Semiconductor detectors

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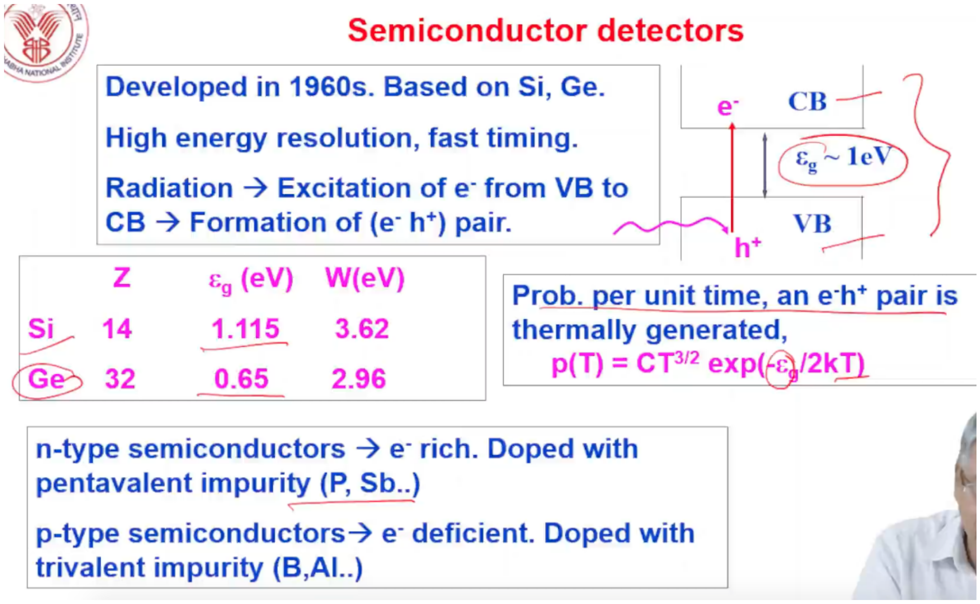
Lecture-10, module-2

Hello everyone. In the previous lecture, I discussed the detectors for gamma ray counting based on scintillation detectors and mainly the sodium iodide thallium detector which we discussed in details. Also, some of the more advancements in the scintillation technology. Today, I will discuss one of the most advanced detector systems for gamma spectrometry that is based on semiconductor detectors.



Semiconductor detectors

Developed in 1960s. Based on Si, Ge.

High energy resolution, fast timing.

Radiation → Excitation of e^- from VB to CB → Formation of (e^- h^+) pair.

	Z	ε_g (eV)	W(eV)
Si	14	1.115	3.62
Ge	32	0.65	2.96

Prob. per unit time, an e^-h^+ pair is thermally generated,

$$p(T) = CT^{3/2}\exp(-\varepsilon_g/2kT)$$

n-type semiconductors → e^- rich. Doped with pentavalent impurity (P, Sb..)

p-type semiconductors→ e^- deficient. Doped with trivalent impurity (B,Al..)

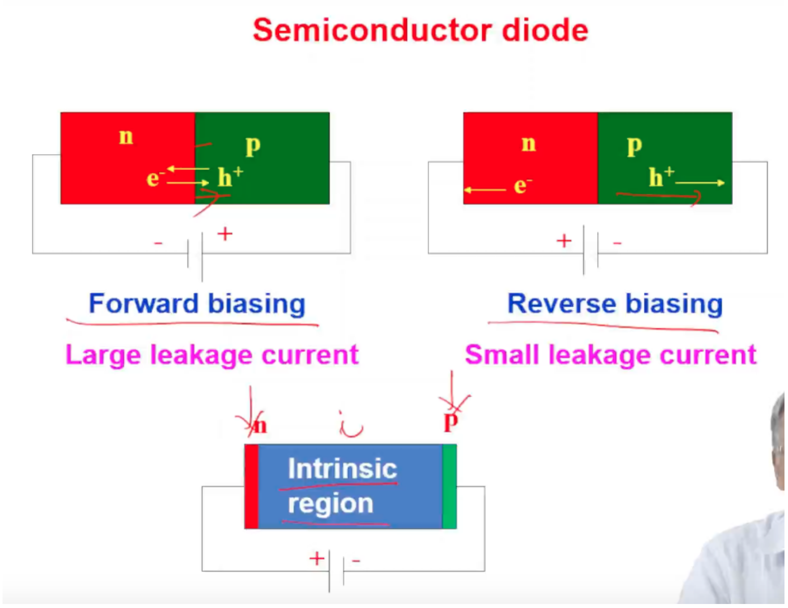
So, as you know the semiconductors are materials which have the band gap in the range of few electron volts. They are between metals and insulators. And these detectors were developed in 1960s and are mainly based on the two semiconductor materials, namely, silicon and germanium. They have a lot of advantages over the detectors that we have discussed so far. Namely, they have the excellent energy resolution. They have the fast timings.

Of course, the efficiency for detection for gamma ray is not that high because of the low atomic number of these materials like silicon is 14, germanium is 32. But overall the detectors are one of the best detectors for the spectroscopy of gamma rays. The basic principle of the detectors is similar to the gas-filled counters like ionization chambers. In the ionization chambers, the incoming radiation ionizes the gas medium creating positive ions and electrons. Whereas in the case of semiconductors, the radiation when it falls on the detector material generates electron hole pairs.

So, electron hole pairs are analogous to the positive ion and electron pair in a gas detector. So basically, the semiconductor detectors function based on collection of electrons and holes at the respective electrodes. So this is a schematic of the semiconductor material. We have the valence band and we have the conduction band. In a semiconductor, the bulk of the electrons will be in the valence band, but, even at room temperature you will find there will be a significant quantity of electrons in the conduction band.

So there are electron hole pairs generated thermally in a semiconducting material and the probability per unit time that an electron hole pair will be generated depends upon the band gap, this is the band gap and the temperature. So even at room temperature, there will be a sizable number of electron hole pairs in the conduction band and therefore, when you want to use detectors for counting of different types of radiations, we need to take care of this particular aspect. So the band gap of this main detector material silicon and germanium are given here. Silicon is 1.115 electron volt, germanium is 0.65 electron volt and the W value as I mentioned earlier also, W values are higher than the band gaps or the ionization potential in the gaseous media, again, because every interaction may not lead to electron hole pair formation. Many times, these electrons and hole will get trapped and so they are not really useful for the collection of the charge. So, germanium being higher Z is used mainly for the gamma ray spectroscopy, gamma ray counting, whereas silicon being the lower Z is used for alpha counting or even the other charged particles like protons and heavy ions. Both these detector materials in fact have been widely used for charged particles spectroscopy or gamma ray spectroscopy. I will discuss mainly the germanium-based detectors and little bit touch upon the silicon-based ones.

Now, what is the basic principle of these detectors? Any of these semiconducting materials you have, in fact, you cannot have a pure germanium crystal, 100% pure or pure silicon crystal. But by the process of manufacturing, they will be always associated with some impurity. So if you have a electron rich impurity doped in these materials like tetravalent silicon and germanium, the pentavalent impurities like phosphorus and antimony, then we call it n-type because over the tetravalent there is a pentavalent so there is an excess electron due to these impurities centers and so they are called electron rich centers or n-type semiconductors. On the other hand, if there are electron deficient impurities like boron and aluminum, trivalent ones with respect to the tetravalent silicon and germanium, then they are electron deficient with respect to the bulk material and we call them as p-type semiconductors. So how do we make use of this p-type or n-type materials for detection of radiation that I try to explain in this next slide.



Semiconductor diode

Forward biasing

Large leakage current

Reverse biasing

Small leakage current

So basically, what we need to have is a semiconductor diode. So how do you make a diode? You take a n-type and take a p-type and join them electronically. So when you say n-type material means it is rich in electrons, when we have p-type material it is rich in holes or electron deficient material. So when you join them then depending upon the type of biasing that you invoke you can have different scenario. So, I try to explain based on what way we bias this diode.

This is a two-electrode system n-type and p-type materials are there connected to the anode and cathode of detectors and the biasing system. So when you do a forward biasing, what do you mean by forward biasing? That means the electrons are going across the junction to the anode and the holes are going across the junction to cathode. So when we join the n and p-type of semiconductor materials and if there is a forward biasing then you will find there is a flow of electrons and holes across this junction and there will be a large amount of current generated even without any radiation falling on the detector system. So this is called the forward biasing and this mechanism results in a large amount of leakage current. That means inherently there is a lot of current flowing through the circuit in the system in the forward bias mode.

So, this forward bias mode is not utilized for using this as a radiation detector. On the other hand let us see the reverse biasing mode. The reverse biasing mode n-type semiconductor is connected to the anode. So, you have the electrons going towards anode and you have the electron deficient side connected to the cathode. So, what is happening now when you apply the reverse bias to this diode material you will find that the electrons are going to anode the holes are going to cathode and so there is a net no net flow of electrons and holes across the junction.

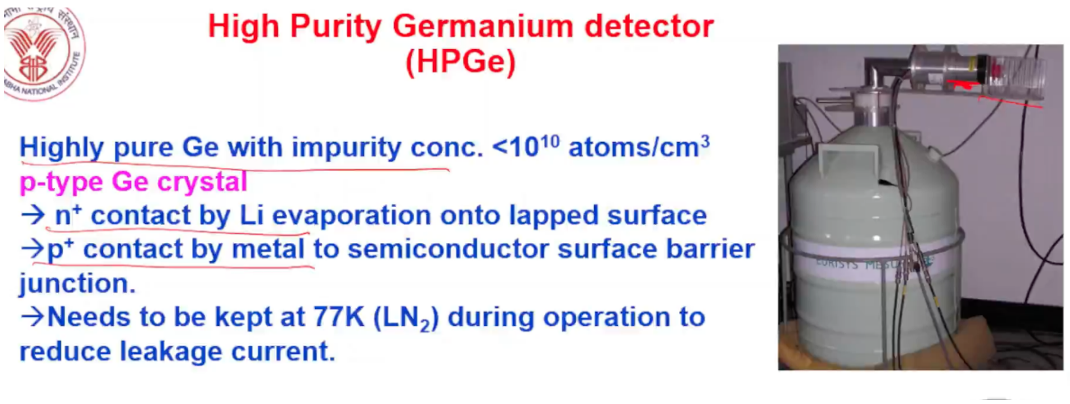
So, there is a very very small leakage current. Of course there will be some electrons on the p side which will cross the junction there will be some holes in the n side which will cross the junction. So there will be a small leakage current anyway but the bulk leakage current that was flowing in the forward biasing case is not flowing in the reverse biasing. So the detectors the semiconductor materials if you want to use them as detectors we use them in the reverse biasing. So, I hope the concept of reverse biasing is clear.

By reverse biasing we decrease the leakage current significantly by connecting the n side to the anode and the p side to the cathode. In fact it was the case earlier when we did not have the semiconductor materials of very high purity. So you have inherently a high concentration of impurities like n-type or p-type and if you want to make a detector then you have to necessarily compensate for the impurity concentrations by making the diode. But nowadays the technology of semiconductor materials has become so good that whatever pure materials that you have the concentrations of impurities are of the order of 10^{10} atoms per cc or even less than that. People are talking about 13 n purity.

When you say 13 n purity, 99.999999 and so on total there will be 13 nines so that is called 13 n purity. They are highly pure materials so the impurity concentration become 10^{10} atoms per cc or so. So such a detector material like germanium or silicon then there are very very few impurities and this is called as the intrinsic detector material. That means the number of electrons and holes is very very low so there will be very very less leakage current flowing through the diode junction.

Now to make this as a detector anyway you have to need a n-p junction. So what you do you create a n-type layer on one side and you create a p-type layer on the other side. So you may have a n inherent this is called the intrinsic detector material so n-i-p. So essentially if you have this reverse bias you are actually creating an intrinsic region which is where there are no excess electrons or holes and so you can take a pure material relatively pure material and then if this is a pure material then you need to create n-type and p-type layers on both sides. So how do you create n-type layer? n-type layer like if you take a germanium crystal you can take it you can diffuse the lithium from one side lithium will go in the interstitial positions and you generate the n-type or you can implant phosphorus or a pentavalent impurity by ion implantation.

Similarly, the p-type you can create a surface barrier like in you can etch the surface so there will be an oxide layer and oxide layer become a surface barrier and then you have a gold coating to protect it to make electronic contacts. So you can create n-type layer or p-type layer of a few microns on both sides and the bulk material is intrinsically pure. So there again n-site you connect to the anode and p-site to the cathode and now you have the detector system ready for operation.



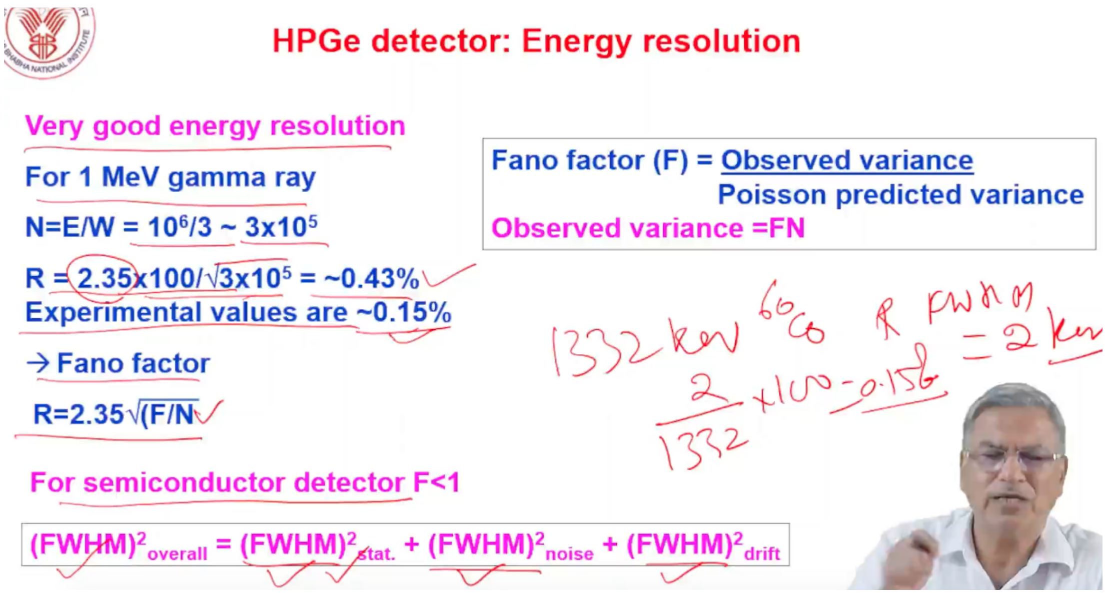
High Purity Germanium detector (HPGe)

Highly pure Ge with impurity conc. $<10^{10}$ atoms/cm^3
p-type Ge crystal
→ n$^+$ contact by Li evaporation onto lapped surface
→p$^+$ contact by metal to semiconductor surface barrier junction.
→Needs to be kept at 77K (LN$_2$) during operation to reduce leakage current.

So, the germanium detector that are now available with highly pure crystals are called HPGe high purity germanium detector. This is a particular photograph of a detector so you have the crystal here germanium crystal which is in the vacuum because it should not come to room temperature.

So when you are using them for gamma spectroscopy to further reduce the leakage current they need to be kept at liquid nitrogen and so you have a cold finger connected to the cryostate then you need to have a detector vacuum otherwise it will start sweating and then you have the system for different geometry with the samples at different distance and you have the preamplifier all inside this casing so we have a FET (field effective transistor) to take care of the shaping of the pulse. So this is the typical 30 litre dewar containing liquid nitrogen to cool the detector when it is in operation. So the HPGe detector has concentrations of impurity less than 10^{10} atoms per cc and depending upon whether you take n-type or p-type you can have the germanium detector based on them. If it is a p-type germanium crystal then you can prepare a n-contact by lithium evaporation onto lapped surface or if it is an n-type you can make a p-type contact a surface barrier means you etch this with an acid and then expose to air you get oxide layer.

So that is how you can make n-type and p-type junctions on both sides of an intrinsic germanium detector. Of course earlier times you know people did not have high purity germanium so you have to diffuse lithium they call lithium drifted germanium detectors but once you drift lithium in germanium it has to be always kept at liquid nitrogen otherwise this lithium will keep on drifting at room temperature. So there was a drawback of lithium drifted germanium detectors (Ge(Li) but now we do not need the Ge(Li) detectors we have the intrinsic germanium only when you want to operate them for gamma spectrometry you need to keep it at liquid nitrogen to reduce the leakage current.



HPGe detector: Energy resolution

Very good energy resolution

For 1 MeV gamma ray

$N=E/W = 10^6/3 \sim 3\times10^5$

$R = 2.35\times100/\sqrt{3\times10^5} = \sim0.43\%$

Experimental values are ~0.15%

→ Fano factor

$R=2.35\sqrt{(F/N}$

For semiconductor detector F<1

$(FWHM)^2_{overall} = (FWHM)^2_{stat.} + (FWHM)^2_{noise} + (FWHM)^2_{drift}$

$$\text{Fano factor (F)} = \frac{\text{Observed variance}}{\text{Poisson predicted variance}}$$

Observed variance =FN

1332 keV ^{60}Co R FWHM = 2 keV

$\frac{2}{1332}\times100 = 0.15\%$

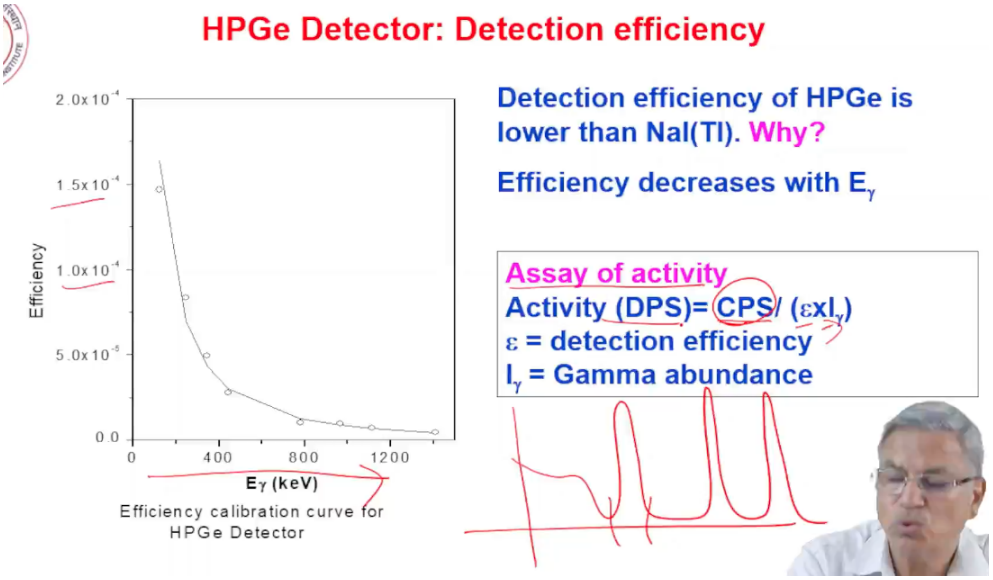
Okay so let us discuss the properties of germanium detector I was mentioning about the energy resolution. So you have excellent resolution in germanium detectors. Let us just typically do a calculation if you have a 1 MeV gamma ray and the W value that is the energy required to produce one electron volt pair, is 3 eV, then for 1 MeV gamma ray you have $10^6/\ 3 = 3\times10^5$ electron hole pairs and if we assume that all of them are collected at the respective electrodes then the resolution is

$R= (2.35/\sqrt{n})* 100\%$ that's a percentage.

So if you calculate this number 2.35 is the FWHM for a Gaussian 2.35 σ and so it becomes $1/\sqrt{n}$ so in terms of percentage so it becomes about 0.43% is the resolution compare this with NaI(Tl) which is about 6 to 7% but this is the calculated resolution and the experimental values are of the order of 0.15. Typically, you know at 1332 keV of 60 cobalt we have the resolution FWHM = 2 keV. So $(2/1332) \times 100$ it goes to 0.15% or so. So this is the kind of resolution that we are getting with the germanium detector. So, this is even better than the what you expect based on the statistical fluctuation in the number of electron hole pairs and that's why the concept of Fano factor (F) that was introduced to take care of the decreased resolution or rather the improved resolution compared to what we expect based on the Poisson's distribution.

So, the Fano factor actually is the reduction in the value of FWHM from the statistical value. So that is $2.35\sqrt{F/N}$ where N is the number of ion pairs that are produced and for semiconductors the Fano factor is less than 1. You can see here 0.15/0.43 that will be the kind of Fano factors that we will be getting. In fact we did not talk about the different factors that are responsible for the improved resolution of the detector because inherently the detector was not having good resolution but in case of germanium the resolution is so good that we start taking care of the different factors that contribute to the FWHM of the gamma ray peak. So we have the statistical fluctuation in the full width at half maximum because of the number of ion pairs of electron volt pairs that we collect that is the statistical factor plus the noise. So when you have a few volts signal then you will find the noise of few millivolts 10, 20 or 30 millivolts will also start affecting the resolution. So, the due to the noise that will add up and the drift over a period of time the system may drift due to the amplifiers, the multi-channel analyzers, different electronic circuits you know will have a small drift.

So, the overall FWHM is actually a resultant of the statistical fluctuation in the fwhm, the noise and the drift in the electronic system. They all add so when you set up a germanium detector you need to reduce the noise, you need to see that there is no drifting in the pulse height and anyway the statistical fluctuations are taken care because of the fano factor being less than one the resolution is anyway excellent. So, these are the kind of state-of-the-art detector systems that people use for gamma spectra. The Fano factor in case of germanium is less than one there are other detector systems where fano factor can be more than one. So fano factor is nothing but observed variance upon Poisson predicted variance 2.35F/√N. So, if you expect N ion pairs then the observed variance is less than N by a factor of F where F is less than one. So excellent resolution for germanium detectors for gamma rays.



HPGe Detector: Detection efficiency

Efficiency calibration curve for HPGe Detector

Detection efficiency of HPGe is lower than NaI(Tl). Why?

Efficiency decreases with E_γ

Assay of activity

Activity (DPS)= CPS/ $(\varepsilon x I_\gamma)$

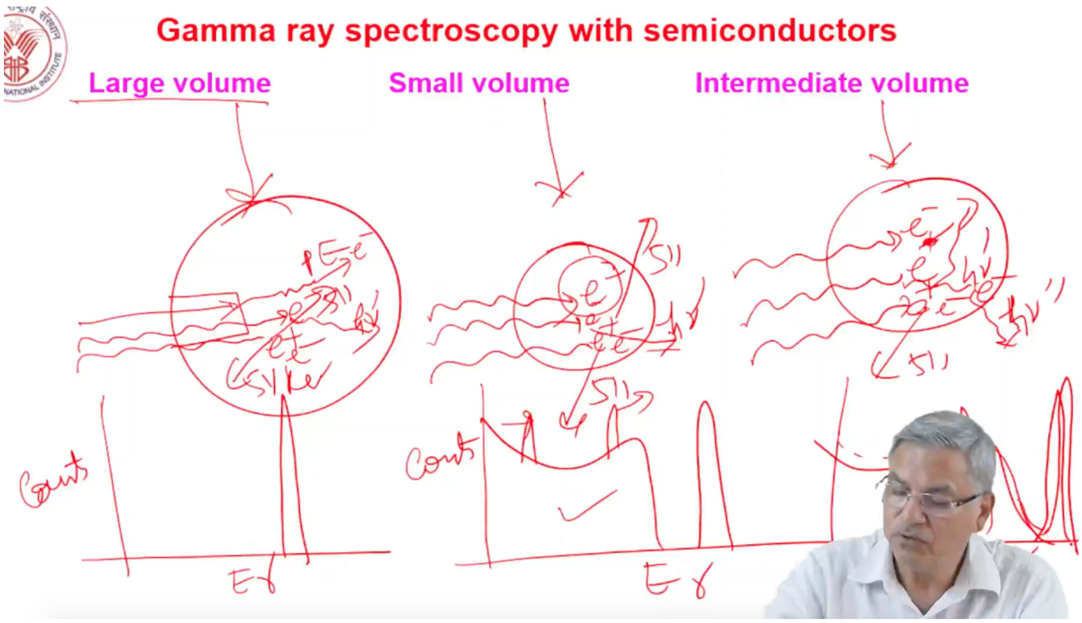
ε = detection efficiency

I_γ = Gamma abundance

Second part is the detection efficiency and the detection efficiency of a system depends upon the atomic number because the photo fraction will be high with the high atomic number for NaI(Tl), iodine, Z=53 for lanthanum bromide, lanthanum, Z = 57 and so on. So high Z of a material will lead to high photo fraction. For germanium atomic number 32 and so the photo fraction is less and therefore we will find that inherently the detection efficiency for the photo peak is less than NaI(Tl).

Otherwise also in general in the case of the gamma detection the efficiency for detection decreases with the increasing energy because the photoelectric effect probability decreases with the increasing energy of the gamma. So typical efficiency you can see here $1.5x10^{-4}$ and so in that range it can be 10^{-4} 10^{-3} and so on. So, when you are doing the efficiency calibration for the gamma ray you need to take the source of multiple gamma energy and calculate the efficiency by this formula. So here when you do assay of activity so what you do in the peak area you will see a gamma spectrum like this.

You take the peak area so divide by the time will be counts per second and this counts per second divide by the efficiency of detection into the branching intensity of gamma ray to get the absolute activity. In other words you want to get efficiency to take a source of known activity, measure the counts per second, intensity of the gamma ray is known so you can determine the efficiency. That is what is plotted here as a function of gamma ray. Now as I mentioned already detection efficiency of the germanium detector is much less than sodium iodide thallium. Why? Because of the low atomic number of germanium and the efficiency decreases with the increasing energy of the gamma ray because the photoelectric absorption cross section decreases with the increasing energy of the gamma ray.



Gamma ray spectroscopy with semiconductors

Large volume

Small volume

Intermediate volume

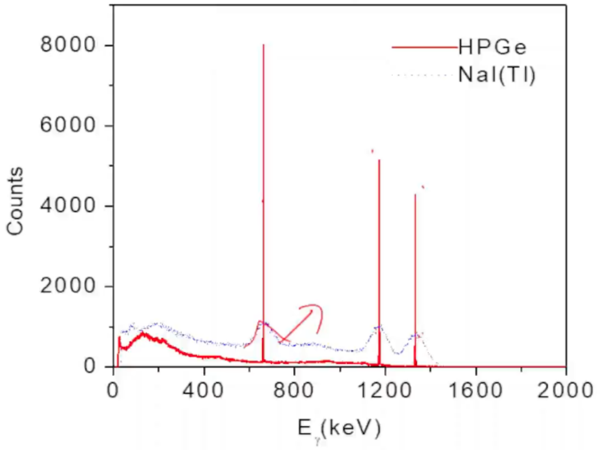
Now let us see how a gamma spectrum is appearing in the case of gamma spectrometry with semiconductors. So I will take two to three cases.

One is a large volume detector so I will take a case of a large volume detector and you can even take a well type. So, you could take this one you take a well type germanium it is like a sphere and the gamma ray comes it interacts by a photoelectric effect so it will give an electron and the photon is absorbed. So this electron will deposit energy in detector material another gamma ray comes and undergo the Compton scattering and then detector is large in volume so Compton scattered photon also may further undergo photoelectric effect and deposits all energy. Similarly, you can have a gamma ray going for pair production so electron positron is produced and this positron may annihilate with another electron to give to 511 keV gamma ray. So, all these 511 keV photons also may get absorbed because the volume of detector is large. So because of this large volume detector all three processes photoelectric effect Compton scattering and pair production so this is the gamma ray energy and this is the counts you will find you will have the full energy deposition in the detector and so gamma ray spectrum will have a single peak. So for large volume detectors you get a single peak in the gamma spectrum but that is a little bit hypothetical case it may not be possible to have a such a large volume detector.

Let us discuss about the small detector so you have a small detector whereby you have again the gamma ray undergoing photoelectric effect in generating an electron and the photon is absorbed so in this particular process will give to full energy deposition. Now you have the Compton scattering electron and the hν' and because the detector is very small in size the Compton photon may escape. Similarly, the pair production electron positron pair this may annihilate and give two 511 keV gamma rays. This 511 keV gamma rays may escape the detector volume because it is small in size. So only the photoelectron that is depositing energy as a result of these processes you will see counts you will have a full energy deposition and you will have a Compton scattering. The Compton scattered photon are escaping you get a Compton edge and since the 511 keV photons are escaping you will see here single photon escape and double photon escape of 511 keV. This is the scenario for a small detector.

Now let us see for the intermediate volume that is the practical size that we will be using. So you have a slightly bigger detector now compared to small one we have here the photoelectric effect the photoelectron depositing energy in the detector volume. We have the Compton scattering electron is depositing and the photon is there. This photon may further undergo photoelectric effect giving rise to electron and some part of hν'' may escape. After second one more scattered and the pair production of course is possible that the electron positron pair is produced one part 511 may escape but other may not escape. So, the net result of these three processes you will see in now the intermediate volume detector is gamma so you have the photoelectric peak due to photoelectric absorption and now whatever was there earlier the Compton scattering there will be now multiple Compton scattering. So, there will be now the valley will be getting filled here and you may have a single escape peak of hν-511 keV. So this is the typical gamma spectrum that you get with the practical detectors you have the full energy peak you have the Compton edge you have the escape of one of the analysis in gamma ray spectra. So these are the kind of features that you get with a germanium detector when you are doing gamma ray spectrometry.

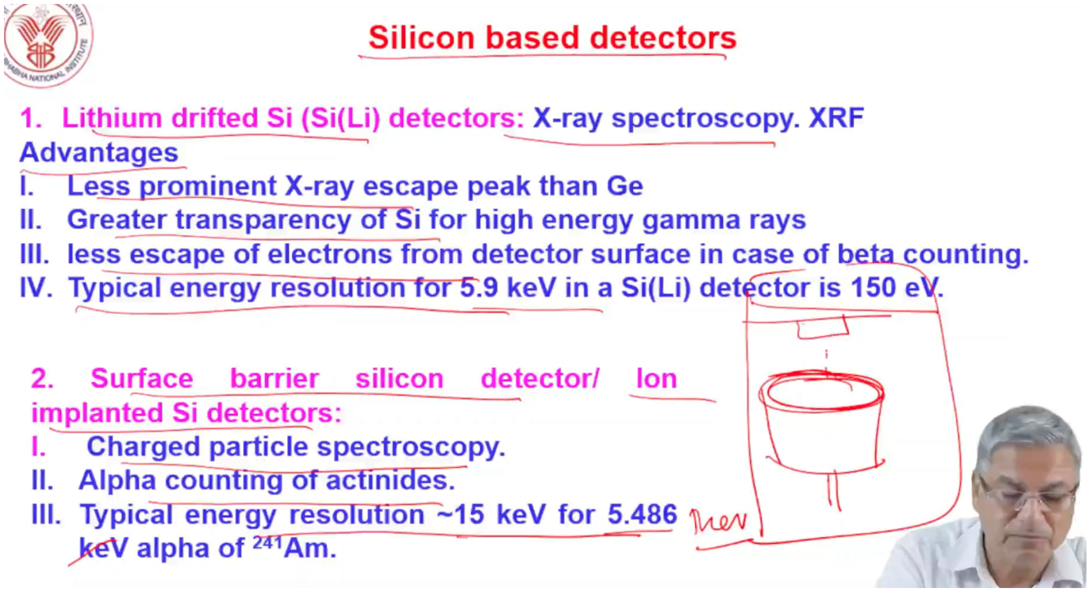
Comparison between HPGe and NaI(Tl)



Gamma ray spectra of ^{137}Cs and ^{60}Co recorded with HPGe and NaI(Tl) detectors

Just to compare the gamma ray spectra with the sodium iodide thallium for the germanium detectors you can see here the blue one is for the sodium iodide thallium you can see two gamma rays of cobalt 60 1172 and 1332 and this is due to cesium-137 gamma ray 660 keV and over the same spectrum which is superimposed a gamma spectrum due to germanium detector you can see here 662, 1172 and 1332 the resolution due to the germanium is much much better compared to that of the sodium iodide. So, whenever if you are doing gamma spectroscopy always go for germanium detectors of course germanium detectors are little costly the typical cost of a germanium detector will be about 15 to 20 lakhs whereas a sodium iodide thallium will cost anywhere between 2 to 3 lakhs.

So, one has to decide the kind of information that you want if you want the high resolution you have to go for germanium detector systems.



Silicon based detectors

1. **Lithium drifted Si (Si(Li) detectors:** X-ray spectroscopy. XRF

Advantages

- I. Less prominent X-ray escape peak than Ge
- II. Greater transparency of Si for high energy gamma rays
- III. less escape of electrons from detector surface in case of beta counting.
- IV. Typical energy resolution for 5.9 keV in a Si(Li) detector is 150 eV.

2. **Surface barrier silicon detector/ Ion implanted Si detectors:**

- I. Charged particle spectroscopy.
- II. Alpha counting of actinides.
- III. Typical energy resolution ~15 keV for 5.486 Mev ~~keV~~ alpha of ^{241}Am.

Now so detectors based on germanium are widely used for gamma ray spectroscopy but in addition to that there are detectors based on silicon or there are also called lithium drifted silicon that is called Si(Li) detectors. In fact see for if you want to do for x-ray counting you cannot use germanium because the germanium will have its own x-ray and that x-ray may escape from the germanium crystal. So if you use a small germanium crystal for x-ray counting then you may have problem of germanium x-ray escape. Whereas in the case of silicon the x-ray is very small energy and so x-ray escape probabilities are much low.

So, if you are doing x-ray counting go for lithium-difted silicon. Now why lithium-difted silicon because silicon alone you may not be able to have a big size silicon so you as you compensate for the p-type impurity by diffusing lithium and in silicon in fact the lithium does not diffuse at room temperature. So once you diffuse lithium at high temperature it remains in the silicon at its position. So, for x-ray spectroscopy or x-ray fluorescence experiments if you use x-ray counting you use lithium-drifted silicon detectors.

Advantages of these Si(Li) detectors are many. They have their less prominent x-ray escape compared to germanium so the problem is not there. Then the greater transparency of silicon for high energy gamma. So suppose there is a background of high energy radiations high energy gamma rays they will not impact the spectrum because most of the high energy gamma will pass through the silicon system. Then similarly less escape of electron from detector surface in case of beta counting. You can use for beta counting also so the escape of electron from the surface is much less in the case of silicon.

And lastly the resolution of these detectors is about 150 electron volt for the 5.9 keV of Fe-55. So you will find the silicon detectors based on the lithium-drifted silicon are ideal for x-ray counting. Then if you want to do alpha spectroscopy or alpha counting you can use gas based counters but if you want to do alpha spectroscopy use detectors based on silicon. You can have surface barrier so you have a detector of this type. Very thin you don't need to maybe few millimeters thick silicon and you have this on the surface you have the gold coating you have a source here and you put the whole thing in a vacuum because alpha will get attenuated in the air. So surface barrier silicon detectors where you need the p-type barrier layer on this silicon crystal to make a p-type junction or you can even have ion implanted if you take a p-type silicon then you can have an ion implanted phosphorous layer on the surface to make a n-p junction. So, this silicon detectors for high for alpha counting you don't need a germanium detector you can use a thin silicon crystal because their ranges are very small.

So if you are doing charged particle spectroscopy alpha spectroscopy you are counting actinides for their assay, suppose you have mixture of plutonium and americium they have different alpha energy if you want to resolve them you use silicon based detectors. And the typical resolution of this surface barrier silicon or ion implanted silicon is 15 keV at 5486 keV of the alpha energy. you can see the kind of resolution that you get for alpha spectra in semiconductor detectors. If you are counting mixtures of actinides, plutonium, americium or alpha counting you can simultaneously count alpha of plutonium, and americium in a silicon detector and you can determine their activity.

I have not discussed much about this but the basic principle remain the same in the case of silicon based detectors for alpha counting silicon based lithium drifted silicon for x-ray counting and the germanium detectors for gamma. So today if you are doing the spectroscopy of charged particles or gamma ray go for semiconductor detectors. So I will stop here. Thank you very much. Thank you.