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EXPERIMENTAL RESULTS, METHODS, AND FACILITIES

Germanium Detector with an Internal Amplification for Investigating Rare Processes*

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Abstract—A device of a new type—a germanium detector with an internal amplification—is proposed. Having the effective threshold of about 10 eV, the detector opens up a fresh opportunity for investigating dark matter, measuring the neutrino magnetic moment, exploring coherent neutrino scattering off nuclei, and studying the solar-neutrino problem. The design of the germanium detector with an internal amplification and prospects for its use are described. © *2000 MAIK "Nauka/Interperiodica".*

1. INTRODUCTION

Detectors with a low background and a low energy threshold are required for investigating rare processes that involve low-energy neutrinos and weakly interacting particles. These detectors can be effectively used to seek dark matter, to measure the neutrino magnetic moment and coherent neutrino scattering off nuclei, and to investigate the solar-neutrino problem. For these purposes, one needs a low-background detector with a mass of a few kg and with a threshold energy less than 1000 eV. Cryogenic and germanium detectors comply partly with these requirements. A drawback of cryogenic detectors is the complexity of their production and use. A drawback of germanium detectors is a rather high threshold of 2–10-keV, which is due to a leakage current and electronic and microphonic noises. It would be very attractive to provide an effective decrease in the detector threshold by an internal proportional amplification of the signal. An internal proportional amplification in semiconductor detectors (SD) is realized now in silicon avalanche photodiodes (APD) [1, 2], where a gain of about 10^2–10^4 is achieved by an avalanche multiplication of electrons at the electric field of $(5–6) \times 10^5$ V/cm in a narrow *p*–*n* junction with a sensitive volume of a few mm^3. Below, we demonstrate the possibility of implementing a germanium detector with internal amplification (GDA) and present its design.

2. PRINCIPLES OF A GDA AND ITS DESIGN

There are conditions for an internal proportional amplification of electrons in semiconductor detectors as well as in a gas proportional counter (PC) or a multiwire proportional chamber (MWPC). It is well known that, in an APD, the critical electric field E_{cr}, which provides the multiplication of electrons at room temperature, is equal to $(5–6) \times 10^5$ V/cm. The field E_{cr} for germanium at liquid-nitrogen temperature can be found from the dependence of the electron drift velocity on the electric field and on the energy of the production of electron–hole pairs and photons [3]. For germanium at 77 K, E_{cr} derived in this way is 9×10^4 V/cm. In an APD and a gas PC, the critical electric field is produced in a different way. In the first case, E_{cr} is achieved by a high concentration of impurities in a narrow junction. As a result, the sensitive volume of the APD is about a few mm^3. In the gas PC, E_{cr} can be achieved by a special configuration of the electric field due to a large difference between the sizes of the cathode and the anode. In high-purity germanium (HPGe) with a sensitive volume of about 100 cm^3, E_{cr} can be obtained in the same way. The electric field in a cylindrical gas PC is

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

where V is the applied voltage; R_1 and R_2 are the radii of the cathode and the anode, respectively; and r is the distance from the anode. One can see from (1) that, at $V = 10^3$ V, $R_1 = 0.001$ cm, and $R_2 = 1$ cm, $E(r)$ is about 10^5 V/cm near the anode.

In contrast to the case of a gas PC, the electric field in a coaxial HPGe detector is determined not only by V, R_1, and R_2, but also by the 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 an HPGe coaxial detector with regards to the impurities is [4]

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

where N is the impurity concentration, e is the electron charge, and ϵ is the dielectric constant of the germanium. The electric field (2) can be expressed in terms of the depletion voltage V_d, which is a minimum voltage necessary for neutralizing the volume charge and to provide the sensitive region in the entire crystal vol-

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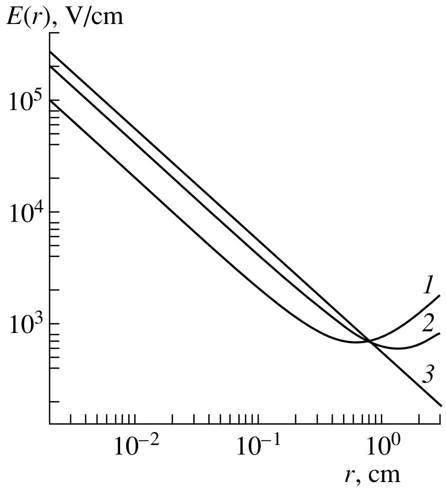

Fig. 1. Electric field as a function of r for an axial HPGe detector of the p type with $V = 4000$ V, $R_1 = 0.002$ cm, and $R_2 = 3.0$ cm for the impurity concentrations of $N = (1)\ 10^{10}$, $(2)\ 4 \times 10^9$, and (3) 0 (no volume charge) cm^{-3}.

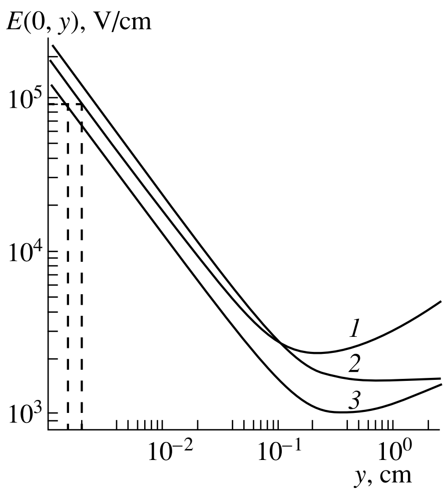

Fig. 2. Dependence $E(0, y)$ for a planar HPGe detector of the p type with $d = 20$ μm and various values of other parameters: (*1*) $N = 10^{10}$ cm^{-3}, $L = 1.5$ cm, and $s = 0.3$ cm; (*2*) $N = 0$ (no volume charge is present), $L = 2.0$ cm, and $s = 0.5$ cm; and (*3*) $N = 2 \times 10^9$ cm^{-3}, $L = 3.0$ cm, and $s = 0.5$ cm. For the options characterized by the parameter values in items (*1*) and (*3*), the length of the avalanche region is 10 and 5 μm, respectively.

ume. Under the assumption that $R_2 \gg R_1$, V_d for the coaxial detector is given by

$$V_d \approx -\frac{Nq}{4\epsilon} R_2^2. \qquad (3)$$

Equation (2) can be recast into the final form

$$E(r) = -\frac{2V_d}{R_2^2} r - \frac{V - V_d}{r \ln(R_2/R_1)}. \qquad (4)$$

The dependence of E on r is shown in Fig. 1 for a coaxial HPGe detector. The electric field near the anode reaches E_{cr}, which is required for the avalanche multiplication of electrons. The coaxial germanium detector with an internal amplification is more appropriate for low-background spectrometers, but the possibility of manufacturing the inner electrode of radius 20 μm is highly doubtful at present. Therefore, we consider a more realistic problem—a fabrication of a planar germanium detector with an internal amplification by using modern technology. A multistrip planar germanium detector is similar in design to an MWPC. The electric field in the MWPC has the form (one-dimensional case)

$$E(0, y) = \frac{\pi V}{s\left[\frac{\pi L}{s} - \ln\frac{\pi d}{s}\right]} \coth\frac{\pi y}{s}, \qquad (5)$$

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

$$E(0, y) = -\frac{2V_d}{L^2} y - \frac{\pi(V - V_d)}{s\left[\frac{\pi L}{s} - \ln\frac{\pi d}{s}\right]} \coth\frac{\pi y}{s}, \qquad (6)$$

where d is the strip width. The dependence $E(0, y)$ for an MGD is shown in Fig. 2. In both cases considered, the electric field near the anode is sufficient for giving rise to an avalanche multiplication of electrons ($E > 10^5$ V/cm). The amplification factor can be estimated as $K = 2^{h/l}$; here, l is the free electron path for inelastic scattering, and h is the length of the avalanche region where $E > E_{cr}$. The free electron path in germanium at 77 K is 0.5 μm, and, for $L = 3$ cm, h is equal to 5 μm (Fig. 2); therefore, it is possible to achieve $K = 10^3$. If one does not need a high amplification factor, it is possible to decrease V or to increase the strip width s.

It is assumed to use a GDA for investigating rare processes; therefore, a spectrometer with a GDA must have a large mass of the detector. It can be manufactured from separate modules of weight about 0.7 kg each. One module includes a multistrip planar germanium detector constructed from HPGe (p type) with an impurity contamination less than 10^{10} cm^{-3} and a volume of $70 \times 70 \times 30$ mm^3 (Fig. 3). Twelve anode strips 20 μm wide and 65 mm long are manufactured by the photomask method [5]. The cathode area is 65×65 mm^2, and the fiducial volume is 130 cm^3. There are guard electrodes in the anode and cathode planes. The anode strips can be connected together; however, it is more convenient to pick up signals from separate strips to suppress the background Compton photons.

In order to manufacture a GDA, it is necessary to use germanium crystals with a uniform distribution of impurities to provide a uniform electric field near the anode. Second, it is important to provide a small depth and width of the junction layer under the strips, which allows the electric field near the strips to be determined by junction dimensions. The design of the GDA must provide stable cooling of the crystal since the critical electric field and the amplification factor depend on the free path of charge carriers, which in turn depends on temperature.

3. ENERGY RESOLUTION AND THRESHOLD OF GDA

The energy resolution of a semiconductor detector is given by

$$\Delta E = \sqrt{(\Delta E_{\rm int})^2 + (\Delta E_{\rm el})^2}, \quad (7)$$

where $\Delta E_{\rm int}$ is a quantity that has the meaning of an intrinsic energy resolution of the detector and which is determined by statistical fluctuations in the number of charge carriers created in the detector sensitive volume, while $\Delta E_{\rm el}$ is the energy resolution determined by associated electronics. In the case of a GDA, these two terms are

$$\Delta E_{\rm int} = 2.34\sqrt{\varepsilon E(F+f)K^2}, \quad (8)$$

$$\Delta E_{\rm el} = \frac{4.52\varepsilon}{e}\sqrt{\frac{0.6kT}{\tau S}C^2 + kT\tau\left[\frac{1}{R_\Sigma} + \frac{e}{2kT}(I_s + I_b f K^2)\right]}, \quad (9)$$

where ε is the energy required for creating 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 the multiplication, K is the amplification factor, e is the electron charge, T is the absolute temperature of the resistors, C is the total capacitance at the input of the preamplifier, τ is the time constant of the RC circuits of the preamplifier, S is the steepness of the field-effect transistor, R_Σ is the resistance at the input of the preamplifier, I_s is the surface leakage current of the detector, and I_b is the bulk leakage current of the detector due to a thermal generation of charge carriers. According to the calculation for a GDA with $K >$ 10, one must take into account, in the formula for $\Delta E_{\rm el}$, only the last term due to the bulk leakage current, and formula (7) for the GDA can be rewritten as

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

where ε and E are in eV, I_b is in nA, and τ is in µs. The GDA energy threshold is determined by I_b, or, more precisely, by the last term in (10):

$$E_{\rm th} \geq \sqrt{5.8\times 10^4 I_b \tau f}. \quad (11)$$

Relative energy resolution $\Delta E/E$ versus energy

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

One can estimate $E_{\rm th}$ for a microstrip planar HPGe detector with an internal amplification of volume 100 cm^3 as follows. At $N = 10^{10}$ cm^{-3}, $I_b = 0.01$ nA per strip, $\tau = 0.5$ µs, and $f = 0.5$, one has $E_{\rm th} \geq 12$ eV. The dependence of the relative energy resolution $\Delta E/E$ on energy in the more interesting energy range 50–5000 eV for a GDA is shown in the table.

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

4. PROSPECTS FOR USING GDA

Presently, germanium detectors are in considerable use in low-background measurements for high purity of germanium crystals: their radioactive-impurity content does not exceed 10^{-13} g/g. If the internal amplification is realized in germanium detectors and if their threshold is lowered to a few eV, the possibility of using them will considerably increase.

In dark-matter experiments, the main effort is presently aimed at suppressing the background and at lowering the energy threshold. In searches for dark-matter

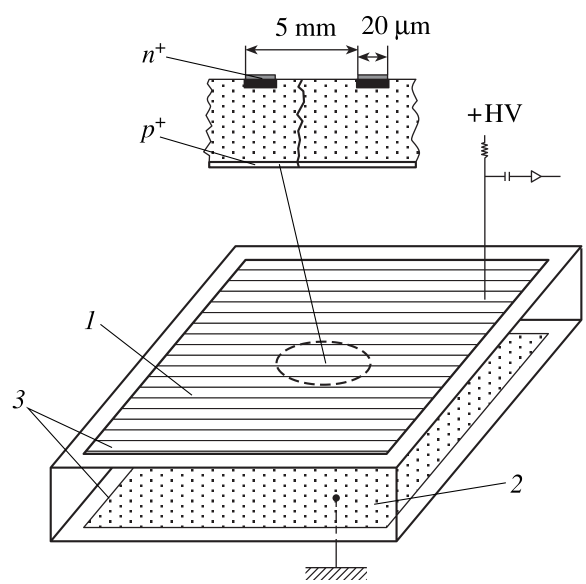

Fig. 3. Germanium detector with an internal amplification (schematic view): (*1*) anode strips, (*2*) cathode, and (*3*) guard electrodes. The scheme of n^+ and p^+ layers is shown in the upper part of the figure.

particles in the low-mass range, the CRESST collaboration is planning to use a cryogenic detector with four 250-g sapphire detectors having a threshold energy of 500 eV [6]. The use of several GDAs of mass 1 kg each with a threshold about 10 eV would be very effective in this investigations.

Nowadays, there are several projects devoted to measuring the neutrino magnetic moment (NMM). In this case, one needs a low-background and low-threshold detector again. In general, the threshold of the detectors aimed at searches for the neutrino magnetic moment is about a few hundred keV, but, in [7], the authors plan to use a low-background germanium spectrometer of mass 2 kg with a threshold of 4 keV to achieve the limit on the neutrino magnetic moment about $4 \times 10^{-11}\mu_B$ (μ_B is the Bohr magneton) within two years of reactor measurements. Now, there is a project that combines an artificial tritium antineutrino source of 40 MCi with a cryogenic silicon detector having a mass of 3 kg and a threshold of a few eV [8]. The goal of this project is to push the limit on the neutrino magnetic moment down to $3 \times 10^{-12}\mu_B$ within one year of measurements.

Detectors of the GDA type can open up the possibility of investigating coherent neutrino scattering by nuclei. This interaction is of great importance in interstellar processes; so far, it has not been observed in a laboratory because of very low kinetic-energy transfer to a nucleus. For the germanium nucleus and the reactor-antineutrino spectrum, the maximum kinetic recoil energy is about 2.5 keV, and only one third of the energy is imparted to the electron on ionization. If, in a reactor experiment, one uses a GDA with a threshold of 10 eV, it is possible to detect about 70 event/(kg d) at the antineutrino intensity of 2×10^{13} ν/cm^2 s due to weak interaction. The counting rate due to electromagnetic interaction (at $\mu_\nu = 3 \times 10^{-11}\mu_B$) will be about 0.15 event/(kg d). Thus, the measurement of coherent neutrino scattering with a GDA makes it possible (i) to refine our knowledge of the weak-interaction constants; (ii) to investigate neutrino oscillations in an alternative way; (iii) to set the more stringent limit on the NMM; and (iv) to measure more accurately the quenching factor for germanium at low energy transfer, which is of interest for dark-matter experiments.

The investigation of the solar-neutrino problem with a GDA can allow a simultaneous measurement of the whole neutrino spectrum, but one needs a large-mass detector in this case. It is believed that GDAs will find wide use in applied fields.

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