Nuclear Detectors

Semiconductor Detectors

- A **semiconductor detector** in ionizing radiation detection physics is a device that uses a semiconductor (usually silicon or germanium) to measure the effect of incident charged particles or photons.

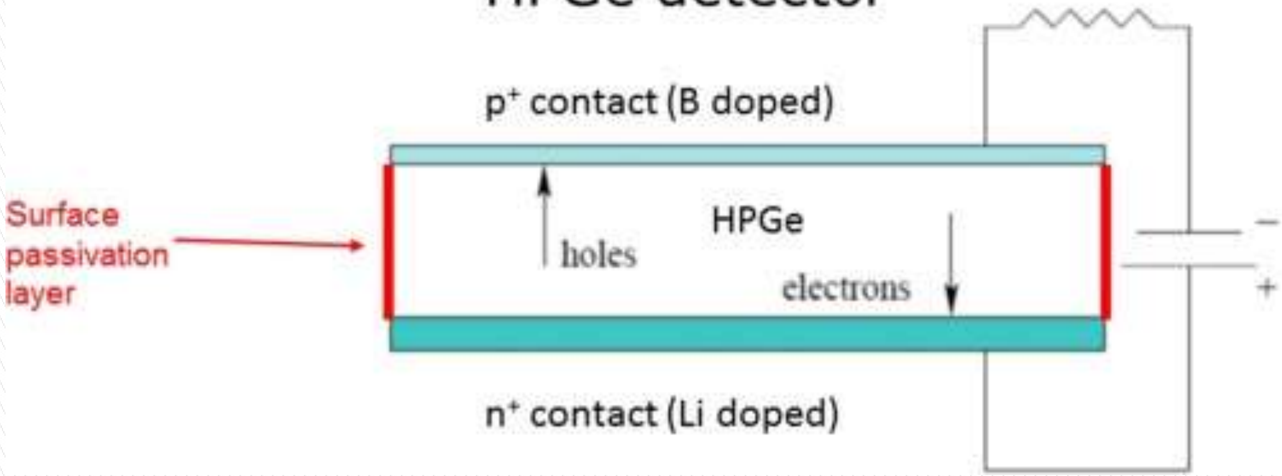
- In semiconductor detectors, ionizing radiation is measured by the number of charge carriers set free in the detector material which is arranged between two electrodes, by the radiation.
- Ionizing radiation produces free electrons and holes. The number of electron-hole pairs is proportional to the energy of the radiation to the semiconductor. As a result, a number of electrons are transferred from the valence band to the conduction band, and an equal number of holes are created in the valence band.
- Under the influence of an electric field, electrons and holes travel to the electrodes, where they result in a pulse that can be measured in an outer circuit. The holes travel in the opposite direction and can also be measured.

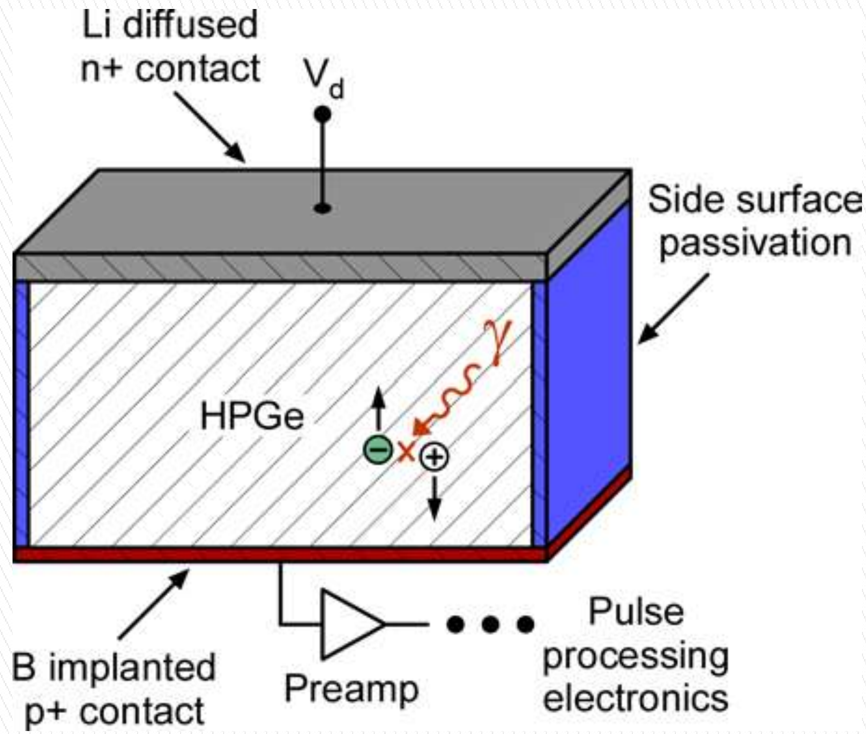
- As the amount of energy required to create an electron-hole pair is known, and is independent of the energy of the incident radiation, measuring the number of electron-hole pairs allows the intensity of the incident radiation to be determined.
- The energy required to produce electron-hole-pairs is very low compared to the energy required to produce paired ions in a gas detector. Consequently, in semiconductor detectors the statistical variation of the pulse height is smaller and the energy resolution is higher. As the electrons travel fast, the time resolution is also very good, and is dependent upon rise time.
- Compared with gaseous ionization detectors, the density of a semiconductor detector is very high, and charged particles of high energy can give off their energy in a semiconductor of relatively small dimensions.

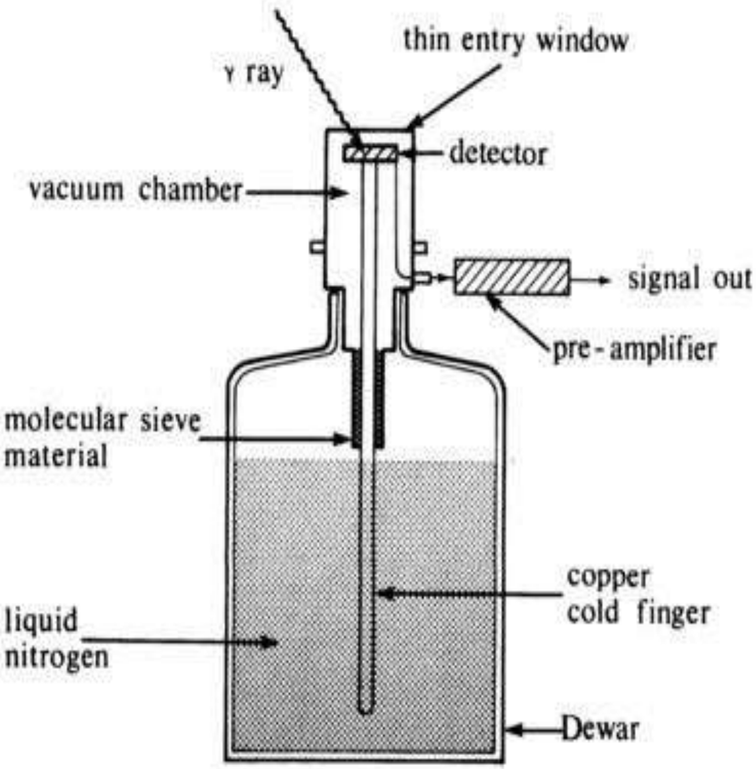
Germanium detectors

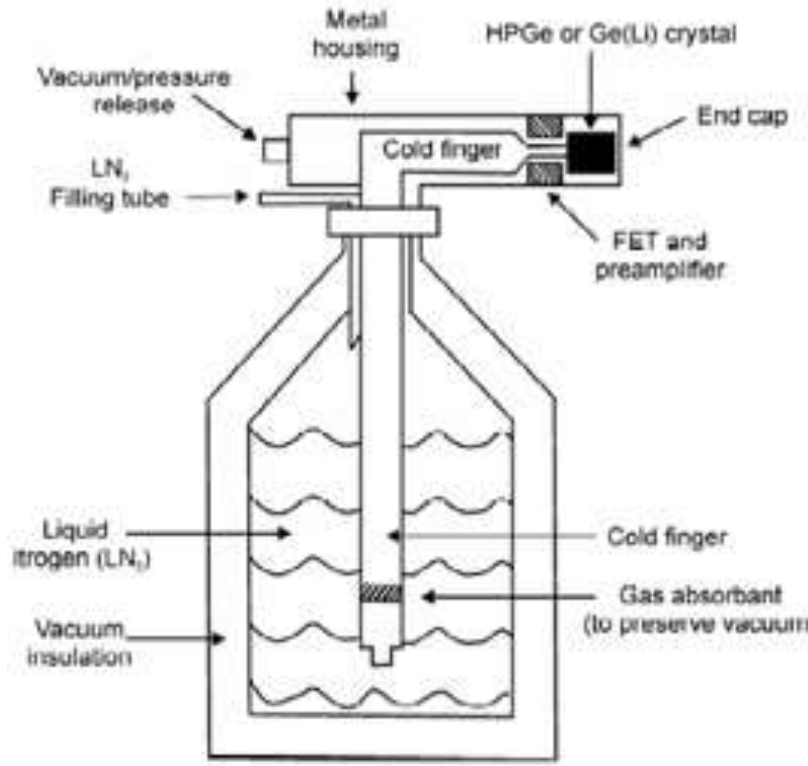
- Germanium detectors are mostly used for gamma spectroscopy in nuclear physics, as well as x-ray spectroscopy. While silicon detectors cannot be thicker than a few millimeters, germanium can have a depleted, sensitive thickness of centimeters, and therefore can be used as a total absorption detector for gamma rays up to few MeV.
- These detectors are also called high-purity germanium detectors (HPGe) or hyperpure germanium detectors.
- The major drawback of germanium detectors is that they must be cooled to liquid nitrogen temperatures to produce spectroscopic data. At higher temperatures, the electrons can easily cross the band gap in the crystal and reach the conduction band, where they are free to respond to the electric field, producing too much electrical noise to be useful as a spectrometer.

HPGe detector









Schematic diagram of high purity germanium (HPGe) or Ge (Li) detector with liquid nitrogen Dewar

- **High-purity germanium detectors** (**HPGe detectors**) are the best solution for precise gamma and x-ray spectroscopy.
- In comparison to silicon detectors, germanium is much more efficient than silicon for radiation detection due to its atomic number being much higher than silicon and due to lower average energy necessary to create an electron-hole pair, which is 3.6 eV for silicon and 2.9 eV for germanium.
- Due to its higher atomic number, **Ge** has a much lager linear attenuation coefficient, which leads to a shorter mean free path.
- Moreover silicon detectors cannot be thicker than a few millimeters, while germanium can have a depleted, **sensitive thickness of centimeters**, and therefore can be used as a total absorption detector for gamma rays up to few MeV.

- Purity of a detector material is of the highest importance. The electron-hole pair collection within the detector must be done within a reasonably short time. Moreover there must be no traps which can prevent them reaching the collecting contacts. Trapping centres can be due to:

- Impurities within the semiconductor lattice
- Interstitial atoms and vacancies within the lattice due to structural defects
- Interstitial atoms caused by radiation damage

- Impurities in the crystals trap electrons and holes, ruining the performance of the detectors. Consequently, germanium crystals were doped with lithium ions (Ge(Li)), in order to produce an intrinsic region in which the electrons and holes would be able to reach the contacts and produce a signal.

- In order to achieve maximum efficiency the **HPGe detectors** must operate at the very low temperatures of liquid nitrogen, because at room temperatures the noise caused by thermal excitation is very high.
- Since HPGe detectors produce the highest resolution commonly available today, they are used to measure radiation in a variety of applications including personnel and environmental monitoring for radioactive contamination, medical applications, radiometric assay, nuclear security and nuclear plant safety.

Parts of HPGe Detectors

- Because germanium has relatively low band gap, these detectors must be cooled in order to reduce the thermal generation of charge carriers to an acceptable level.
- Otherwise, leakage current induced noise destroys the energy resolution of the detector. Recall, the band gap (a distance between valence and conduction band) is very low for germanium (E_{gap}= 0.67 eV). Cooling to liquid nitrogen temperature (-195.8°C; -320°F) reduces thermal excitations of valence electrons so that only a gamma ray interaction can give an electron the energy necessary to cross the band gap and reach the conduction band.
- Therefore, **HPGe detectors** are usually equipped with a **cryostat**.

- Germanium crystals are maintained within an evacuated metal container referred to as the **detector holder**. The detector holder as well as the “end-cap” are thin to avoid attenuation of low energy photons. The holder is generally made of aluminum and is typically 1 mm thick. The end-cap, is also generally made of aluminum.
- The HPGe crystal inside the holder is in thermal contact with a metal rod called a **cold finger**. The cold finger transfers heat from the detector assembly to the liquid nitrogen (LN_2) reservoir.
- The combination of the vacuum metal container, the **cold finger** and the **Dewar flask** for the liquid nitrogen cryogen is called the **cryostat**.
- The germanium detector preamplifier is normally included as part of the cryostat package. Since the preamp should be located as close as possible so that the overall capacitance can be minimized, the preamp is installed together.

- The input stages of the preamp are also cooled. The cold finger extends past the vacuum boundary of the cryostat into a Dewar flask that is filled with liquid nitrogen.
- The immersion of the cold finger into the liquid nitrogen maintains the HPGe crystal at a constant low temperature.
- The temperature of the liquid nitrogen is held constant at 77 K (-195.8°C; -320°F) by slow boiling of the liquid, resulting in the evolution of nitrogen gas. Depending on the size and design, the holding time of vacuum flasks ranges from a few hours to a few weeks.

HPGe Detector – Principle of Operation

- The operation of semiconductor detectors is summarized in the following points:
- Ionizing radiation enters the sensitive volume (**germanium crystal**) of the detector and interacts with the semiconductor material.
- High-energy photon passing through the detector ionizes the atoms of semiconductor, producing the electron-hole pairs. The number of electron-hole pairs is proportional to the energy of the radiation to the semiconductor.
- As a result, a number of electrons are transferred from the valence band to the conduction band, and an equal number of holes are created in the valence band.
- Since germanium can have a depleted, sensitive thickness of centimeters, they are able to **absorb high-energy photons totally** (up to few MeV).

- Under the influence of an electric field, electrons and holes travel to the electrodes, where they result in a pulse that can be measured in an outer circuit.
- This pulse carries information about the energy of the original incident radiation. The number of such pulses per unit time also gives information about the intensity of the radiation.

- In all cases, a photon deposits a portion of its energy along its path and can be absorbed totally.
- Total absorption of a 1 MeV photon produces around 3 x 10^5 electron-hole pairs. This value is minor in comparison the total number of free carriers in a 1 cm^3 intrinsic semiconductor.
- Particle passing through the detector ionizes the atoms of semiconductor, producing the electron-hole pairs. But in germanium-based detectors at room temperature, **thermal excitation** is dominant. It is caused by impurities, irregularity in structure lattice or by dopant.
- It strongly depends on the E_{gap} (a distance between valence and conduction band), which is very low for germanium (Egap= 0.67 eV). Since thermal excitation results in the detector noise, active cooling is required for some types of semiconductors (e.g. germanium).

Reverse Biased Junction

- The semiconductor detector operates much better as a radiation detector if an external voltage is applied across the junction in the **reverse biased direction**.
- The **depletion region** will function as a radiation detector.
- Improvement can be reached by use of a reverse-bias voltage to the **P-N junction** to deplete the detector of free carriers, which is the principle of the most semiconductor detectors.
- Reverse biasing a junction increases the thickness of the depletion region because the potential difference across the junction is enhanced.
- Germanium detectors have a p-i-n structure in which the intrinsic (i) region is sensitive to ionizing radiation, particularly X rays and gamma rays.

- Under reverse bias, an electric field extends across the intrinsic or depleted region. In this case, negative voltage is applied to the p-side and positive to the second one.
- Holes in the p-region are attracted from the junction towards the p contact and similarly for electrons and the n contact.
- This charge, which is in proportion to the energy deposited in the detector by the incoming photon, is converted into a voltage pulse by an integral charge sensitive preamplifier.

Resolution of a detector

- The resolution of a detector measures its capability to resolve adjacent gamma rays. It helps to eliminate unwanted gamma rays near the photo peak of interest.
- Another important parameter characterizing gamma ray detector is the efficiency which measures the fraction of incoming gamma rays of any given energy that contribute to the corresponding photo peak. Ideally a detector should have as good a resolution (low R) and as higher an efficiency as possible.
- Both these requirements are fulfilled by high purity germanium (HPGe) detector which has much superior resolution though its efficiency is somewhat lowered. However, in recent years high efficiency HPGe detectors have become available.
- These are attached to a large cryostat which makes them bulky and difficult to handle. Schematic diagram of a typical HPGe or Ge (Li) detector with Dewar attached to it is shown in Figure. Such detectors are usually characterized by their resolution, efficiency, and peak-to Compton ratio.

5.4 Semiconductor Detectors

These are the solid state analogue of the ionization detector. An ionization event in the sensitive volume is followed by charge separation achieved by the application of a voltage bias.

A semiconductor device has a number of important advantages over the gas-based detector :

- the sensitive material has a far greater density and therefore the interaction efficiency rises in proportion.
- the deposited energy required to produce an ion pair (W-value in a gas) is a factor of 10 lower. (W in air for fast electrons = 33.8 eV/ion pair: w in crystalline silicon = 3.55 eV/electron-hole pair).
- the speed of charge collection is greater due to the higher mobility of both charge carriers. Drift velocities of an ion and an electron in air at one atmosphere

are 1.4 and 1.9 $cm^2 V^{-1} s^{-1}$ respectively. Mobilities of holes and electrons in crystalline silicon are 450 and 1450 $cm^2 V^{-1} s^{-1}$ respectively.

- their energy resolution is very high. For photons in the range 1.5 to 10 MeV manufacturers might expect a resolution (FWHM) between 0.08 and 0.1%. Various factors that arise in the production process worsen this to the range 0.1 - 3% depending on the geometry, purity, etc.
- advances in silicon and germanium technology enable a semiconductor to be miniaturized and adapted to meet many different needs.

Disadvantages include :

- poor time resolution for photon detection compared with scintillator detectors,
- a loss of sensitivity after prolonged irradiation. This effect is most pronounced in n-type materials.

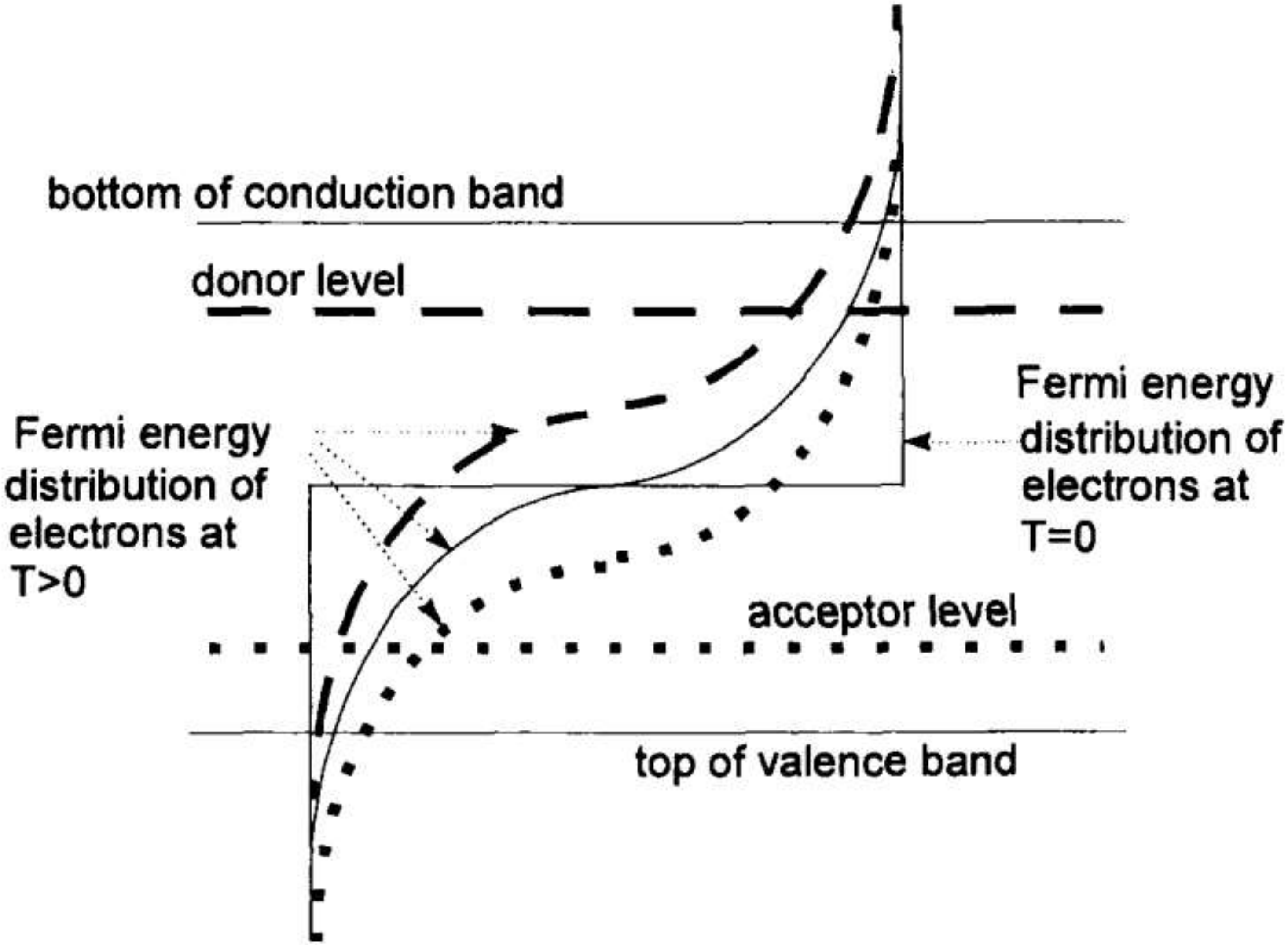


Fig.(5.25) Fermi energy distribution of electrons in a semiconductor. The three curves correspond to intrinsic (solid line), n-type (dash line) and p-type (dotted line), [2].

In an intrinsic (pure) material at absolute zero, there is an infinitely sharp jump between 1 and 0 exactly at the half-way point of the energy band gap. This indicates that at $T = 0$ there is maximum probability of finding the electron in the valence band and zero probability of finding one in the conduction band. As the temperature increases, thermal excitation gives rise to a non-zero probability that the electron resides in the conduction band. This is balanced by a corresponding reduction in the probability of finding it in the valence band.

An extrinsic (doped) semiconductor has an excess of charge carriers. These are electrons (n-type) when the valence of the dopant is greater than the valence of the host (*e.g.* P in Si), and holes (p-type) when it is smaller (*e.g.* B in Si).

In n-type material the impurity atom, having one more electron than is required for lattice binding of the host atoms, provides an excess electron. Although still localized on the impurity, this has a reduced binding energy and a larger orbit radius, Fig.(5.26). This electron occupies a donor state.

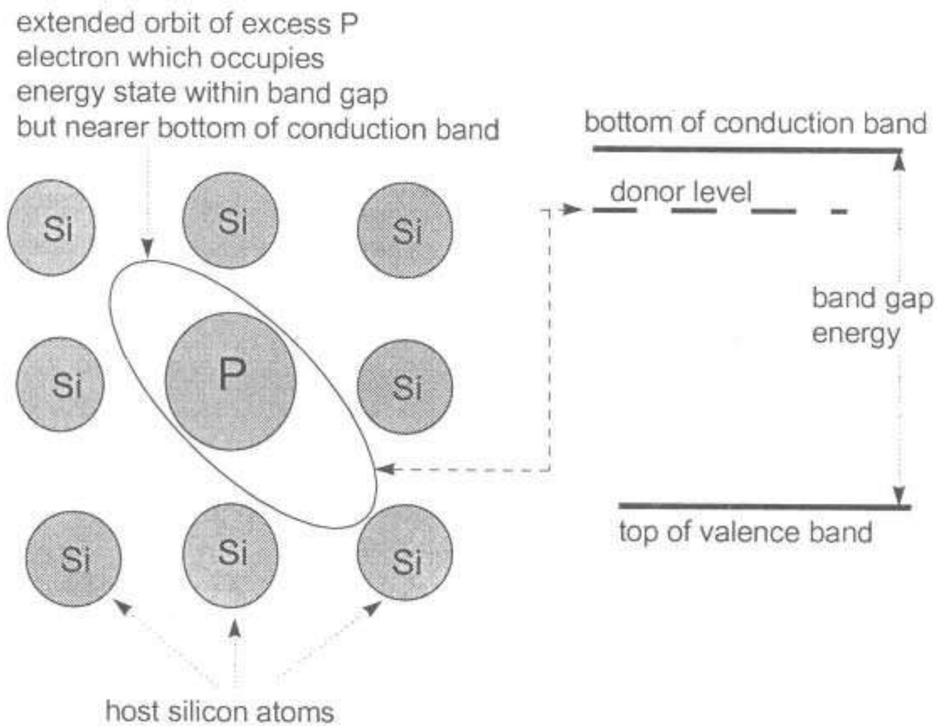


Fig. (5.26) Representation of the orbit and reduced binding energy of an excess electron in an n-type semiconductor, [12]. With permission from John Wiley and Sons, Inc.

Because even the purest silicon contains small amounts of boron, native silicon is always p-type. The situation is then the reverse of that shown in Fig. (5.26). A boron impurity has one fewer valence electron (3) than the surrounding silicon atoms (4), thereby creating an unsaturated covalent bond between the B and Si atoms. This "hole" is termed an acceptor state. An electron falling into this state has a slightly smaller binding energy than would be the case if the boron atom were replaced by a host silicon atom. The energy level is therefore not at the top of the valence band but slightly above it *i.e.* just into the band gap.

5.4.1 The p - n junction

All semiconductor detectors rely on charge compensation to produce a region which is initially devoid of free charge carriers. This charge-compensated region, called the depletion layer, must :

- have a high resistivity in order to maintain the electric field needed to collect charges produced following the interaction of radiation,
- have a known thickness in order to be able to assess the nature of the incident radiation,
- be bounded by sufficiently thin electrode materials that the energy spectrum of the incident radiation is not de-graded as it enters the depletion layer.

Given that totally intrinsic material is practically impossible to achieve, charge compensation can be attained in the vicinity of the junction between n-type and p-type material (see Fig.(5.25) and section 7.14). Commercial detectors are based almost entirely on silicon or germanium host materials, with boron, phosphorus, lithium and arsenic as the most widely-used dopants.

5.4.2 *Germanium detectors*

The higher atomic number of germanium (Z=32) and the higher attainable purity make possible the widespread use of high purity germanium (HPGe) photon detectors. Production steps for HPGe are :

- polycrystalline germanium is first zone-refined, after which the impurity levels will have fallen by a factor of about 100,
- a single crystal is grown from the melt by the *Czochralski* method,
- the crystal is cut, machined and lapped to the required dimensions. A co-axial detector is cylindrical with a blind axial hole for the central electrode contact.
- contacts are made using lithium ion diffusion for the n-type contact (~700 μm thick) and boron implantation for the p-type contact (~0.3 μm). These are illustrated for the two configurations in Fig.(5.27).

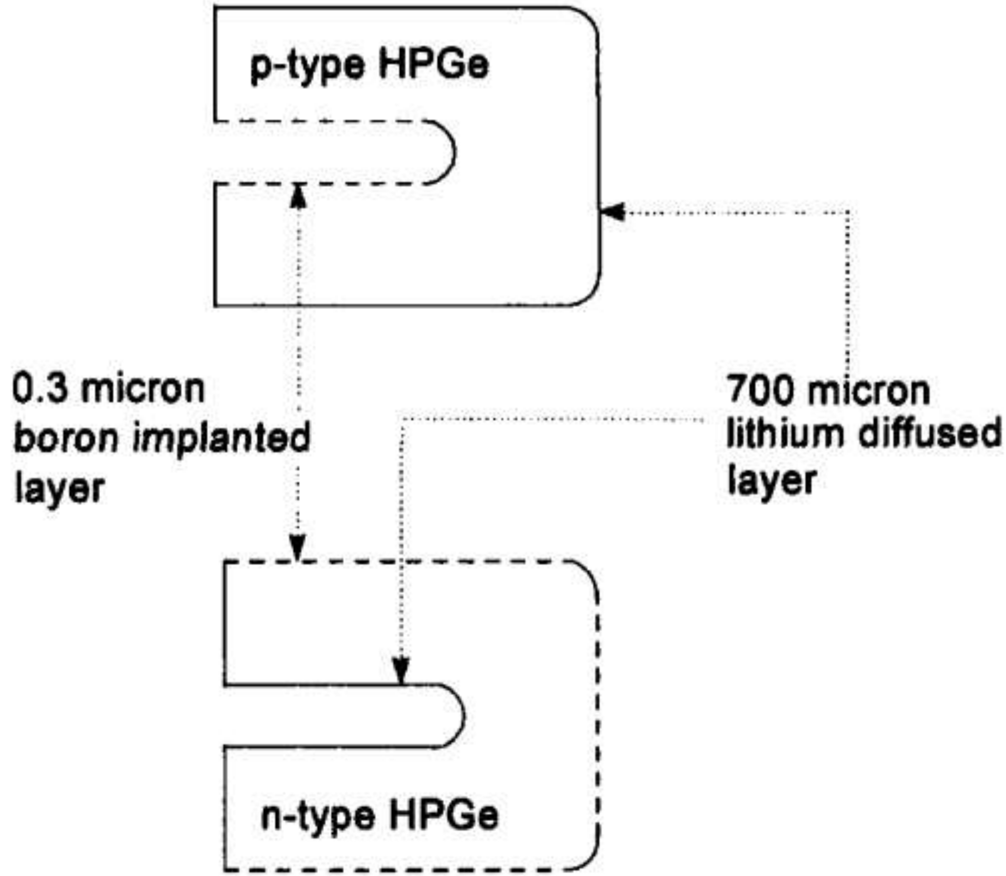


Fig. (5.27) Basic configurations of HPGe detectors, [17].

The crystals shown in Fig.(5.27) are mounted onto the end of a copper cooling rod which dips into a liquid nitrogen reservoir. A field-effect-transistor (FET) is also mounted on this rod as close as possible to the crystal. The cooled FET plays an important role in reducing signal noise. It is also prone to failure if the high bias voltage that is required (~ 2.5 – 3.5 kV) is applied suddenly. A good illustration of the physical configuration of the elements in a HPGe detector is given by Knoll [6].

The efficiency of a HPGe detector is usually compared against a “standard" 76 cm thick, 76 cm diameter NaI(Tl) scintillator. Other parameters of practical interest are the energy resolution at 122 keV and 1330 keV, and the Peak:Compton ratio. Energy resolution is specified as the Full Width at Half maximum divided by the mean energy as in Eq.(5.16). The Peak:Compton ratio is specified as the ratio of the highest count in the photopeak to a count in the Compton continuum associated with that peak. Table (5.4) shows some typical performance parameters for co-axial HPGe detectors.

Table (5.4) Typical specification of co-axial HPGe detectors. Data taken from [17].

Efficiency (%)	% resolution at (122 keV)	% resolution at (1330 keV)	Peak:Compton
150	1.07	0.17	90:1
100	0.98	0.16	83:1
10	0.68	0.13	41:1

Detector Efficiency

- The most common way to describe an HPGE detector’s efficiency is to specify its efficiency relative to that of a 3” x 3” NaI detector:

$$Relative\ efficiency = 100\ x\ \frac{Efficiency\ of\ HPGe\ detector}{Efficiency\ of\ 3''\,x\,3''\ NaI\ detector}$$

- The HPGe and NaI efficiencies are for the 1332.5 keV peak of a Co-60 point source 25 cm away from the detector.

- The most common detector efficiency currently being manufactured is 50%.

- Relative efficiency is used to compare one detector with another, not to quantify radioactive material.
- The efficiency usually employed to quantify a gamma emitting radionuclide indicates the fraction of the gammas emitted by the source that produce a count in the photopeak.
- This efficiency depends on the:
    - size and shape of the source
    - source-detector distance
    - source matrix which affects self absorption
    - photon energy

- **Detector Resolution**

- The resolution of a detector describes the width of the photopeaks. The narrower the peak, the greater the ability of the system to distinguish different gamma rays of similar energies.

- The resolution depends on the photon energy: the lower gamma ray energy, the narrower the peak.

- The resolution of a HPGe detector is usually expressed as the Full Width at Half Maximum (FWHM) for the 1332.5 keV peak of Co-60. It is expressed in keV.

- This contrasts with the resolution for a scintillation detector which is usually described as a percent relative efficiency for the Cs-137 peak.

- HPGe detector resolutions at 1332.5 keV are usually in the 1.6 - 2.0 keV range.
- It is also common to specify the resolution at 122 keV (Co- 57). If the detector is capable of low energy spectroscopy, its resolution will also be specified at 5.9 keV (Mn x-ray).
- All other things being equal, a p-type germanium detector has better resolution than an n–type detector.
- The higher the detector efficiency (i.e., the larger it is), the poorer the resolution.

- **Peak to Compton Ratio**

- Each photopeak on a spectrum has an associated Compton continuum. The latter increases the background at the lower energies and this results in poorer counting statistics and minimum detectable activities (MDAs).

- To reflect the "size" of the Compton continuum associated with a given detector, manufacturers specify the peak to Compton ratio: ratio of the count at the center of the Co-60 1332 keV photopeak divided by the average counts per channel at the Compton edge between 1040 and 1100 keV.

- The larger the peak to Compton ratio, the better. Bigger more efficient detectors have higher ratios than smaller detectors.

5.4.3 *Nuclear spectroscopy using a Ge photon detector*

The response of any detector, whether designed for photons or particles, is mainly determined by the following :

- the size of the sensitive volume compared with the characteristic attenuation length of the radiation,
- the thickness of any window material through which the incident radiation has to travel before reaching the sensitive volume,
- the proximity of any material which can scatter back into the sensitive volume radiation which might otherwise have escaped.

For photons the response is entirely due to energy deposition by secondary electrons. It is the range, angle of scatter and energy distribution of these electrons that distinguishes one detector arrangement from another. The larger the crystal the greater the probability that an incoming photon is completely absorbed. This gives rise to a full-absorption peak (also called a photopeak) which characterizes the energy of the photon. A detector with a smaller sensitive volume has a larger probability that part of the photon energy is not deposited within the detector. In this case a pulse of lower amplitude is produced.

An example is provided by the likely response to 1.5 MeV photons of a 50 mm thick, 50 mm diameter Ge crystal surrounded by an annulus of lead. Assuming a relative efficiency somewhat less than 100%, Table (5.4) suggests that a Peak/Compton ratio of ~50 : 1 might be expected. Data from Table (5.5) is then required to consider :

- the photons interacting directly with Ge,
- the photons initially interacting in the Pb shielding and then being scattered into the Ge,
- the photons being transmitted through the Ge and then being back-scattered from the copper cooling rod and other backing material.

Total cross-section data in Table (5.5) can be used to show that 72% of a flux of 1.5 MeV photons incident normally on the face of the crystal interact within it. The remainder do not interact and are transmitted into the material behind the crystal. Eq.(3.15) shows that these photons can be scattered back into the Ge with an energy of ~ 0.22 MeV (using $\alpha = h\nu_0/m_0c^2 = 1.5/0.511 = 2.935$).

Table (5.5) Cross-sections (barn atom^{-1}) and total mass attenuation coefficient for 1.5 MeV photons [18]. σ(coh) = Rayleigh coherent scatter; σ(inc) = Compton incoherent scatter; σ(PE) = photoelectric absorption; σ(PP) = pair production absorption; σ(tot) = total. $\mu = \sigma(\text{tot})\, N_A / A$, where N_A is the Avogadro constant.

	ρ (g cm^{-3})	Z	A	σ(coh)	σ(inc)	σ(PE)	σ(PP)	σ(tot)	μ (cm^2 g^{-1})
Ge	5.46	32	72.63	0.0323	5.490	0.0397	0.0531	5.615	0.04656
Pb	11.35	82	207.22	0.4636	14.02	2.863	0.6144	17.96	0.05220
Cu	8.93	29	63.54	0.0246	4.976	0.0251	0.0424	5.068	0.04803

The relative probabilities in Table (5.5) indicate that ~98% ($\sigma_{inc}/\sigma_{tot}$) of the initial interactions in each of the three materials involve Compton incoherent scatter. In the Ge crystal therefore the interactions are: 0.6% Rayleigh scatter, 0.71% photoelectric absorption, 97.8% Compton scatter and 0.95% pair production. Many of the subsequent interactions of the initially Compton-scattered photons, however, can also result in full absorption of the 1.5 MeV incoming energy.

Photon interactions which contribute to the energy-dependent response of a detector in this simple example can therefore be summarized as follows :

(a) Photo-electric absorption

In addition to the photo-electron, photo-electric absorption produces one or more characteristic X-rays or Auger electrons. When the interaction takes place within the crystal and both of these secondary radiations are absorbed locally, the total deposited energy contributes to the photopeak. Although the range of the Auger electrons is generally small enough for this always to be the case, a characteristic X-ray may have sufficient energy to escape the crystal. In this case, a small peak will appear just below the main photopeak. The energy difference will be equal to the X-ray energy. Equally, a characteristic X-ray generated in nearby shielding material may enter the crystal from outside. In the case of a lead shield in the above example, it is likely that a peak due to the most prominent characteristic lead X-ray ($K_{\alpha 1}$ at 74.97 keV) would be detected.

(b) Compton scatter

A single Compton scatter event at 1.5 MeV produces a photon with an energy between zero and 1.282 MeV. If the crystal is sufficiently large, a single 1.5 MeV photon can suffer many collisions (multiple scatter) via the Compton process. If this photon does not leave the crystal volume (i.e. it is ultimately absorbed), the event registers as a total absorption and contributes to the photopeak at 1.5 MeV. However, if the photon is able to leave the crystal after several Compton scatter events, the energy deposited in the crystal will be less than 1.5 MeV. It will contribute to the energy region between the photopeak and the Compton edge for single scatter. Photons which interact in the Ge crystal after scatter from any surrounding material will show a broad energy distribution. The mean energy is lower for back-scattered photons than for those that have suffered only a small change of direction.

(c) Pair production

A pair production interaction in the crystal gives rise to two photons with energy 0.511 MeV. If both photons are absorbed then, again, there is a contribution to the photopeak. If one is able to escape the crystal, the energy deposited will be 1.5 MeV minus 0.511 MeV. If both escape, a peak will appear at 1.5 - 1.022 = 0.478 MeV. If pair production takes place in the lead shield and one annihilation photon interacts in the crystal, a peak is observed at 0.511 MeV.