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Charge collection efficiencies and reverse current densities of GaAs detectors

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Abstract

GaAs surface barrier diodes with different areas have been fabricated and tested as particle detectors. It is shown that the reverse current is affected both by the area of the Schottky contact and by its circumference. The charge collection properties can be explained on the basis of a model that takes into account trapping effects and the distribution of the electric field within the detector. From this model (several) rules for optimizing GaAs detectors are derived.

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1 Introduction

The development of fast and radiation resistant detectors is an important requirement in view of HEP experiments at the high luminosity ($10^{33} - 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$) pp-collider LHC. Especially inner tracking detectors have to withstand doses of $\leq 10 \text{ Mrad/yr}$ and neutron fluencies in the range of $\leq 10^{14} \frac{n}{\text{cm}^2} / \text{yr}$ [1].

The radiation resistance of devices made of GaAs and their successful application in high speed electronics are well known [2]. GaAs is one of the most familiar materials of the III-V semiconductor compounds and is commercially easily available. So it is a very promising material for solid state detectors that can be used in a high radiation environment. The energy required to create an electron-hole pair in GaAs (4.27 eV) is nearly the same as in Si (3.76 eV) [3]. Because of the high Z (32) and density (5.32 gcm^{-3}), the radiation length of GaAs is $X_0 = 2.3 \text{ cm}$. Considering the resulting high specific energy loss for minimum ionizing particles in GaAs ($(\frac{dE}{dx})_{\text{mop}} \sim 0.56 \frac{\text{keV}}{\mu\text{m}}$, mop: most probable value), a $200 \mu\text{m}$ thick GaAs-detector with 100 % charge collection efficiency will give signal of ≈ 26000 electrons.

Taking into account the high Z, GaAs is a very promising material for use in photon detection systems. GaAs is an attractive candidate also in the case of medical applications, where, in addition to high spatial resolution, a large detection efficiency for low energy photons (30-80 keV) is demanded in order to reduce the total dose for the patient.

2 Properties of detectors made of SI-GaAs

The material mainly used for applications in HEP is SI-GaAs which is grown by LEC (Liquid Encapsulated Czochralski), VGF (Vertical Gradient Freeze) or HB (Horizontal Bridgman) [4]. Crystals grown by these methods have a large background concentration of impurities which are mainly Si and C in concentrations of $10^{14} - 10^{16} \text{ cm}^{-3}$. These impurities act as shallow donors or acceptors and become compensated [4] by deep levels located close to the midgap.

Deep levels can be introduced either by doping

with Cr or by a special thermal treatment that creates lattice defects correlated with a deep level called EL2. Commonly used concentrations of Cr or EL2 are in the order of $10^{15} - 10^{16} \text{cm}^{-3}$. The result of compensating impurities by deep levels is a high resistivity material with $10^7 - 10^8 \Omega \text{cm}$. Considering the correspondingly low carrier concentration ($\sim 10^7 - 10^8 \text{cm}^{-3}$) one can show [5] that the built-voltage is sufficient to fully deplete Schottky-diodes made of SI-GaAs. The deep levels influence the behaviour of the detectors in some additional points :

- They act as recombination and trapping centers which reduce the carrier lifetime.
- Due to band bending in the vicinity of the Schottky contact, they become ionized [6] and the charge density distribution becomes very inhomogeneous. The electric field distribution splits the detector in an active part where E is large and charge transport can occur and in an inactive part with very low electric field.

Based on these phenomena we developed a model [7] which explains well several of the properties of the detectors.

3 Detector fabrication & behaviour

All detectors were processed at the 1st Institute of Physics in Aachen in collaboration with the Institute of Semiconductor Technology and the Institute of Solid State Physics. The investigated SI-GaAs is manufactured by Freiburger [8] and AXT [9]. Fig.1 shows a schematic layout of the detectors. The 2"-wafers used have

Figure 1: Schematic layout of a GaAs-detector thicknesses from 250 – 508 μm . The frontside is

covered by Schottky contacts (e.g.Pads, Strips), which define the detector geometry, and the backside is covered by an Ohmic contact or a Schottky contact biased in the forward direction which thus is similar to an Ohmic contact. To build Schottky contacts a metalization of NiCr/Au or Ti/Pt/Au is used, for the Ohmic contacts a system of Ni/AuGe/Ni/Au followed by a diffusion process. A thin surface layer ($\sim 1\mu\text{m}$) is removed by etching with $\text{H}_2\text{SO}_4 : \text{H}_2\text{O}_2 : \text{H}_2\text{O}$ to 'clean' the wafer and, immediately before evaporation, native oxides become removed by dipping in ammonia buffered HF. No passivations are used and the described steps lead to a process with high reproducibility and high yield (90-100%).

3.1 Test of Electrical Properties

Fig.2 shows the I-V-characteristics in reverse direction for several pad-detectors with four different geometries. The thickness of the detectors

Figure 2: I-V-characteristics of different pad-detectors.

is 508 μm . It is obvious that all detectors with identical dimensions show an identical behaviour. This indicates the high homogeneity of the material and the stability of the production process. The slope of the I-V-characteristics in the plateau region indicates a contribution of surface currents

beneath the saturation current. A detailed analysis of the I-V- characteristics enables the separation of the two contributions. Fig.3 shows the linear correlation between the area of the pad and the saturation current. The slope of the fitted

Figure 3: Saturation current for different pad-detectors as a function of pad area.

curve corresponds to the saturation current density and is $12.5 \frac{\text{nA}}{\text{mm}^2}$. This is in good agreement with the expected value of $8 \frac{\text{nA}}{\text{mm}^2}$ [10]. In fig.4 the slope of the I-V- characteristics is plotted as a function of the pad circumference. A correlated

Figure 4: Slope of I-V-characteristics as a function of pad-circumference.

variation is clearly visible, indicating the presence of surface currents. A passivation or a guard-ring structure should reduce these currents.

The backside has a strong influence on the value of the breakdown voltage. Plotted in fig.5 are the I-V-characteristics for pad detectors with identical front-contacts and different back-contacts: one detector has a Schottky contact on the back-

Figure 5: I-V-characteristics for pad-detectors with identical front-contacts and different back-contacts.

side, the other has an Ohmic contact. The different breakdown voltages are clearly visible: the detector with the Ohmic contact shows a breakdown voltage of 125V, the detector with the backside Schottky contact shows a much higher breakdown voltage of 210V. This can be explained on the basis of hole injection from the backside caused by tunneling or by thermionic emission of holes. The understanding of this behaviour and the improvement of backside contacts are important in view of safe operation and good signal to noise ratio.

4 Model of Charge Transport

Relatively low and bias voltage dependent charge collection efficiencies of detectors fabricated from

SI-GaAs are widely [11] observed for all kind of particles. The reduced charge collection efficiency of the detectors can be explained on the basis of trapping effects and the ionization of deep levels (Cr,EL2...) caused by band-bending.

Taking into account these phenomena, the electric field distribution inside the detector can be calculated numerically by solving the Poisson equation in conjunction with the continuity equation [6] and considering input parameters like donor-, acceptor-, and trap-concentrations and trap energy levels. The difference of the quasi

Figure 6: a) Difference of quasi Fermi level and trap energy level across the detector, b) Distribution of space charge density, c) of potential and d) of electric field in a GaAs-detector ($d=368 \mu\text{m}$) with a Schottky contact.

Fermi level and the trap energy level across a GaAs detector (thickness: $d=368 \mu\text{m}$) is shown in fig.6a. In a domain close to the Schottky con-

tact (up to roughly $190 \mu\text{m}$ from it) this difference is rather small ($< 0.14 \text{ eV}$). Consequently a considerable amount of deep levels can be ionized. At larger distances from the Schottky contact, this difference becomes large and only few ionizations can occur. The corresponding space charge is plotted in fig.6b. The peak occurring at $\sim 190 \mu\text{m}$ is the result of the field dependent drift velocity for electrons in GaAs [5]. Consequences of the nonuniform charge density distribution of fig.6b are the distribution of the potential (fig.6c) and the inhomogeneous electric field distribution shown in fig. 6d. Also shown is the boundary X_A for the active region, within which the charge transport occurs [7]. X_A corresponds to an electric field of roughly $2 \frac{\text{kV}}{\text{cm}}$ for which the drift velocity for electrons saturates. The width of the active region is mainly a function of bias voltage and not of detector thickness d [6].

The influence charge can be calculated on the basis of a transport model [7]. It is assumed in this model, that due to trapping and recombination the initial number of electrons and holes decreases exponentially as they move through the detector. The model predicts the local charge collection ef-

Figure 7: Local cce $\varepsilon(x_0)$ for different active layer widths.

iciency (cce) $\varepsilon(x_0)$ within the detector, which is plotted in fig.7 for different bias voltages (corresponding to different active layer widths), taking into account field dependent drift velocities and different carrier lifetimes for the high and low field

regions. This function describes the fraction of charge that will be collected if a certain amount of electron-hole-pairs is created at x_0 and is the basis for calculating the cce's for α -, γ -, and minimum ionizing particles. The function $\varepsilon(x_0)$ can also be used inside the GEANT code [12] to simulate detailed spectra [7].

Plotted in fig.8 are simulated and measured charge collection efficiencies for α -, γ -, and minimum ionizing particles for detectors of different thickness but identical crystal material. The ex-

Figure 8: Simulated and measured charge collection efficiencies for α -, γ -, and minimum ionizing particles (^{90}Sr -electrons) for detectors of different thickness.

cellent agreement between data and simulation is obvious. The calculations for the different thicknesses and for the different kinds of particles have been performed with a single set of parameters re-

lated to the properties (e.g. carrier lifetimes, trap concentrations) of the base material used.

Based on this model an optimisation of GaAs detectors can also be carried out. Fig.9 shows the charge collected for a minimum ionizing particle as a function of detector thickness d (in μm - lower scale-) and as a percentage of the radiation length X_0 (-upper scale-). Each solid curve cor-

Figure 9: Collected charge in electrons for a minimum ionizing particle as a function of detector thickness.

responds to a particular value of the thickness X_A of the active layer resulting from a certain bias voltage. Considering the signal at constant detector thickness, it is clear that the thickness of the active layer X_A should be as high as possible. On the other hand, the plot shows that signal will be lost, if the detector is thicker than the active layer width X_A ; the best case will be $X_A = d$. For this case the signal can only be improved by the use of material with improved charge transport properties (higher carrier lifetimes) and with lower trap concentrations. (The active layer thickness is roughly inversely proportional to the trap concentration [6]).

Presently under investigation is a promising alternative technique to improve the signal and to reduce the radiation length by making use of avalanche layers [13]. The dotted curve in fig.9 shows that with an detector of $100\mu\text{m}$ thickness and an amplification factor of $M=2$ a signal of

more than 20000 electrons can be expected.

5 Conclusion

Several GaAs detectors have been fabricated and tested as particle detectors in Aachen. The dependance of leakage current on detector geometry and the influence of the backside contact on the breakdown voltage have been clearly demonstrated. In view of safety of operation and good signal to noise ratio the optimisation of the backside contact is strongly required. A promising method, presently under investigation, to suppress hole injection is the use of a n^+ -layer underneath the backside contact.

Detector properties like charge collection efficiency could be understood on the basis of a model that takes into account material and detector parameters. Especially the strong dependence on detector thickness was clearly demonstrated. In this connection some rules towards optimisation of the detectors are given. They concern both detector parameters (e.g. bias voltage, detector thickness) and material parameters (e.g. carrier lifetimes, concentrations of deep levels).

Furthermore a promising possibility to improve the signal by using avalanche layers has been presented. First results of this new method will be forthcoming.

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