Germanium Detector with Internal Amplification for Investigation of Rare Processes

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Abstract

Device of new type is suggested - germanium detector with internal amplification. Such detector having effective threshold about 10 eV opens up fresh opportunity for investigation of dark matter, measurement of neutrino magnet moment, of neutrino coherent scattering at nuclei and for study of solar neutrino problem. Construction of germanium detector with internal amplification and perspectives of its use are described.

1 Introduction

The detectors having low background and low threshold are required for investigation of rare processes involving low energy neutrino and weak interacting particles. Such detectors can be used effectively for search for the dark matter, for measurement of neutrino magnetic moment and coherent neutrino scattering by nuclei and for investigation of solar neutrino problem.

For above investigations one needs low background detector of mass several kg and with threshold less than 1000 eV. The cryogenic and germanium detectors partly correspond to these requirements. The drawback of the cryogenic detectors is the complexity of their production and use. The drawback of germanium detectors is a rather high threshold 2 ÷ 10 KeV which is due to a leakage current and electronic and microphonic noises. It would be very attractive to provide effective decreasing of the detector threshold using the internal proportional amplification of signal. Internal proportional amplification in the semiconductor detectors is realized now in the silicon avalanche photodiodes (APD) 1, 2, where a gain of about $10^2 ÷ 10^4$ is achieved by avalanche multiplication of electrons at electric field $(5 ÷ 6) \times 10^5 V/cm$ in narrow $p-n$ junction with sensitive volume several $mm^3$. Below we shall demonstrate the possibility of realizing the germanium detector with internal amplification (GDA) and present its design.
2 Principles of GDA and its design.

In semiconductor detectors (as in a gas proportional counter-PC, or multiwire proportional chamber-MWPC) the conditions for internal proportional amplification of electrons can be fulfilled. It is known that in APD critical electric field $E_{cr}$, that provides multiplication of electrons at room temperature, is equal $(5 \div 6) \times 10^5 \text{ V/cm}$. The $E_{cr}$ for germanium 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 [3]. For germanium at 77K the magnitude of $E_{cr}$ derived in this fashion is equal $9 \times 10^4 \text{ V/cm}$. In APD and gas PC the critical electric field is produced by a different way. In the first case $E_{cr}$ is achieved by high concentration of impurities in narrow junction. As a result the sensitive volume of APD is several $\text{mm}^3$. In gas PC the $E_{cr}$ can be achieved by special configuration of the electric field, due to large difference of cathode and anode sizes. In high purity germanium (HPGe) with a sensitive volume near $100 \text{ cm}^3$ the $E_{cr}$ can be obtained by the same manner.

Electric field in the gas cylindrical PC is of the form:

$$E(r) = \frac{V}{r \ln (R_2/R_1)}$$  \hspace{1cm} (1)

where $V$ is applied voltage, $R_1$ and $R_2$ are the radii of cathode and anode correspondingly, $r$ is a distance from anode.

One can see from (1) that at $V = 10^3 \text{ V}$, $R_1 = 0.001 \text{ cm}$ and $R_2 = 1 \text{ cm}$ $E(r)$ is about $10^5 \text{ V/cm}$ near the anode. Unlike gas PC the electric field in the coaxial detector from high purity germanium is defined not only by $V$, $R_1$ and $R_2$ but the concentration of donor (n-type) or acceptor (p-type) impurities as well. The magnitude of the volume charge in the sensitive volume of crystal depends on these impurities. The electric field in coaxial detector from HPGe with regards to the impurities will be [4] :

$$E(r) = \frac{N e}{2\epsilon} r - \frac{[V + (N e/4\epsilon) (R_2^2 - R_1^2)]}{r \ln (R_2/R_1)}$$  \hspace{1cm} (2)

where $N$ is impurity concentration, $e$ is the electron charge, $\epsilon$ is the dielectric constant of germanium.

The electric field (2) can be expressed with a depletion voltage $V_d$, which is a minimum applied voltage necessary to neutralize the volume charge and to provide the sensitive region in the whole crystal volume. The $V_d$ for the coaxial detector, taking into account that $R_2 \gg R_1$, may be given by :

$$V_d \approx -\frac{N q}{4\epsilon} R_2^2$$  \hspace{1cm} (3)

and the equation (2) may be rewritten for n-type germanium in the final form :

$$E(r) = -\frac{2V_d}{R_2^2} r - \frac{V - V_d}{r \ln (R_2/R_1)}$$  \hspace{1cm} (4)
The dependence $E(r)$ on $r$ is shown on fig. 1 for coaxial detector from HPGe. Electric field near the anode reaches $E_{cr}$ - magnitude required for avalanche multiplication of electrons. The coaxial germanium detector with internal amplification is the more appropriate for the low background spectrometers but the possibility of fabrication of inner electrode of 20 micron radius is highly conjectural presently. So we shall consider the more realistic problem - fabrication of planar germanium detector with internal amplification, multistrip planar germanium detector, similar in design to MWPC. The electric field in MWPC is of the form for one dimension case (the coordinates $x$ and $y$ relate to an centered on the wire, $x$ is parallel to the wire plane, $y$ is perpendicular):

$$E(0,y) = \frac{\pi V}{s} \left[ \frac{\pi L}{s} - \ln \frac{\pi d}{s} \right] \coth \frac{\pi y}{s}$$

where $V$ is applied voltage, $s$ is wire spacing, $d$ is a diameter of the wire and $L$ is the thickness of the planar detector. As in the case of coaxial germanium detector one must take into account for multistrip planar germanium detector the depletion voltage $V_d$. In the case of planar germanium detector $V_d = -\frac{N_e}{\epsilon} L^2$. The electric field for multistrip planar germanium detector is of the form:

$$E(0,y) = -\frac{2V_d}{L^2} y - \frac{\pi}{s} \left( \frac{V - V_d}{s} \right) \coth \frac{\pi y}{s}$$

where $d$ is the strip width. The dependence of $E(0,y)$ on $y$ for multistrip planar germanium detector is shown on fig. 2. In the cases being considered 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 $l$ in germanium at 77$K$ is equal 0.5 micron and for $L = 3$ $cm$ $h$ is equal 5 micron (see fig. 2) so for this case it is possible to achieve $K = 10^3$. If one does not need high amplification factor it is possible to decrease $V$ or to increase the strip width $s$.

The GDA is assumed to use for investigation of rare processes so the spectrometer including GDA must have large mass of detector, it can be fabricated from separate modules of mass about 0.7 $kg$ each. One module represents the multistrip planar germanium detector from HPGe having impurity concentration less than $10^{10}$ $cm^{-3}$, measures $70 \times 70 \times 30$ mm$^3$ (see fig.3). The 12 anode strips of 20 micron width and of 65 mm length are fabricated by photomask method [5]. The cathode area is equal 65 $\times$ 65 mm$^2$ and the fiducial volume is equal to 130 cm$^3$. There are the guard electrodes in the anode and cathode planes. The anode strips can be connected together however it is more convenient to take signals from separate strips to suppress the background Compton gamma-quanta.
For the fabrication of GDA it is necessary to use the germanium crystals of uniform distribution of impurities to provide homogenous electric field near the anode. Second in importance it is the providing small depth and width of junction layer under the strips so the electric field near the strips is defined by junction dimensions. The design of GDA must guarantee the reliable cooling of crystal since the critical electric field and amplification factor depend on free path of charge carriers which in its turn depends on temperature.

3 The energy resolution and threshold of GDA.

The energy resolution of semiconductor detector will be given by

$$\Delta E = \sqrt{(\Delta E_{int})^2 + (\Delta E_{el})^2}$$  \hspace{1cm} (7)

where $\Delta E_{int}$ is the intrinsic energy resolution of detector which is defined by statistical fluctuation in the number of charge carriers created in detector sensitive volume, $\Delta E_{el}$ is the energy resolution which is defined by associated electronics. In the case of GDA these two terms will be of form

$$\Delta E_{int} = 2.34\sqrt{\varepsilon E(F + f)K^2}$$  \hspace{1cm} (8)

and

$$\Delta E_{el} = \frac{4.52\varepsilon}{e} \sqrt{\frac{0.6kT}{\tau S}C^2 + kT\tau \left[ \frac{1}{R\Sigma} + \frac{e}{2kT}(I_s + I_b fK^2) \right]}$$  \hspace{1cm} (9)

where $\varepsilon$ is the energy to create one pair of charge carriers, $E$ is the energy deposited in the detector, $F$ is the Fano factor, $f$ is the excess noise factor due to the fluctuation of multiplication, $K$ is the amplification factor, $e$ is the electron charge, $T$ is the absolute temperature of the resistors, $C$ is the total capacitance presented at the input of preamplifier, $\tau$ is the time constant of the RC circuits of the preamplifier, $S$ is the steepness of the field effect transistor characteristic, $R\Sigma$ is the resistance at the input of the preamplifier, $I_s$ is the detector leakage surface current and $I_b$ is the detector leakage bulk current due to the thermal generation of charge carriers. According to the calculation for GDA with $K > 10$ one must take into account in the formula for $\Delta E_{el}$ only the last term due to the bulk leakage current and the formula (7) for GDA can be rewritten as

$$\Delta E \approx 2.36 \cdot K \sqrt{\varepsilon E(F + f) + 10^4I_b\tau f}$$  \hspace{1cm} (10)

where $\varepsilon$ and $E$ is in eV , $I_b$ is in nA and $\tau$ is in $\mu$sec. The GDA energy threshold is defined by $I_b$ or more exactly by the last term in (10):

$$E_{th} \geq 2.36\sqrt{10^4 \cdot I_b\tau f}$$  \hspace{1cm} (11)
One can estimate the $E_{th}$ for microstrip planar detector from HPGe of volume 100 cm$^3$ with internal amplification: at $N=10^{10} cm^{-3}$, $I_b=0.01$ nA per one strip, $\tau=0.5 \, \mu$sec and $f=0.5$ : $E_{th} \geq 12 \, eV$.

The dependance of relative energy resolution $\Delta E/E$ on energy in the more interesting energy range $50 \div 5000 \, eV$ for GDA is shown in table.

| $E$ (eV) | 50 | 200 | 400 | 600 | 800 | 1000 | 5000 |
|----------|----|-----|-----|-----|-----|------|------|
| $\Delta E/E$ (%) | 57 | 25  | 17  | 13  | 11  | 10   | 4.3  |

The internal amplification of GDA degrades the performance somewhat, but such energy resolution of GDA is adequate to the investigation of above problems. It is interesting to note that common planar detector from HPGe of volume 100 cm$^3$ produced by "Canberra" (type GL3825R) has relative energy resolution about 8% at $E=5900 \, eV$.

4 The prospects of GDA use.

Presently germanium detectors are in considerable use in low background measurements for high purity of germanium crystals: their content of radioactive impurity does not exceed $10^{-13} g/g$ [6]. If the internal amplification is realized in germanium detectors and their threshold is lowered to several $eV$ the possibility for their use will considerably increase. Firstly, the lowering of the detector threshold makes it possible to extend the kinematical domain of investigations, secondly, it enables in some cases significantly to decrease the level of background. Following are brief discussions of prospects of GDA using for neutrino magnetic moment ($\mu_\nu$) measurement, for investigation of neutrino coherent scattering by nuclei and for search for "light" WIMPs.

**Neutrino magnetic moment (NMM) measurement.**

A laboratory measurement of the NMM is based on its contribution to the (anti)neutrino - electron scattering. For a non-zero NMM the differential over the kinetic energy $T$ of the recoil electron cross section $d\sigma/dT$ is given by the sum of the weak interaction cross section and the electromagnetic one. At a small recoil energy the weak part practically constant, while the electromagnetic one grows as $1/T$ towards low energies. For improving the sensitivity to $\mu_\nu$ it is necessary to lower the threshold for detecting the recoil electrons as far as the background conditions allow. Now there is number of the projects dedicated to the NMM measurements with detectors of mass $2 \div 1000 \, kg$ and with thresholds of $3 \div 500 \, KeV$. Authors of proposal [7] are going to use germanium detector with mass of 2 kg and threshold
of 3 KeV to achieve for two years reactor measurement the limit on $\mu_\nu \sim 3 \times 10^{-11} \mu_B$, with $\mu_B = e/(2m_e)$ being the Bhorh magneton. The use of GDA with internal amplification in this experiment would provide possibility to achieve limit on $\mu_\nu$ about $2 \times 10^{-11} \mu_B$. However, one can not significantly low the GDA threshold in the reactor experiment for two reasons. Firstly, one must take into account atomic binding effect for electrons. The total $\bar{\nu}_e$ cross section will be 30% less due to the binding effects (in the energy range 200 ÷ 3000 eV). The secondly at $T<500$ eV the effect neutrino coherent scattering (NCS) by germanium nuclei will surpass the effect of $\bar{\nu}_e$ scattering and NCS will present physical background relative to the $\bar{\nu}_e$ scattering. Nevertheless the low GDA threshold can be used in full measure if one uses artificial neutrino source (ANS) instead of reactor. Nowadays there are several proposals on development ANS with activity $5 ÷ 40$ M Ci [8]. Although the development and construction of the ANS is rather expensive and challenging problem the use of ANS offers some advantages over the reactor based experiments:

1) ANS can provide significantly higher neutrino flux density (up to $10^{15} 1/cm^2 \cdot s$),
2) ANS can be used in deep underground laboratory, where level of background is significantly lower than in shallow box near the reactor,
3) one can use the optimum ratio of effect and background measurement times, that is impossible in the reactor experiment,
4) the uncertainties of the neutrino spectrum and flux density are small.

Presently the more appropriate ANS for NMM measurement is a tritium source proposed in [9] for measurement of NMM by means of low threshold cryogenic silicon detector. The end-point energy of tritium beta spectra is 18.6 KeV and for maximum recoil electron energy a kinematical limitation gives:

$$T_{\text{max}} = \frac{2E_\nu^2}{2E_\nu + m_e c^2} = 1260 \text{eV}. \quad \text{(12)}$$

If one uses tritium ANS with activity 40 M Ci then the neutrino density flux will be $6 \times 10^{14} 1/cm^2 \cdot s$ in the detector position. The limit on NMM about $3 \times 10^{-12} \mu_B$ can be achieved during one year measurement time with silicon detector mass of 3 kg in the energy range 1 ÷ 300 eV. The very same limit on NMM can be achieved by use the GDA with mass of 3 kg during one year of measurement time in the energy range 30 ÷ 500 eV. In the GDA case the count rate due to electromagnetic neutrino interaction will be 0.24 event/d (at $\mu_\nu = 3 \times 10^{-12} \mu_B$), the count rate due to weak interaction will be one order of magnitude less. Now let us consider the background count rate. If one takes into account that $\sigma_{EM} \sim \ln (T_{\text{max}}/T_{\text{min}})$ then the value of $\sigma_{EM}$ in the energy range $3 ÷ 50$ KeV($\Delta E_1$) and $30 ÷ 500$ eV($\Delta E_2$) will be the very same. The best level of background for germanium detector was achieved in [10] and it is equal 0.1 event/keV-kg-d. If one assume that level of background does not depend on energy in the energy range of interest then the level of background in
the second energy interval will be two order of magnitude less since \((\Delta E_2/\Delta E_1) \sim 10^{-2}\) and will be 0.15 event/d. In addition in the case of tritium ANS there is no physical background due to the NCS since in this case the maximum recoil energy of germanium nuclei \(T^a_{\text{max}}\) is equal 0.01 eV.

**Neutrino coherent scattering by nuclei.**

The use of GDA can open up the possibility to investigate the coherent neutrino scattering by nuclei. This interaction is of great importance into interstellar processes and up to now did not observed in laboratory because the very low kinetic energy transferred to nucleus in the process of neutrino-nucleus scattering. For germanium nucleus and reactor antineutrino spectrum the maximum kinetic recoil energy is about \(T^a_{\text{max}}=2500\) eV and taking into account quenching effect only one third of this energy are imparted on ionization \[^{[1]}\]. So one needs germanium detector with threshold significantly lower 800 eV for investigation of NCS by germanium nuclei. Such low threshold can be provided by GDA having internal amplification about 10^2. The differential cross section of NCS by nuclei \[^{[12],[13]}\] can be expressed by:

\[
\begin{align*}
\frac{d\sigma^c_W}{dT} &\sim \frac{G_F^2}{4\pi} N^2 M \left(1 - \frac{M T_n^a}{2 E^2_{\nu}}\right) \\
\frac{d\sigma^c_{\text{EM}}}{dT} &\sim \left(\frac{\mu_w}{\mu_B}\right)^2 \pi \alpha^2 m_e^2 Z^2 \left(\frac{1}{T_n}\right)
\end{align*}
\]

where \(M, N\) and \(Z\) are the mass, neutron and charge numbers of nuclei correspondingly and \(T^a\) - nucleus recoil energy. If one uses GDA with mass of 3 kg and threshold 30 eV in the reactor experiment the count rate due NCS in the energy range \(30 \div 300\) eV will be near 100 event/d at antineutrino intensity \(2 \times 10^{13} \nu/cm^2 \cdot s\) due to the weak interaction. The count rate due to the electromagnetic interaction (at \(\mu_w = 2 \times 10^{-11} \mu_B\)) will be 0.45 event/d. The level of detector background will be only 0.1 event/d if one uses the above estimations of detector background, taking into account that the energy range is equal 0.3 KeV in this case. So one can see that use of GDA for measurement NCS makes it possible:

- to improve the weak interaction constants,
- to investigate the neutrino oscillations by alternative way,
- to make more precise the quenching factor for germanium nuclei at low energy transfer which is of interest for dark matter experiments.

**The GDA use in the Dark Matter Experiment.**

Presently in Dark Matter Experiments the main efforts are directed at decreasing of the background and lowering of the energy threshold of the detector, since for more appropriate dark matter candidate- WIMPs or weakly interacting massive particles - the expected count
rate for WIMPs-nuclear scattering is in the range $0.001 \div 1.0$ event/kg·d and expected recoil energy $T^a$ lies in the wide energy range beginning of some tens eV and above. Significant success was achieved by CDMS (Cryogenic Dark Matter Search) collaboration in radiation background decreasing \[^{14}\]. The rejection of 99% of photon background was achieved use detectors which simultaneously measure the recoil energy in both-photon and charge mediated signals. However, this method is effective at detector threshold above 15 KeV. So experiments for search for WIMPs with mass lower than 10 Gev/$c^2$ (at very low T) are carried out now by CRESST (Cryogenic Rare Event Search with Superconducting Thermometers) collaboration \[^{15}\] which plans to use cryogenic detector including four 250 g sapphire detectors with threshold 500 eV. The using of several GDA modules of mass 1 kg each with threshold about 30 eV would be very effective in this investigations.

The investigation of Solar Neutrino Problem with use GDA can provide possibility to detect simultaneously the whole neutrino spectrum \[^{12}\] but one needs of course to use large mass detector in this case. It is beleived that GDA being developed will find also use in the applied fields.

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References

[1] J. P. Pansart, Nucl. Instr. and Meth. A387 (1997) 186.

[2] R. Farrel, F. Olschner, K. Shah, M. R. Squillante, Nucl. Instr. and Meth. A387 (1997) 194.

[3] G. Bertolini and A. Coche, Semiconductor Detectors. North-Holland publishing company - Amsterdam, 1968, p. 71 ; E. Sakrai, H. L. Malm and I. L. Fovler, paper presented at the Gatlinburg Conference (1967).

[4] J. M. Marler, P. V. Hewka, IEEE NS - 21, n.1 (1974) 287.

[5] D. Gutknecht, Nucl. Instr. and Meth. A288 (1990) 13.

[6] A. A. Vasenko, I. V. Kirpichnikov, A. S. Starostin et al, Mod. Phys. Lett. A5, n.17 (1990) 1299-1306.

[7] A. G. Beda, E. V. Demidova, A. S. Starostin and M. B. Voloshin, Yad. Fiz. 61, n.1 (1998) 72 [Phys.At.Nucl. (Engl. Transl.) 61, n.1 (1998) 66].
[8] V. N. Karnoukhov, ITEP Report N 90-94, 1994; A. V. Davydov and Yu. N. Isaev, Yadern. Fiz. 59, n.3 (1996) 486 [Phys. At. Nucl. (Engl. Transl.) 59, n.3 (1996) 459]. L. A. Mikaelyan, V. V. Sinev, and S. A. Fayans, Pis’ma Zh. Eksp. Teor. Fiz. 67, No.7, 435 [JETP Letters (Engl. Transl.), 67, No.7 (1998) p. 453].

[9] V. N. Trofimov, B. S. Neganov and A. A. Yukhimchuk, Yad. Fiz. 61 (1998) 1373.

[10] Brodzinski, R. L., Avignone, F. T., et al., Nucl. Instrum. Methods A 292 (1990) 337. Beck M. et al. (Haidelberg-Moscow Coll.), Phys. Lett. 336B (1994) 141.

[11] R. Bernabei, Riv. Nuovo Cimento 18, n.5 (1995) 35.

[12] B. Cabrera, L. M. Krauss and F. Wilczek, Phys. Rev. Lett. 55 (1985) 25.

[13] A. C. Dodd, E. Papageorgiu and S. Ranfone, Phys. Lett. B 266 (1991) 434.

[14] D. S. Akerib, D. O. Caldwell, B. Sadoulet et al., astro-ph/9712343; Rep. at TAUP97 Conf., Sept 7-11, 1997, LNGS, Italy.

[15] M. Buhler, L. Zerle, F. Probst et al., Nucl. Instr. and Meth. A 370 (1996) 237.
Figure 1: Dependence of the electric field on $r$ for axial detector from HPGe n-type at $V = 4000 \, V$, $R_1 = 0.002 \, cm$, $R_2 = 3.0 \, cm$ and at different impurity concentrations: 1 - $N = 10^{10} \, cm^{-3}$, 2 - $N = 4 \times 10^9 \, cm^{-3}$, 3 - $N = 0$ (volume charge is absent).
Figure 2: Dependence $E(0,y)$ on $y$ for planar detector from HPGe n-type with $d = 20$ microns at $V = 4000$ V and at different values of the others parameters: 1 - $N = 10^{10}$ cm$^{-3}$, $L = 1.5$ cm and $s = 0.3$ cm; 2 - $N = 0$ (volume charge is absent), $L = 2.0$ cm and $s = 0.5$ cm; 3 - $N = 2 \times 10^9$ cm$^{-3}$, $L = 3.0$ cm and $s = 0.5$ cm. For (1) and (3) the length of avalanche region is equal 10 and 5 microns, accordingly.
Figure 3: Germanium detector with internal amplification. 1 - anode strips, 2 - cathode, 3 - guard electrodes, the scheme of $n^+$ and $p^+$ - layers are shown in the upper part.