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**GALLIUM ARSENIDE PARTICLE DETECTORS: A STUDY
OF THE ACTIVE REGION AND CHARGE-COLLECTION EFFICIENCY**

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Abstract

Gallium arsenide particle detectors made by Alenia SpA have been tested within the context of the RD-8 project and found to have a high charge-collection efficiency (75%). We have analysed the data and found the overall behaviour of these detectors to be coherent and understandable in terms of one function: the local charge-collection efficiency. Two ways have been used to measure the width of the active region and the increase of such a width as a function of bias is found not to be consistent with a simple square-root law.

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1. Introduction

Gallium arsenide (GaAs) particle detectors have been shown to work with full detection efficiency and to be radiation hard to substantial doses of γ and neutrons [1, 2]. The only unsatisfactory aspect of these detectors is the partial charge-collection efficiency (cce), i.e. only a fraction of the charge released by a minimum ionizing particle (mip) (a 3.5 MeV beta particle in our tests) gets collected. This is due to two facts: a) the electric collection field inside the detector does not easily reach the back of the detector and b) there is trapping even where there is field [3]. Presumably this is due to the presence of deep energy levels near the middle of the forbidden gap [4, 5]. By getting ionized when the bias is applied to the detector, these levels prevent the collection field from extending through the detector and act as traps.

Detectors built by Alenia SpA on Sumitomo material have reached a high collection field with a cce of 75%. We have measured, together with the cce, the behaviour of the width (W) of the active region (i.e. the region where the charge collection is non zero) as a function of the applied bias with two methods. The question of the functional dependence of W on bias is very relevant since any model of the electric field will have to predict a square-root dependence if it assumes a constant charge distribution in the active region. Eventually any model of the detector will have to predict this behaviour of W as a function of bias, starting from the analysis of the traps: their energy, their density, and their capture cross-sections [6].

2. Experimental method

Charge-collection efficiency is the ratio between the measured charge and the charge produced by the particle. The charge (number of electrons) produced is the ratio between the energy deposited in the crystal by the particle, i.e. the energy of the alpha or X-ray or the value of dE/dx times the detector thickness for mip's, and the energy needed to produce one pair: $\xi = 4.2$ eV. The value of the most probable energy loss for mip's in GaAs is taken to be equal to that of Ge: 5.6 MeV/cm [7].

The charge is measured with a standard spectroscopy chain made of an Ortec 142 A preamplifier followed by an EG&G 672 amplifier, as described in Ref. [1]. Charge spectra have been taken with a shaping time of 0.5 μ s; this value minimizes the noise, but does not maximize the measured charge. The peaks of the spectra are taken as the measured charge; counting rates are the total number of events in the spectra divided by the time it takes to accumulate the data.

The alphas are 5.68 MeV particles from ^{241}Am ; the X-rays come from the same source and have an energy of 60 keV. For betas we have used a ^{106}Ru source (3.5 MeV end point).

Detectors are 3 mm diameter roundels with Schottky metallization; the ohmic metallization covers the entire back of the chip (4 roundels per 1 cm^2 chip). A description of the manufacturing technique and metals used is given in Ref. [4]. The Schottky contact requires a negative voltage to be reverse biased.

3. Results

In Fig. 1 we have summarized the cce's for alpha particles (ϵ^α), beta particles (ϵ^β), and X-rays (ϵ^X) as a function of reverse bias for one Alenia diode. The detector has been

irradiated on the front (Schottky contact) and on the back (ohmic contact). As can be seen, the behaviour and the values of the different cce's as a function of bias are quite different: we would like to show that these results are coherent despite the appearance.

To do so, we define a function $\epsilon = \epsilon(x)$, which is the fraction actually collected of the charge produced at a distance x from the front of the detector. This local collection efficiency correlates the global cce's for betas and X-rays through the following relation:

$$\epsilon^\beta = \frac{1}{t} \int_0^t \epsilon(x) dx = \frac{W}{t} \frac{1}{W} \int_0^W \epsilon(x) dx = \frac{W}{t} \epsilon^X, \quad (1)$$

where t is the thickness and W is the active width of the detector, i.e. the width of GaAs where the charge collection is non zero. Outside this region $\epsilon = \epsilon(x)$ is zero by definition: this allows us to change the upper integration limit from t to W in Eq. (1); a discussion of this formula can be found in the appendix.

Basically, relation (1) says that the cce of betas is low because a) we normalize to the total energy deposited in the physical width of the detector (t) rather than in its active width (W) and b) because the collection efficiency is not 100% even in the active region (W) as shown by the fact that charge produced by the absorption of X-rays in the active region is not completely collected.

Relation (1) also allows us to measure the active width of the detector from the two independent measurements of ϵ^β and ϵ^X :

$$W = t \epsilon^\beta / \epsilon^X. \quad (2)$$

Notice that for a bias such that $W = t$, the two collection efficiencies become equal. This conclusion is borne out by the data in Fig. 1, where $\epsilon^\beta = \epsilon^X$ at a bias for which signals from alphas hitting the diode on the back contact become visible, i.e. at a bias for which the collection field reaches through the detector. In Fig. 2, we have plotted the behaviour of W as measured from the data of Fig. 1 using relation (2). To be precise, we have calculated the points in Fig. 2 from the ratio of the best fits of ϵ^β and ϵ^X in Fig. 1a. The active width of the detector can also be measured using the fact that the counting rate for x-rays of a detector is proportional to W . In order to get an active width from a counting rate, it is necessary to multiply the rate by a constant that takes into account the intensity of the source and the acceptance of the detector. Since such a constant is difficult to reckon from geometry, we have calculated it from the ratio of the rates (from front and back irradiation) and the W one (from Fig. 2) at the highest bias. In Fig. 3, we compare the counting rates, multiplied by such constants, with W from Fig. 2 as a function of applied bias for the same 220 μm thick detector used to get the data in Fig. 1a. It is interesting to see that the overlap is very good for a bias above 120 V, but the curves deviated at lower voltages. However, we think that this is a systematic error induced by the fact that rates and cce are obtained from the same charge spectra; at a bias above 120 V the peaks of the spectra are easily seen above the noise, whilst it is very possible that, at lower voltages, with a large fraction of the spectrum under the noise distribution, the rates are underestimated especially if the spectra are no longer symmetric. In fact, we think that these methods of measuring the active widths, although useful for the understanding of the behaviour of our detectors, are probably not the best ones for evaluating a large number of detectors, because i) their use is limited to high bias, ii) they are time consuming, iii) they are imprecise. A routine technique to measure the depletion widths has not yet been proposed. In conclusion, from Figs. 2 and 3 we see rather a linear behaviour for the active region as a function of bias. These same methods of measuring the active width have been used on

a commercial Si detector; Fig. 4 gives all the cce's, showing an overall picture similar to GaAs; for this detector we have to assume that the local collection efficiency is one inside and zero outside the depleted region. Figure 5 shows that we get the expected behaviour for both the X-ray counting rate and the calculated W by multiplying the cce for betas by the detector thickness ($320\text{ }\mu\text{m}$).

4. Conclusions

Detectors made by Alenia SpA on Sumitomo material have shown a large collection efficiency, such that their use in a high-energy physics experiment can be proposed [8]. Their general behaviour is well understood and consistent with, but better than, previously tested detectors.

We have proposed two ways to measure the active width of these detectors and found that they become completely active at the highest bias. The increase of the active width is found not to follow a square root law throughout the bias range (100V – 200 V) useful for mip detection. However, we believe that the data taken at high bias must necessarily be completed with data at lower voltages to be able to state with exactitude what power of bias the active region increases. We plan to shed some light on the question of the dependence of active region on bias at low bias with a direct measurement of the local charge collection.

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Appendix

Formula (1) can easily be justified. A straight-through particle (mip or beta) deposits energy (dE/dx) equally in each infinitesimal length (dx) of detector. The charge released is: $dQ = e (dE/dx) (dx/\xi)$, where $\xi = 4.2$ eV is the energy spent to produce a pair and e is the electron charge. The total charge released crossing the detector is therefore: $Q = e (dE/dx) (t/\xi)$, with t = detector thickness. The contribution to the charge measured from any dx is $dQ_M = dQ \epsilon(x)$: this is, in fact, the definition of $\epsilon(x)$. The total charge measured is therefore $Q_M = e(dE/dx)\xi^{-1} \int_0^t \epsilon(x) dx$. By definition: $\epsilon^\beta = Q_M/Q = 1/t \int_0^t \epsilon(x) dx$, i.e. ϵ^β is the average value of $\epsilon(x)$ throughout the detector thickness.

Each X-ray that produces a photoelectron at coordinate x will be counted if, and only if, x is within the active region ($x < W$); the charge will be measured with an efficiency of $\epsilon(x)$. A charge spectrum is the distribution of the values of $\epsilon(x)$ within the active region; since this spectrum is symmetric the peak is the average value of $\epsilon(x)$ within the active region, i.e. $\epsilon^X = (1/W) \int_0^W \epsilon(x) dx$, i.e. ϵ^X is the average value of $\epsilon(x)$ throughout the active region. Relation (1) follows from these two equalities and the fact that $\epsilon(x)$ is zero outside the active region.

Figure 1: (a) Charge-collection efficiencies for alpha, beta, and gamma particles irradiating the front and back contacts of a 220 μm thick detector built by Alenia SpA. (b) Same as (a) for a 200 μm detector. Charge-collection efficiencies for betas on the front or the back contact turn out to be identical, as they should be.

Figure 2: The behaviour of W as measured from the data of Fig. 1a and using relation (2) as explained in the text.

Figure 3: (a) The behaviour of the counting rate for 60 keV X-ray irradiation as a function of V_{bias} for front irradiation; (b) the same for back irradiation: both for the diode in Fig. 1a. The behaviour of these rates is similar to the one shown by W as a function of V_{bias} in Fig. 2 and reproduced here.

Figure 4: Charge-collection efficiencies for the same sources as in Fig. 1 for a commercial Si detector.

Fig. 5

Figure 5: (a) The cce for betas multiplied by the detector thickness for a commercial Si detector as a function of bias; (b) The counting rate for X-rays as a function of bias for the same detector. The agreement of the two curves is similar to that in Fig. 3.