Nuclear Instruments and Methods in Physics Research A 641 (2011) 92–100

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Space charge reconstruction in highly segmented HPGe detectors through capacitance-voltage measurements

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ARTICLE INFO

Article history:
Received 17 November 2010
Received in revised form
7 February 2011
Accepted 7 February 2011
Available online 23 March 2011

Keywords:
Gamma ray instruments
Segmented germanium detectors
Pulse shape analysis

ABSTRACT

The space charge distribution inside highly segmented large volume HPGe detectors determined from capacitance–voltage (CV) measurements is investigated. A computer code was developed to understand the impact of impurity concentrations on the resulting capacitances between core contact and outer contact for HPGe detectors biased at different high voltages. The code is intended as a tool for the reconstruction of the doping profile within irregularly shaped detector crystals. The results are validated by comparison with the exact solution of a true coaxial detector. Existing methods for space charge parameter extraction are briefly reviewed. The space charge reconstruction under cylindrical symmetry is derived. An extension of this scheme to higher dimensions for inhomogeneous space charge distributions is illustrated for a two-dimensional segmented coaxial detector.

1. Motivation

The novel generation of spectrometers like AGATA [1] and GRETA [2] is based on the concept of γ-ray tracking which enables the reconstruction of all the paths of the detected γ-ray throughout the spectrometer in real time. The main prerequisite is highly segmented, large volume HPGe detectors which enable in combination with Pulse Shape Analysis (PSA) methods the localization of the individual interaction points to a precision of a few millimeters. PSA exploits the unique position dependent pattern of signal shapes of core and segment signals in order to determine location, energy deposition and time of the individual interaction points inside the crystal volume. As implemented in AGATA, PSA utilizes a library of calculated pulses of single interactions for comparison with experimental traces and the consecutive conversion into position information. The achieved position resolution values are typically an order of magnitude better than the size of the physical segmentation.

Evidently, the performance of the PSA strongly depends on the quality of the simulated pulses and the calculated data base. The simulation requires a very detailed understanding of the crystal properties: fields and potentials, space charge, crystal orientation, mobility of electrons and holes. Moreover precise electronic response functions and related cross talk properties of the detector assembly are demanded. Characterization aims at a full disclosure of these properties and the analytical reproduction of final pulse shape information.

A complementary approach is based on measured position dependent data bases of detector pulses. For this purpose characterization facilities are currently in use within the AGATA community, devoted to the preparation of HPGe detectors for the use with PSA [3]. These scanning tables use heavily collimated γ-ray sources to measure the position dependent single interaction response inside the Ge detector for careful adjustment of the results of the simulation code. These measurements are quite involved and very time consuming. Intense research is dedicated to the development of new characterization procedures to quantify these relevant detector properties in a practical, fast, sensitive but economic way [4].

One of the most influential parameters for a reliable simulation of such detectors is undoubtedly the space charge distribution caused by the remaining impurity concentration inside the HPGe material. At the same time, this is one of the parameters which is least known and which is hard to access after the HPGe crystal is encapsulated by the manufacturer and processed into a detector. The concentration varies from crystal to crystal and even throughout the volume of the crystals. These individual concentrations are created during the crystal growing process. The crystal manufacturer typically provides measured average impurity concentrations for the top and bottom of the crystal from a Van der Pauw measurement [5]. In practice, the provided values seem to be an approximation to the true bulk space charge, as there is often a contradiction between the given measured values and the observed depletion voltage.

The direct influence of the space charge on the detector signals is shown in Fig. 1. Signals for three fixed positions in the coaxial part of the detector—near the outer segmentation, near the

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doi:10.1016/j.nima.2011.02.110

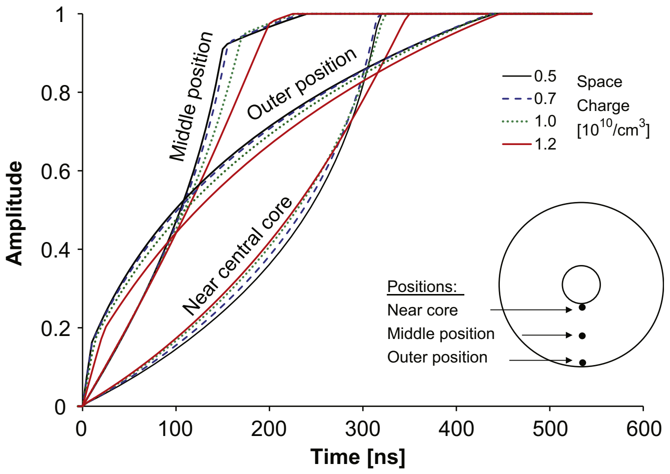

Fig. 1. Influence of the space charge on the core signal rise times in the coaxial part of an AGATA detector. The signals are simulated with realistic parameters for three fixed positions as shown in the insert. The space charge was assumed to be constant throughout the crystal, and was changed between 0.5 and $1.2\times10^{10}/\mathrm{cm}^3$.

average radial position and near the core electrode—were calculated assuming realistic parameters. (Preamplifier responses were not included.) For an extensive explanation on the shape of these signals, see e.g. Ref. [6]. For each of these positions, the space charge was assumed to be constant throughout the crystal, and was changed between 0.5 and $1.2\times10^{10}/\mathrm{cm}^3$. One observes that variations larger than 10% both in amplitude as in rise time are possible. The consequences for PSA follow from the fact that these variations are of the same order as the influence of the crystal orientation, which is known to play a crucial role in PSA [7].

In this paper we discuss a new and independent method to access the space charge variation throughout the bulk volume of a segmented HPGe detector and to reconstruct the physical geometry of the depleted germanium material. Although intended for n-type AGATA detectors [8], this method is potentially more widely applicable to other segmented detectors based on semiconductor material. The method is believed to be very beneficial for optimization of PSA with these specialized detectors. Besides the HPGe based tracking spectrometer AGATA and GRETA also other detector arrays like GERDA [9], Majorana [10], Compton imaging detectors or imaging detectors for homeland security [11], waste management monitoring and medical applications [12] may benefit.

2. About the method

To identify the impurity concentration in HPGe, several methods exist [13]: chemical analysis, ultraviolet spectroscopy, neutron activation, low temperature photoluminescence, Fourier-transform-infrared-spectroscopy, secondary ion mass spectroscopy, Rutherford backscattering, Röntgen fluorescence. Most of these techniques cannot be applied to our crystal as they are destructive or need a direct access to the germanium surface, which due to the encapsulation technology is not possible. Only Deep-Level Transient Spectroscopy (DLTS) is non-destructive and could be applied for identification of the impurities. However DLTS would require a dedicated cryostat for a controlled heating of the crystal. Nuclear spectroscopic methods are also applicable. For instance the bias voltage dependent measurement of the γ-ray detection efficiency of the crystal combined with a comparison to Monte-Carlo simulations. Or the determination of the depletion boundary using a collimated gamma source in a scanning system. This approach was realized recently with an AGATA crystal at the Liverpool scanning table [14].

Finally a capacitance–voltage (CV) measurement [15] is a non-destructive technique which has the great benefit that it can be applied directly to a working detector in its final assembly. It is based on a measurement of the capacitance of the detector as function of the bias voltage. The method dates back to the early work of Shockley [16] and has become a standard quality control technique in the production of silicon wafers. In the case of planar probes it allows to extract a profile of the impurity concentration as function of the depth d below the surface. The doping profile reconstruction is based on the following two equations:

$$C(d)=\frac{\varepsilon A}{d} \tag{1}$$

$$N(d)=-\frac{C^3}{\varepsilon e A^2}\left(\frac{dC}{dV}\right)^{-1} \tag{2}$$

The first equation is the well known equation for a parallel plate capacitor with a medium of permittivity ε and relates the capacitance C to the depletion depth d below the surface A. The second equation is derived from the charge neutrality condition of the device. It relates the remaining net space charge $N(d)=|N_D-N_A|$ at the boundary of the depletion region to the variations in capacitance with bias voltage. N_D and N_A are the donator and acceptor concentration levels of the crystal. By changing the bias voltage a scan through the depletion depth of the sample is obtained. The relationship between measured capacitance and applied bias voltage is sufficient to reconstruct the doping profile. It is important to notice that the one-dimensional reconstruction is based on a planar approximation, and assumes a homogeneous net space charge distribution only depending on the depth d.

The intention of the novel approach is a full three-dimensional reconstruction of the impurity profile throughout the bulk of the Ge crystal without assumption on symmetries. The technique should be applicable for any detector geometry, not only for planar detectors. To our knowledge, only one publication was found on a similar attempt to reconstruct the two-dimensional doping profile of a transistor [17].

Highly segmented detectors open the possibility to extend the planar method by measuring not only the total bulk capacitance as function of bias voltage, but also the individual core to segment capacitances. The use of an electronic pulser to determine the capacitance [18] is very appealing here because of its simplicity and the considerable amount of segments. The capacitance measurement can be extremely sensitive. By design of the detectors and preamplifiers, the pulser line stability is typically guaranteed to be below 10^{-4}. Only at lowest bias voltages the increasing noise contribution affects the precision of the results. For AGATA, a dedicated high precision electronic pulser, integrated in the core preamplifier [19,20], can be exploited for this purpose. The relation between pulser signal amplitude and capacitance for this particular AGATA pulser is subject of discussion in Ref. [21].

3. Numerical method: a simulation code

For detector geometries showing a high degree of symmetry, explicit analytical solutions such as in Eqs. (1) and (2) can be derived. Doping profiles of irregularly shaped geometries can be achieved by numerical methods, for instance using a least square fitting procedure. For this purpose, a three-dimensional simulation code was developed capable of simulating the field and the depletion boundary of a detector. In addition the relevant capacitances are calculated for comparison with experimental results.