NOVEL CONCEPTS OF SOFT X-RAY DETECTOR BASED ON SEMI-INSULATING GaAs

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1. Introduction

The fusion project based on tokamak requires on-line hot plasmas diagnostics using a topical spectrometric detection system operating in soft X-ray region. The used detectors must be resistant to the damage by fast neutrons and gamma rays produced by hot plasmas. The required detection performances include: (i) operation in the soft X-ray range: (0.5) 1 ÷ 5 (10) keV, (ii) energy resolution: < 1 (0.7) keV FWHM, (iii) noise threshold: < 1 (0.5) keV and resistance to overall neutrons up to a total fluency of ~ 1×10^{14} cm^{-2} and gamma rays.

The best available spectrometric detectors such as Si drift chambers or Si *pin* diodes are out of consideration due to the large damage induced in these devices by relatively low doses (about 1 kGy) of fast neutrons. Among the possible suitable candidates for soft X-ray spectrometry, 4H-SiC detectors show excellent spectrometric performances and also higher resistance to damage by neutrons and gamma rays [1]. However, since high purity epitaxial SiC, required for detector fabrication, is very expensive, a lot of efforts have been addressed to the investigation of lower cost materials. Semi-insulating (SI) GaAs became an important candidate for fabrication of low cost X-ray detectors (and other devices) due to its good physical characteristics, high quality of base material, developed technology and relatively high hardness to radiation and neutron damage [2]. On the other hand SI GaAs exhibits short carriers lifetimes (in a range of ns), so that the drift length of carriers in the best material reaches only a few hundreds of µm. This property must be taken into account in the design of novel spectrometric detector based on SI GaAs. The novel design is expected to bring: (i) higher detector volume, (ii) more homogenous electric field distribution in the active volume, (iii) lower bias operation (appx. ½ of the single-sided blocking electrode arrangement with the same base thickness), and (iv) lower detector capacitance and hence smaller contribution to the detector noise figure.

In this work we present the results of a study of a novel radiation detector potentially applicable in soft X-ray spectrometry. The novel topology includes *two blocking electrodes symmetrically arranged on the top and the bottom of a semiconductor wafer connected in parallel and a third (virtual) ohmic electrode(s) placed around the small area blocking contact(s).* Such idea was originally proposed by Gatti and Rehak [3] and applied in the development of Si drift chamber topology. However, the idea was used in a different way: the ohmic n^+ contact, *cathode,* was formed as a small collection electrode placed in the center of the top anode barrier contacts. Such electrode arrangement is ineffective in semiconductors with short carriers lifetimes, such as SI GaAs. In addition to the novel topology, recent developments in SI GaAs contacts metallization [4, 5] could also be used to obtain further improvements of SI GaAs detector spectrometry.

The presented study includes a basic numerical modeling of the novel detector which considers Si, for simplicity, as the base detector material. *I-V* and *C-V* characteristics, 2D distribution of the electric field, current and space charge density are simulated. Numerical modeling and optimization of the detector structure is supported by the advanced 2-D mixed mode electro-physical simulation. The novel design is expected to bring a higher detector volume with a more homogenous distribution of the electric field in the active volume and a lower detector capacitance, hence a lower contribution to the detector noise figure. A preliminary test detector, fabricated on the basis of the novel concept applied to SI GaAs, shows reverse current at room temperature as low as 1×10^{-10} A and low capacitance less than 0.4 pF at bias of -200 V. The energy resolution and the noise threshold are limited by the noise of the used preamplifier (~ 3 keV).

2. Novel detector concept: numerical modeling

Electro-physical model of the detector structure was prepared using Synopsys numerical modeling tool Mesh and subsequent electro-physical simulations by Dessis tool program and applied in the study of the role of detector geometry and electrode topology. Several models of detector with different geometries such as contacts width and space between together with the base thickness were evaluated. Large dimensions and approximate symmetry of the device allowed us to use in the simulation only selected fragment of the overall structure. The combination of selected parameters playing a role in defining the breakdown voltage and the distribution of current density such as gap between electrodes, contacts area and base length are taken into account in the study. Fig 1a shows the simulated *I-V* characteristics for different Schottky barrier contacts in a multiple electrode arrangement shown in Fig. 2: the structure is symmetrical around the centre (x = 0) and consists of three ohmic contacts labelled OK1 - OK3 separated by two barrier contacts in a shape of annulus placed symmetrically on top (SK1, SK2) and bottom (SK3, SK4) sides of the wafer. With the used geometry the breakdown voltage reaches values of 165 V and 175 V in correspondence

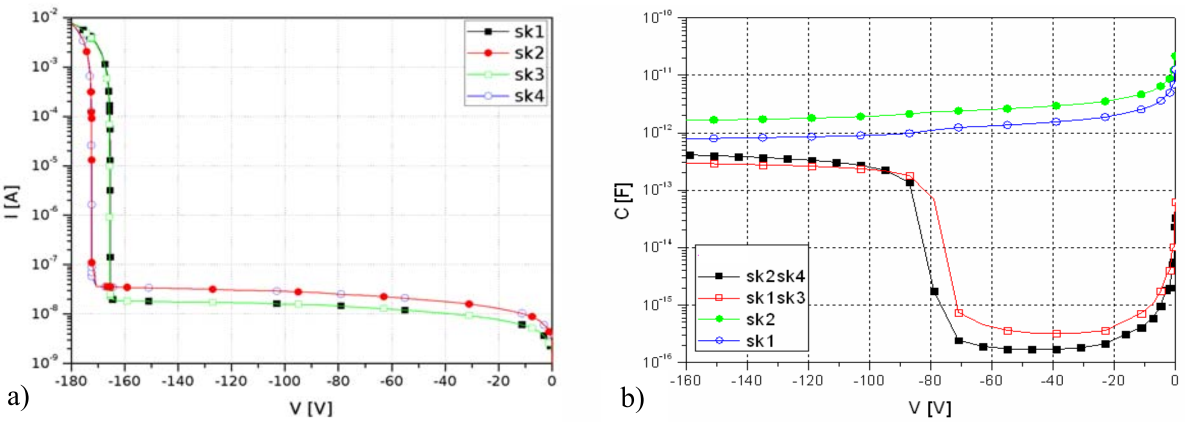


Fig. 1: *(a) I-V characteristics of the structure with barrier contact in different configurations (see text) and (b) C-V dependences of standard sandwich configuration (circles) and connected barrier contacts vs. ohmic surface electrode (squares).*

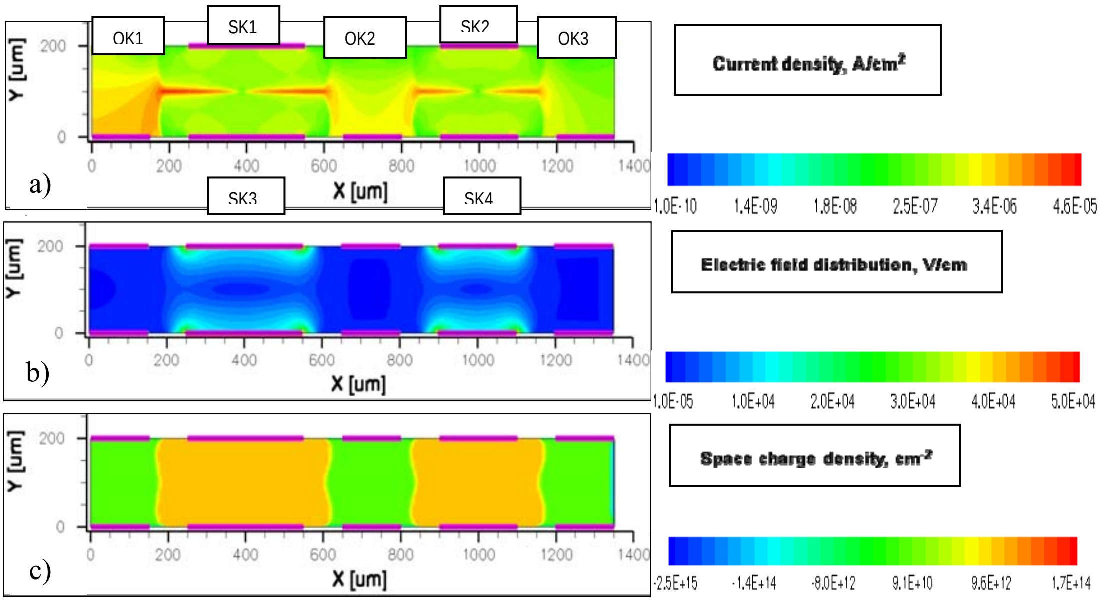


Fig. 2: *2D demonstration of numerical simulation: current density (a), electric field distribution (b), and space charge density (c) at reverse bias voltage of 150 V.*

to a current of about 3×10^{-8} A for the different sets of barrier contacts. The calculated reverse *C-V* dependences of different barrier contacts are shown in Fig. 2b for the standard "sandwich" detector configuration (circles) and the novel detector concept with planar ohmic electrode. It should be noted the extremely low capacitance (< 1 fF for bias voltage between -10 V and -70 V, see Fig.1b) corresponding to the novel electrode configuration.

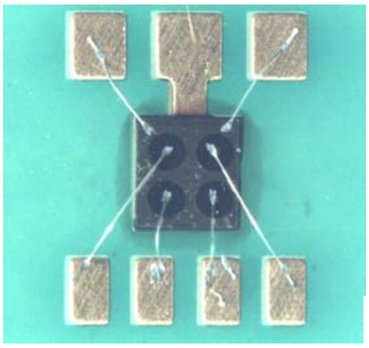
The results of 2-D simulation at a reverse bias voltage of -150 V are shown in Fig. 2 where the current density, the distribution of electric field, and the space charge density in the detector structure are reported. As it can be seen in Fig. 2a the current density increases just in a narrow part between the space charge regions of the two barriers and at the edge of the internal ohmic contact OK1. Moreover the high electric field regions are located at the edges of the Schottky barrier contacts (Fig. 2b), while the space between the blocking contacts is completely depleted (Fig. 2c).

3. Novel detector concept: preliminary application in SI GaAs

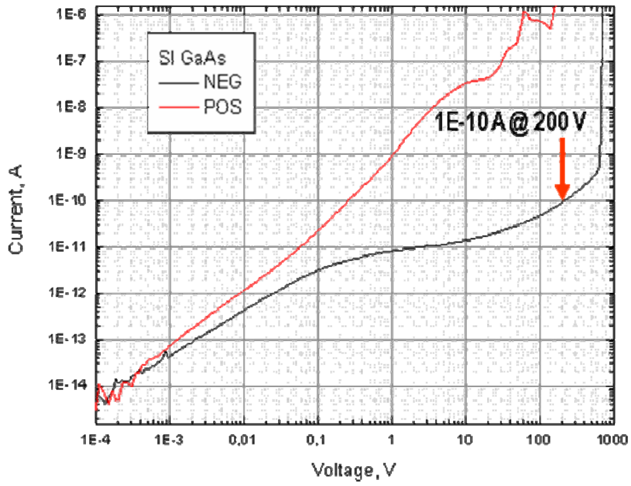
The novel detector concept was applied to SI GaAs-based detector with "point-like" Schottky barrier contact. A quaternion of detectors mounted and contacted onto a PCB holder is depicted in Fig. 3a. A wafer fragment of bulk SI GaAs, with thickness of 250 µm, polished from both sides was applied in the technology. Both-sided photolithography masking and lift off was used in the processing. The diameter of the small anode contact is 120 µm while the internal diameter of the planar ohmic contact is 720 µm. All contacts are formed by Pt/Au (40/60 nm) blocking metallization forming a back-to-back diodes system. The measured *I-V* characteristics of the fabricated diode in both bias polarities are illustrated in Fig. 3b. Pulse height spectra of the ^{241}Am radionuclide source gives an energy resolution of about ~ 3 keV (FWHM) mainly determined by the noise of the used laboratory spectrometric chain. Hence an ultra low noise preamplifier will be necessary for a more precise evaluation of the detector spectrometric ability.

Conclusions

2-D numerical modeling and simulations were applied to the study of electro-physical behavior and reliability of novel 3-electrode Si-based radiation detectors. The numerical mode-



a)



b)

Fig. 3: *Photo of quaternion fabricated SI GaAs detectors with "point-like" barrier contact topology (a) and measured I-V characteristics of one detector (b).*

ling was performed for two key detector topologies: "point-like" and multiple electrodes. The simulation of static *I-V* and *C-V* characteristics was used for the analysis of electrical properties and the optimization of the designed detector structures. The results of the study demonstrate improvements of the novel electrode arrangement with respect to the standard sandwich electrode configuration. The modeling shows that the idea of a virtual ohmic contact can be applied as a "point-like" as well as the multiple electrode detector topology. The used design of SI GaAs-based 3-electrode detectors includes carrier drift length of about 150 µm. The results of the modeling were experimentally verified using a "point-like" detector topology and showed the applicability of the idea.

The preparation of new lithographic masks has been completed and the fabrication of a set of SI GaAs detectors with multiple electrode topology will start in the near future. This investigation will also include different types of barrier and ohmic contact metallizations following recent experimental observations. The evaluation of the spectrometric performances of the detectors using an ultra low noise preamplifier will be also accounted for.

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