \)-type material, holes are the majority carrier and dominate the electrical conductivity. The filled acceptor sites represent fixed negative charges which balance the positive charge of the majority holes.

One measure of the impurity level of semiconductor materials is the electrical conductivity, or its inverse, the resistivity. The resistivity of the intrinsic material, in which all charge carriers are created by thermal excitation, can be predicted from Eq. 11-1. The corresponding values for silicon and germanium are listed in Table 11-1. In practice, these theoretical values of resistivity are never observed because of the unavoidable residual impurities. Using the most advanced purification methods available at this writing, silicon resistivity of about 50,000 \( \Omega \cdot \text{cm} \) can be achieved, compared with a theoretical value of over 200,000 \( \Omega \cdot \text{cm} \).

At room temperature, the influence of impurities on resistivity is much more pronounced for silicon than for germanium. Thermally excited electron hole pairs are much more common in germanium because of its lower band gap energy, and therefore a greater concentration of impurity is required to significantly change the intrinsic resistivity. For example, in silicon an impurity concentration of \( 10^{13} \) atoms per \( \text{cm}^3 \) for \( p \)-type material corresponds to a resistivity of about 500 \( \Omega \cdot \text{cm} \) (Ref. 3), markedly below the intrinsic resistivity of over \( 10^5 \) \( \Omega \cdot \text{cm} \). The same impurity concentration in germanium results in resistivities of 50 \( \Omega \cdot \text{cm} \) for \( p \)-type material and 15 \( \Omega \cdot \text{cm} \) for \( n \)-type germanium, not greatly reduced from the intrinsic value of 50 \( \Omega \cdot \text{cm} \). On the other hand, if germanium is cooled to liquid nitrogen temperature, the increased intrinsic resistivity is changed by a much greater factor by the same impurity concentration.

4. COMPENSATED MATERIAL

If donor and acceptor impurities are present in a semiconductor in equal concentration, the material is said to be compensated. Such material has some of the properties of an intrinsic semiconductor because electrons contributed by donor impurities are removed to some extent by their capture at the site of acceptor impurities. Despite the potential confusion with purified intrinsic material, compensated regions in semiconductors are commonly given the designation \( i \) because of their near intrinsic properties.

In practice, it is impossible to achieve exact compensation at the time of fabrication of the doped material because any small imbalance in the acceptor
or donor concentration quickly leads to \( n \)-type or \( p \)-type behavior. At present, the only practical means for achieving compensation over large volumes in silicon or germanium is through the lithium ion drifting process after the crystal has been fabricated. This important procedure is discussed in Chapter 12.

5. HEAVILY DOPED MATERIAL

Thin layers of semiconductor material that have an unusually high concentration of impurity are often given a special notation. Thus \( n^+ \) and \( p^+ \) designate heavily doped \( n \)- and \( p \)-type layers which, as a result, have very high conductivity. These layers are often used in making electrical contact with semiconductor devices, because the very low minority carrier density allows their application as “blocking” contacts described later in this chapter.

E. Trapping and Recombination

Once electrons and holes are formed in a semiconductor, they will tend to migrate either spontaneously or under the influence of an applied electric field until they are either collected at an electrode or recombination takes place. There are theoretical predictions\(^{15}\) that the average lifetime of charge carriers before recombination in perfectly pure semiconductors could be as large as a second. In practice, lifetimes at least three or four orders of magnitude smaller than a second are actually observed which are dominated entirely by the very low level of impurities remaining in the material. Some of these impurities, such as gold, zinc, cadmium, or other metallic atoms occupying substitutional lattice positions, introduce energy levels near the middle of the forbidden gap. They are therefore classified as “deep impurities” (as opposed to acceptor or donor impurities which, because the corresponding energy levels lie near the edges of the forbidden band, are called “shallow impurities.”) These deep impurities can act as traps for charge carriers in the sense that if a hole or electron is captured, it will be immobilized for a relatively long period of time. Although the trapping center ultimately may release the carrier back to the band from which it came, the time delay is often sufficiently long to prevent that carrier from contributing to the measured pulse.

Other types of deep impurities can act as recombination centers. These impurities are capable of capturing both majority and minority carriers, causing them to annihilate. An impurity level near the center of the forbidden gap might, for example, first capture a conduction electron. At a slightly later time, a hole from the valence band might also be captured, with the electron then filling the hole. The impurity site is thus returned to its original state and is capable of causing another recombination event. In most crystals, recombination through such centers is far more common than direct recombination of electrons and holes across the full band gap.

Both trapping and recombination contribute to the loss of charge carriers and tend to reduce their average lifetime in the crystal. For the material to serve as a
good radiation detector, a large fraction (preferably 100 percent) of all the carriers created by the passage of the incident radiation should be collected. This condition will hold provided the collection time for the carriers is short compared with their mean lifetime. Collection times of the order of $10^{-7}$ to $10^{-8}$ s are fairly common, so that carrier lifetimes of the order of $10^{-5}$ s or longer are usually sufficient.

Another widely quoted specification is the *trapping length* within the material. This quantity is simply the mean distance traveled by a carrier before trapping or recombination, and is given by the product of the mean lifetime and the average drift velocity. In order to have an acceptable detector, the trapping length should be long compared with the physical dimensions over which the charge must be collected.

In addition to impurities, structural defects within the crystal lattice can also lead to trapping and charge carrier loss. These imperfections include point defects such as vacancies or interstitials which tend to behave as acceptors or donors, respectively. Carrier loss may also occur at line defects or dislocations which may be produced in crystals that have been stressed. A dislocation represents the slippage of one crystal plane with respect to another, and its intersection with the surface of the crystal leads to a pit upon chemical etching. The density of these etched pits is often quoted as a measure of the crystalline perfection of a semiconductor sample.

**II. THE ACTION OF IONIZING RADIATION IN SEMICONDUCTORS**

**A. The “Ionization Energy”**

When a charged particle passes through a semiconductor with the band structure shown in Fig. 11-1, 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 “delta rays”) which subsequently lose their energy in producing more electron-hole pairs. Regardless of the detailed mechanisms involved, the quantity of practical interest for detector applications is the average energy expended by the primary charged particle to produce one electron-hole pair. This quantity, often loosely called the “ionization energy” and given the symbol $\epsilon$, is experimentally observed to be largely independent of both the energy and type of the incident radiation. This important simplification allows interpretation of the number of electron-hole pairs produced in terms of the incident energy of the radiation, provided the particle is fully stopped within the active volume of the detector.

The dominant advantage of semiconductor detectors lies in the smallness of the ionization energy. The value of $\epsilon$ for either silicon or germanium is about 3 eV (see Table 11-1), compared with about 30 eV required to create an ion pair in typical gas-filled detectors. Thus, the number of charge carriers is 10 times
greater for the semiconductor case, for a given energy deposited in the detector. The increased number of charge carriers has two beneficial effects on the attainable energy resolution. The statistical fluctuation in the number of carriers per pulse becomes a smaller fraction of the total as the number is increased. This factor often is predominant in determining the limiting energy resolution of a detector for medium to high radiation energy. At low energies, the resolution may be limited by electronic noise in the preamplifier, and the greater amount of charge per pulse leads to a better signal/noise ratio.

More detailed examination shows that \( \epsilon \) depends on the nature of the incident radiation. Most detector calibrations are carried out using alpha particles, and the values for \( \epsilon \) shown in Table 11-1 are based on this mode of excitation. All experimental values obtained using other light ions or fast electrons seem to be fairly close\(^{16-18} \), but differences as large as 2.2 percent have been reported\(^ {19} \) between proton and alpha particle excitation in silicon. These observed differences point up the need to carry out detector calibration using a radiation type which is identical to that involved in the measurement itself if precise energy values are required.

A much larger difference is measured for \( \epsilon \) when heavy ions or fission fragments are involved. The value of \( \epsilon \) is significantly higher than for alpha particle excitation, leading to a lower than anticipated number of charge carriers. The physical origins of this pulse height defect are discussed later in this chapter.

The ionization energy is also temperature dependent. For the most significant detector materials, the value of \( \epsilon \) increases with decreasing temperature. As shown in Table 11-1, \( \epsilon \) in silicon is about 3 percent greater at liquid nitrogen temperature compared with room temperature\(^ {17} \).

B. The Fano Factor

In addition to the mean number, the fluctuation or variance in the number of charge carriers is also of primary interest because of the close connection of this parameter with energy resolution of the detector. As in gas counters, the observed statistical fluctuations in semiconductors are smaller than expected if the formation of the charge carriers were a Poisson process. The Poisson model would hold if all events along the track of the ionizing particle were independent, and would predict that the variance in the total number of electron-hole pairs should be equal to the total number produced, or \( \frac{E}{\epsilon} \). The Fano factor \( F \) is introduced as an adjustment factor to relate the observed variance to the Poisson predicted variance

\[
F = \frac{\text{observed statistical variance}}{\frac{E}{\epsilon}}
\]

(11-8)

For good energy resolution, one would like the Fano factor to be as small as
possible. Although a complete understanding of all the factors that lead to a nonunity value for $F$ does not yet exist, rather sophisticated models have been developed\textsuperscript{20} which at least qualitatively account for experimental observations. Some numerical values for silicon and germanium are given in Table 11-1.

There is considerable variation in reported experimental values, particularly for silicon. The Fano factor is usually measured by observing the energy resolution from a given detector under conditions in which all other factors that can broaden the full-energy peak (such as noise or drift) can be eliminated. The assumption is then made that the residual width can be attributed to statistical effects only. If nonstatistical residual factors remain, however, the Fano factor will appear to be larger than it actually is. This may explain the historical trend toward lower values as measurement procedures are refined.

### III. SEMICONDUCTORS AS RADIATION DETECTORS

#### A. Electrical Contacts

In order to construct a practical radiation detector, some means must be provided to collect the electrical charges created by the radiation at either boundary of the semiconductor material. An ohmic contact is a nonrectifying electrode through which charges of either sign can flow freely. If two ohmic contacts are fitted on opposite faces of a slab of semiconductor and connected to a detection circuit, the equilibrium charge carrier concentrations in the semiconductor will be maintained. If an electron or hole is collected at one electrode, the same carrier species is injected at the opposite electrode to maintain the equilibrium concentrations in the semiconductor.

The steady-state leakage currents that are observed using ohmic contacts are too high, even with the highest resistivity material available (see following section), to permit their general application to semiconductor detectors. Instead, noninjecting or blocking electrodes are universally employed to reduce the magnitude of the current through the bulk of the semiconductor. If blocking electrodes are used, charge carriers initially removed by the application of an electric field are not replaced at the opposite electrode, and their overall concentration within the semiconductor will drop after application of an electric field. The leakage current can thus be reduced to a sufficiently low value to allow the detection of the added current pulse created by the electron-hole pairs produced along the track of an ionizing particle.

The most appropriate type of blocking contacts are the two sides of a $p$-$n$ semiconductor junction. It is very difficult to inject electrons from the $p$ side of this junction because holes are the majority carrier and free electrons are relatively scarce. At the opposite side, electrons are the majority carrier and holes cannot readily be injected. In this chapter, we will discuss detectors that are created by placing the $p$- and $n$-type materials in direct contact, forming a $p$-$n$ junction. In the Chapters 12 and 13, detectors in which the $p$ and $n$ regions are separated by an intrinsic or compensated region (the $i$ region) are described.
B. Leakage Current

In order to create an electric field large enough to efficiently collect the charge carriers from any semiconductor detector, an applied voltage of typically hundreds or thousands of volts must be imposed across the active volume. Even in the absence of ionizing radiation, all detectors will show some finite conductivity and therefore a steady-state leakage current will be observed. Random fluctuations that inevitably occur in the leakage current will tend to obscure the small signal current that momentarily flows following an ionizing event, and represent a significant source of noise in many situations. Methods of reducing the leakage current are therefore an important consideration in the design of semiconductor detectors.

The resistivity of the highest purity silicon currently available is about 50,000 \( \Omega \cdot \text{cm} \). If a 1 mm thick slab of this silicon were cut with 1 \( \text{cm}^2 \) surface area and fitted with ohmic contacts, the electrical resistance between faces would be 5000 \( \Omega \). An applied voltage of 500 V would therefore cause a leakage current through the silicon of 0.1 A. In contrast, the peak current generated by a pulse of \( 10^5 \) radiation-induced charge carriers would only be about \( 10^{-6} \) A. It is therefore essential to greatly reduce this bulk leakage current through the use of blocking contacts. In critical applications, the leakage current must not exceed about \( 10^{-9} \) A to avoid significant resolution degradation.

At these levels, leakage across the surface of the semiconductor can often become more significant than bulk leakage. Great care is taken in the fabrication of semiconductor detectors to avoid contamination of the surfaces which could create leakage paths. Some configurations may also use grooves in the surface or guard rings to help suppress surface leakage (see Chapter 5).

C. The Semiconductor Junction

1. BASIC JUNCTION PROPERTIES

The radiation detectors described in this chapter are based on the favorable properties which are created near the junction between \( n \)- and \( p \)-type semiconductor materials. Charge carriers are able to migrate across the junction if the regions are brought together in good thermodynamic contact. Simply pressing together two pieces of the material will not suffice because gaps will inevitably be left which will be large compared with the interatomic lattice spacing. In practice, the junction is therefore normally formed in a single crystal by causing a change in the impurity content from one side of the junction to the other.

As an illustration, assume that the process begins with a \( p \)-type crystal that has been doped with a uniform concentration of acceptor impurity. In the concentration profile at the top of Fig. 11-5, this original acceptor concentration \( N_A \) is shown as a horizontal line. We now assume that the surface of the crystal on the left is exposed to a vapor of an \( n \)-type impurity which diffuses some distance into the crystal. The resulting donor impurity profile is labeled \( N_D \) on the figure, and falls off as a function of distance from the surface. Near the
FIGURE 11-5. The assumed concentration profiles for the $n-p$ junction shown at the top are explained in the text. The effects of carrier diffusion across the junction give rise to the illustrated profiles for space charge $\rho(x)$, electric potential $\varphi(x)$, and electric field $E(x)$. 
surface, the donor impurities can be made to outnumber the acceptors, converting the left portion of the crystal to \( n \)-type material.

The approximate variation of equilibrium charge carrier concentration is also plotted at the top of Fig. 11-5 and labeled as \( p \) (hole concentration) and \( n \) (conduction electron concentration). These profiles are subsequently altered in the vicinity of the \( p-n \) junction due to the effects of charge carrier diffusion. In the \( n \)-type region at the left, the density of conduction electrons is much higher than in \( p \)-type. The junction between the two regions therefore represents a discontinuity in the conduction electron density. Wherever such a sharp gradient exists for any carrier that is free to migrate, a net diffusion from regions of high concentration to those of low concentration must take place. Therefore, there will be some net diffusion of conduction electrons into the \( p \)-type material, where they will quickly combine with holes. In effect, this annihilation represents the capture of the conduction electron by one of the vacancies existing in the covalent bonds in the \( p \)-type material. The diffusion of conduction electrons out of the \( n \)-type material leaves behind immobile positive charges in the form of ionized donor impurities. A similar and symmetric argument leads to the conclusion that holes (the majority in the \( p \)-type material) must also diffuse across the junction because they also see an abrupt density gradient. Each hole that is removed from the \( p \) side of the junction leaves behind an acceptor site which has picked up an extra electron, and therefore represents a fixed and immobile negative charge. The combined effect is to build up a net negative space charge on the \( p \) side and a positive space charge on the \( n \) side of the junction.

The accumulated space charge creates an electric field that diminishes the tendency for further diffusion. At equilibrium, the field is just adequate to prevent additional net diffusion across the junction, and a steady-state charge distribution is therefore established.

The region over which the charge imbalance exists is called the depletion region and extends into both the \( p \) and \( n \) sides of the junction. If the concentration of donors on the \( n \) side and acceptors on the \( p \) side are equal, the diffusion conditions are approximately the same for both holes and electrons, and the depletion region extends equal distances into both sides. Usually, however, there is a marked difference in the doping levels on one side of the junction compared with the other. For example, if the donor concentration in the \( n \)-type material is higher than that of acceptor atoms in the \( p \)-type, the electrons diffusing across the junction will tend to travel a greater distance into the \( p \)-type material before all have recombined with holes. In this case, the depletion region would extend farther into the \( p \) side.

The buildup of net charge within the region of the junction leads to the establishment of an electric potential difference across the junction. The value of the potential \( \phi \) at any point can be found by solution of Poisson’s equation

\[
\nabla^2 \phi = -\frac{\rho}{\epsilon} \quad (11-9)
\]
where \( \varepsilon \) is the dielectric constant of the medium, and \( \rho \) is the net charge density.

In one dimension, Eq. 11-9 takes the form

\[
\frac{d^2\varphi}{dx^2} = -\frac{\rho(x)}{\varepsilon}
\]  

(11-10)

so that the shape of the potential across the junction can be obtained by twice integrating the charge distribution profile \( \rho(x) \). Graphical examples are shown in Fig. 11-5. At equilibrium, the potential difference across the junction (called the “contact potential”) amounts to nearly the full band gap value of the semiconductor material. The direction of this potential difference is such that it opposes the further diffusion of electrons from left to right and holes from right to left in Fig. 11-5.

Where a difference in electrical potential exists, there must also be an electric field \( \vec{E} \). Its magnitude is found by taking the gradient of the potential

\[
\vec{E} = -\text{grad} \varphi
\]  

(11-11)

which, in one dimension, is simply

\[
E(x)=-\frac{d\varphi}{dx}
\]  

(11-12)

The electric field will extend over the width of the depletion region, in which charge imbalance is significant and the potential has some gradient. Its variation is also sketched in Fig. 11-5.

The depletion region exhibits some very attractive properties as a medium for the detection of radiation. The electric field which exists causes any electrons created in or near the junction to be swept back toward the \( n \)-type material, and any holes are similarly swept toward the \( p \)-type side. The region is thus “depleted” in that the concentration of holes and electrons is greatly suppressed.* The only significant charges remaining in the depletion region are the immobile ionized donor sites and filled acceptor sites. Because these latter charges do not contribute to conductivity, the depletion region exhibits a very high resistivity compared with the \( n \)- and \( p \)-type materials on either side of the junction. Electron-hole pairs which are created within the depletion region by the passage of radiation will be swept out of the depletion region by the electric field, and their motion constitutes a basic electrical signal.

2. REVERSE BIASING

Thus far, we have discussed a semiconductor diode junction to which no external voltage is applied. Such an unbiased junction will function as a detector, but only with very poor performance. The contact potential of about 1 V which is formed spontaneously across the junction is inadequate to generate

*The carrier density remaining in the depletion region of practical silicon detectors is as low as 100 electrons or holes per cm\(^3\), compared with typical carrier densities of about \( 10^{10} \) in high resistivity material.
FIGURE 11-6. (a) The variation of electric potential across an $n$-$p$ junction from Fig. 4 11-5; (b) The resulting variation in electron energy bands across the junction. The curvature is reversed because an increase in electron energy corresponds to a decrease in conventional electric potential $\phi(x)$ defined for a positive charge; (c) The added displacement of the bands caused by application of a reverse bias $V$ across the junction.
a large enough electric field to make the charge carriers move very rapidly. Therefore, charges can be readily lost due to trapping and recombination, and incomplete charge collection often results. The thickness of the depletion region is quite small, and the capacitance of an unbiased junction is high. Therefore, the noise properties of an unbiased junction connected to the input stage of a preamplifier are quite poor. For these reasons, unbiased junctions are not used as practical radiation detectors, but instead, an external voltage is applied in the direction to cause the semiconductor diode to be reverse biased.

The \( p-n \) junction is most familiar in its role as a diode. The properties of the junction are such that it will readily conduct current when voltage is applied in the “forward” direction, but it will conduct very little current when biased in the “reverse” direction. In the configuration of Fig. 11-5, first assume that a positive voltage is applied to the \( p \) side of the junction with respect to the \( n \) side. The potential will tend to attract conduction electrons from the \( n \) side as well as holes from the \( p \) side across the junction. Because, in both cases, these are the majority carriers, conductivity through the junction is greatly enhanced. The contact potential shown in Fig. 11-5 is reduced by the amount of the bias voltage that is applied, which tends to lessen the potential difference seen by an electron from one side of the junction to the other. This is the direction of forward biasing, and only small values of the forward bias voltage are needed to cause the junction to conduct large currents.

If the situation is reversed, and the \( p \) side of the junction is made negative with respect to the \( n \) side, the junction is reversed biased. Now the natural potential difference from one side of the junction to the other is enhanced, as shown in Fig. 11-6c. Under these circumstances, it is the minority carriers (holes on the \( n \) side and electrons on the \( p \) side) which are attracted across the junction and, because their concentration is relatively low, the reverse current across the diode is quite small. Therefore, the \( p-n \) junction serves as a rectifying element, allowing relatively free flow of current in one direction while presenting a large resistance to its flow in the opposite direction. If the reverse bias is made very large, a sudden breakdown in the diode will occur and the reverse current will abruptly increase, often with destructive effects.

3. PROPERTIES OF THE REVERSE BIASED JUNCTION

When a reverse bias is applied to the junction, virtually all the applied voltage will appear across the depletion region, because its resistivity is much higher than that of the normal \( n- \) and \( p \)-type material. Because the effect of the reverse bias is to accentuate the potential difference across the junction, Poisson’s equation (Eq. 11-9) demands that space charge must also increase and extend a greater distance on either side of the junction. Thus, the thickness of the depletion region is also increased, extending the volume over which radiation-produced charge carriers will be collected. Practical detectors are almost always operated with a bias voltage that is very large compared with the contact
potential, so that the applied voltage completely dominates the magnitude of the potential difference across the junction.

Some properties of the reverse biased junction can be derived if we represent the charge distribution sketched in Fig. 11-5 by the idealized distribution shown below:

\[
\rho(x) = \begin{cases} 
  eN_D & (-a < x < 0) \\
  -eN_A & (0 < x < b)
\end{cases}
\]

Here the electron diffusion is assumed to result in a uniform positive space charge (the ionized donor sites) over the region \(-a < x \leq 0\) on the n-side of the junction. A corresponding negative space charge (the filled acceptor sites) resulting from hole diffusion is assumed to extend over the region \(0 < x < b\) on the p-side. Because the net charge must be zero, \(N_D a = N_A b\).

Equation 11-10 applied to this case takes the form:

\[
\frac{d^2 \varphi}{dx^2} = \begin{cases} 
  -\frac{eN_D}{\varepsilon} & (-a < x < 0) \\
  +\frac{eN_A}{\varepsilon} & (0 < x < b)
\end{cases}
\]

We now carry out an integration and apply the boundary conditions that the electric field \(\vec{E} = -(d\varphi/dx)\) must vanish at both edges of the charge distribution:

\[
\frac{d\varphi}{dx}(-a) = 0 \quad \text{and} \quad \frac{d\varphi}{dx}(b) = 0
\]

The result is then:

\[
\frac{d\varphi}{dx} = \begin{cases} 
  -\frac{eN_D}{\varepsilon} (x + a) & (-a < x < 0) \\
  +\frac{eN_A}{\varepsilon} (x - b) & (0 < x < b)
\end{cases}
\]
The corresponding shape of the electric field \( \xi = - \left( \frac{d\phi}{dx} \right) \) is sketched below:

Another integration will now yield the electric potential \( \varphi(x) \). The difference in potential from the n-side to the p-side of the junction, if we neglect the relatively small contact potential, is just the value of the applied reverse bias \( V \). We can therefore apply the boundary conditions:

\[
\varphi(-a) = V \quad \text{and} \quad \varphi(b) = 0
\]

The solution then takes the form:

\[
\varphi(x) = \begin{cases} 
- \frac{eN_D}{2\epsilon} (x + a)^2 + V & (-a < x \leq 0) \\
+ \frac{eN_A}{2\epsilon} (x - b)^2 & (0 < x < b)
\end{cases}
\]

Since the solutions for either side of the junction must match at \( x = 0 \), we can write:

\[
V - \frac{eN_D a^2}{2\epsilon} = \frac{eN_A b^2}{2\epsilon}
\]

or:

\[
N_A b^2 + N_D a^2 = \frac{2\epsilon V}{e}
\]

Now since \( N_D a = N_A b \), the expression above can be rewritten:

\[
(a + b) b = \frac{2\epsilon V}{eN_A}
\]
The total width of the depletion region \( d \) is the entire distance over which the space charge extends, or \( d = a + b \).

For purposes of the present example, we have assumed that the \( n \)-side doping level is much higher than on the \( p \)-side, so that \( N_D \gg N_A \). Because \( N_D a = N_A b \), it follows that \( b \gg a \), and therefore the space charge extends much farther into the \( p \)-side than the \( n \)-side. Then \( d = b \) and we can write:

\[
d \approx \left[ \frac{2eV}{eN_A} \right]^{1/2}
\]

If we had started from the opposite assumption that the \( p \)-side doping level was predominant, a similar result would be obtained except that \( N_A \) in the above expression would be replaced by \( N_D \). A generalized solution for the thickness of the depletion region is therefore:

\[
d \approx \left[ \frac{2eV}{eN} \right]^{1/2}
\] (11-13)

In this expression, \( N \) now represents the dopant concentration (either donors or acceptors) on the side of the junction that has the lower dopant level. (For surface barriers described later in this chapter, \( N \) is the dopant concentration in the bulk of the crystal.)

The resistivity \( \rho_d \) of the doped semiconductor is given by \( 1/e\mu N \), where \( \mu \) is the mobility of the majority carrier. Equation 11-13 may thus be written

\[
d \approx [2eV\mu\rho_d]^{1/2}
\] (11-14)

Because one often would like the largest depletion width possible for a given applied voltage, it is advantageous to have the resistivity as high as possible. This resistivity is limited by the purity of the semiconductor material before the doping process, because enough dopant must be added to override the nonuniform effects of the residual impurities. A premium is therefore placed on obtaining detectors fabricated from the highest purity material possible.

Because of the fixed charges that are built up on either side of the junction, the depletion region exhibits some properties of a charged capacitor. If the reverse bias is increased, the depletion region grows thicker and the capacitance represented by the separated charges therefore decreases. The value of the capacitance per unit area is

\[
C = \frac{\varepsilon}{d} \approx \left[ \frac{e\varepsilon N}{2V} \right]^{1/2}
\] (11-15)

Good energy resolution under conditions in which electronic noise is dominant
FIGURE 11-7. Nomogram illustrating interrelation between parameters for silicon junction detectors. (Similar to nomogram originally published by Blankenship.)
depends on achieving a small detector capacitance, and is thus promoted by using the largest possible applied voltage.

The maximum electric field will occur at the point of transition between the $n$- and $p$-type material. Its magnitude is given by

$$E_{\text{max}} \approx \frac{2V}{d} = \left[ \frac{2VN\epsilon}{\epsilon} \right]^{1/2}$$

and can easily reach $10^6-10^7$ V/m under typical conditions. For standard (partially depleted) junctions, the depletion layer thickness $d$ is proportional to $\sqrt{V}$ so that the value of $E_{\text{max}}$ increases with applied voltage as $\sqrt{V}$.

The interrelationship between these parameters is illustrated in the nomogram for silicon detectors given in Fig. 11-7. Also shown are scales corresponding to the ranges of various charged particles to allow selection of conditions required to produce a depletion depth which exceeds the range.

The maximum operating voltage for any diode detector must be kept below the breakdown voltage to avoid a catastrophic deterioration of detector properties. Commercially manufactured detectors are supplied with a maximum voltage rating that should always be strictly observed. Additional protection can be provided by monitoring the leakage current during application of the voltage (see the discussion later in this chapter).

To summarize, the reverse biased $p-n$ junction makes an attractive radiation detector because charge carriers created within the depletion region can be quickly and efficiently collected. The width of the depletion region represents the active volume of the detector, and is changed by varying the reverse bias. The variable active volume of semiconductor junctions is unique among radiation detectors, and sometimes is used to good advantage. The capacitance of the detector also varies with applied voltage, and stable operation therefore requires the use of charge sensitive preamplifiers (see Chapter 17).

**IV. SEMICONDUCTOR DETECTOR CONFIGURATIONS**

**A. Diffused Junctions**

One common fabrication method for semiconductor diode detectors starts with a homogeneous crystal of $p$-type material. One surface is treated by exposing it to a vapor of $n$-type impurity (typically phosphorus), which then converts a region of the crystal near the surface from $p$-type to $n$-type material. A junction is therefore formed some distance from the surface at the point at which the $n$- and $p$-type impurities reverse their relative concentration. Typical depths of the diffused $n$-type layer range from 0.1-2.0 µm. Because the $n$-type surface layer is heavily doped compared with the $p$-type original crystal, the depletion region extends primarily into the $p$ side of the junction. Therefore, much of the surface layer remains outside of the depletion region and represents a dead layer or