Need of Internal Amplification and Germanium Detector for Investigation of Rare Physics Processes

V. Singh[1*], V. Sharma[1, 2], M. K. Singh[1, 2], L. Singh[1, 2], H. T. Wong[2], M. K. Singh[1], V. S. Subrahmanyam[1]
[1]Nuclear Physics Section, Physics Department, Banaras Hindu University, Varanasi – 221 005, INDIA
[2]Institute of Physics, Academia Sinica, Nankang, Taipei - 11529, TAIWAN
* Email: venkaz@yahoo.com

Introduction

To observe rare physics processes such as low energy neutrino, neutrinoless double beta decay, neutrino – nucleus coherent scattering cross section, search for suitable dark matter candidate etc., require detectors having low background and low threshold. To investigate the above mentioned processes one needs low background detector of mass several kilograms and with threshold less than 500 eV. Now-a-days, we have achieved detection threshold around 200 eV with Ultra-Low Energy High Purity Germanium detector in ionization mode [1]. The drawback of common HPGe detectors is a rather high threshold of 2 to 10 KeV due to a leakage current, electronics and micro-phonic noises. Effective decrease in the threshold by any genuine means would be very attractive.

We have started shading thoughts on the internal proportional amplification of signal method. Internal proportional amplification in the semiconductor detectors is realized in the silicon avalanche photodiodes (APD) [2] and a gain of about 10^2–10^4 is achieved by avalanche multiplication of electrons at 5–6×10^5 V/cm strength of electric field in a narrow p–n junction having several mm^3 sensitive volumes.

Principles and Design

In semiconductor detectors the conditions for internal proportional amplification of electrons can be fulfilled similarly as in a gas proportional counter (PC) or multi-wire proportional chamber (MWPC). As mentioned above that in APD, the critical electric field (E_{cr}) that provides multiplication of electrons at room temperature is equal 5-6 × 10^5 V/cm. The E_{cr} for germanium (HPGe) at liquid nitrogen temperature can be defined from the dependence of electron drift velocity on electric field and energy of production of electron-hole pairs and photons and is equal to 9×10^4 V/cm. In APD and MWPC, E_{cr} is produced by two different ways. But in case of HPGe with a sensitive volume ~100 cm^3, the E_{cr} can be obtained by the similar manner. The electric field in the coaxial HPGe is calculated with consideration of V, inner (R_1) and outer (R_2) radii of crystal and concentration of donor (n-type) or acceptor (p-type) impurities. The magnitude of the volume charge in the sensitive volume of the crystal depends on these impurities. The electric field in the coaxial HPGe detector will be

$$E(r) = \frac{Ne}{2\varepsilon} r - \frac{[V + (Ne/4\varepsilon)(R_2^2 - R_1^2)]}{r \ln(R_2/R_1)}.$$

Where N is impurity concentration, e is the electron charge, ε is the dielectric constant of germanium. The E(r) can be expressed in terms of a depletion voltage V_d that is a minimum required voltage to neutralize the volume charge and to provide the sensitive volume region. For the coaxial HPGe detector considering $R_2 >> R_1$, the $V_d \sim -(Nq/4\varepsilon) R_2^2$. The E(r) can be defined as:

$$E(r) = -\frac{2V_d}{R_2^2} r - \frac{V - V_d}{r \ln(R_2/R_1)}.$$

The coaxial germanium detector with internal amplification is more suitable for the low background spectrometers. It has been estimated that the required inner radius of the HPGe detector should be 20 μm to achieve E_{cr} – magnitude required for avalanche multiplication of electrons in case of zero impurity. The fabrication of inner electrode of such thin radius is not possible with current technology. Therefore, we are considering a realistic case of fabrication of multi-strip planar HPGe with internal amplification similar in design to MWPC.

Electrode Structure

For the planar or coaxial germanium detector, position and spectral resolution improves as noise decreases. This noise is mainly dependent on the detector capacitance and the noise associated with the preamplifier Field Effect Transistors (FETs), which can be further lowered by designs allowing for the FETs to be cooled within the cryostat and make sure that the cryostat must be able to provide sufficient cooling power to preamplifiers otherwise energy resolution will degraded.

The electric Field: Internal Amplification

The electric field near the anode is sufficient for avalanche multiplication of electrons (E >10^5 V/cm). The amplification factor can be estimated as K =

$2^{(h/L)}$, where L is a free electron path for inelastic scattering and h is a length of avalanche region where $E>E_{cr}$. The L value in case of germanium detector at 77K is equal to 0.5 μm and L=3 cm while h = 5 μm. So with these values it is possible to achieve $K=10^3$. If one does not need high amplification factor then it is possible to decrease applied voltage or to increase the strip width (s).

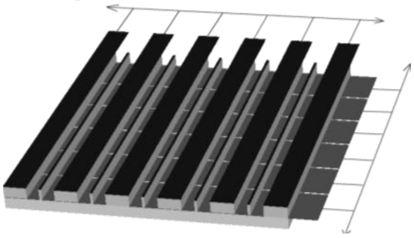

Fig. 1: Typical schematic design of orthogonal strip electrodes.

Complete collection of induced charge is necessary for event identification and pulse shape discrimination. To meet this requirement, parallel plate in high purity germanium detector is necessary. If electrodes are close to the sensitive volume it will help us in achieving low full depletion bias, low collection distances, thickness will not be related to the charge collection distance, charge will not spread, and fast charge sweep out will achieve. If spacing between electrodes will be small it will increase the charge collection due to lower drift distance and will reduce bias voltage as well as increase the electric field strength and therefore, enhances the charge multiplication factors. We should also consider the crystalline structure of germanium which results in a band structure i.e. anisotropic at low temperature and required electric field will be $>10^2$ Vcm^{-1}. This will lead to variations in the drift velocities of holes and electrons and we all know that the pulse shape analysis is dependent on the drift velocity of charge carriers. It means any variation in the strength of electric field will affect the PSA capability of the detector.

Our plan is to work on the design shown in Fig. 2 for the investigation of rare physics processes. For the fabrication of such detector it is necessary to use the HPGe crystals of uniform distribution of impurities to provide homogenous electric field near the anode. Other importance is that it is providing small depth and width of junction layers under the strips so the electric field near the strips is defined by junction dimensions.

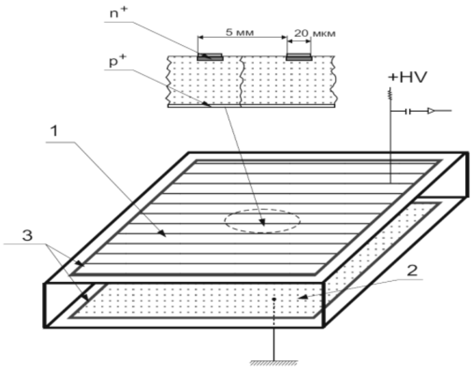

Fig. 2: Schematic diagram of planar germanium detector with orthogonal strips. 1) Charge pickup strips. 2) Sensitive germanium volume. 3) Guard electrodes in the anode and cathode planes. Zoomed portion of pickup strips is shown in the inset.

In case of multi-strip planar germanium detector, with $K>10, \Delta E_{el} \sim I_b f K^2$ the energy resolution

$$\Delta E \approx 2.36K\sqrt{\varepsilon E(F+f)+10^4 I_b \tau f}\,.$$

Where, ε and E is in eV, I_b is in nA and τ is in μs. The detector energy threshold is defined by I_b:

$$E_{th} \geq 2.36\sqrt{10^4.I_b \tau f}\,.$$

The E_{th} for micro-strip planar detector of volume 100 cm^3 with internal amplification at $N=10^{10}cm^{-3}$, $I_b=$ 0.01nA per strip, τ=0.5μs and f=0.5. The derived energy threshold of the planned detector is $E_{th}\geq 12eV$. The dependence of relative energy resolution (ΔE/E) on energy 50(5000) eV is 57% (4.3%). The IA degrades the performance somewhat, but such energy resolution of detector is adequate. It is interesting to note that planar Ge detector of volume $100cm^3$ produced by *Canberra* has relative energy resolution ~8% at energy 5900 eV.

Summary and Outlook

It seems to me that planar segmented HPGe is the requirement of rear decay experiments. We have enough expertise and experiences on data analysis and DAQ handling. Now we should focus and play with detector development and its related electronics. We have already identified various area of improvement and development of segmented HPGe detector and its preamplifier are the thrust areas.

Acknowledgments

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Reference

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