Study of GaAs detectors characteristics for medical imaging

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Abstract-- **In this work we present the results of a systematic study about SI GaAs detectors as a function of substrate and contact type, geometry and thickness. This study has been stimulated from the interest in using GaAs as a detector for medical imaging applications.**

GaAs detectors have been produced using crystals grown with different techniques and changing both the thickness (in the range 200 μm-1 mm) and the contacts type and geometry. We have measured the current-voltage characteristics and, using radioactive sources (^{109}Cd, 20 keV photons, ^{241}Am, 60 keV photons, ^{99m}Tc, 140 keV photons), we have studied the performance of our detectors in terms of charge collection efficiency and energy resolution as a function of the bias voltage. Besides we have also studied the electrical and spectroscopic properties of GaAs detectors with different types and concentrations of the dopants in the substrate. So we have found the optimal doping type and concentration to have the best spectroscopic performances and the higher breakdown voltage.

Simulation programs made with Montecarlo methods have been developed to describe the electric field distribution and the transport of charge carriers toward the electrodes in GaAs detectors. In these simulations we have considered the presence of deep energy levels in the bandgap, the thickness, the bias voltage and the charge deposition in the crystal after photon interaction.

I. INTRODUCTION

SEmi Insulating GaAs is a very good candidate for medical imaging applications because it can allow for a satisfactory detection efficiency in the energy range typical of mammography, radiography and nuclear medicine (15-150 keV). Other important parameters are a high spatial resolution and a satisfactory charge collection efficiency.

In this work we describe the electrical and spectroscopic characterization of SI GaAs produced using crystals grown with different thecniques and changing both the thickness and the contacts type. The detectors have been irradiated with ^{109}Cd (20 keV photons), ^{241}Am (60 keV photons) and ^{99m}Tc (140 keV photons) and spectra have been acquired varying the reverse bias voltage.

For each spectrum we have calculated the c.c.e. (charge collection efficiency) and the energy resolution and we have compared their behavior as a function of the bias voltage with the results obtained with Montecarlo simulations.

II. EXPERIMENTAL SET-UP

We have characterized GaAs detectors of different type.
SI-VGF GaAs detectors were developed by I.M.E.-C.N.R. Institute in Lecce (Italy) from wafers <100> oriented, Vertical Gradient Frozen (VGF) grown, whose values of resistivity and electron mobility, as declared by the factory, are (1.5-2)10^8 ohm cm and (5.5-7.4)10^3 cm^2/Vs, respectively. On the front side a layered structure of 500A Ti/750A Pd/3000A Au was deposited in order to obtain square pixels. On the back side the sample surface was completely covered with a 300A Ge/600A Au/300A Ni/2000A Au multilayer.

SI-LEC GaAs detectors were developed by Alenia Marconi Systems in Rome (Italy) from SUMITOMO wafers <100> oriented, undoped, 3 inch in diameter, Liquid Encapsulate Chocralsky (LEC) grown, whose values of resistivity and electron mobility, as declared by the factory, are (1.1-3.1)10^7 ohm cm and (6.5-6.8)10^3 cm^2/Vsec, respectively.

On one side the Schottky contacts, a Au/Pt/Ti multilayer, were evaporated to obtain square pixels, with and without a guard-ring of 300 μm at a distance of 20 μm from the pixel. On the other side a common not-alloyed Ohmic contact was realized.

To evaluate the electrical properties of GaAs detectors we used a picoammeter/voltage source (KEITHLEY mod.237).

To evaluate the spectroscopic properties of GaAs detectors we used a charge-sensitive preamplifier ORTEC142A, a shaper amplifier ORTEC673 with a shaping time of 1.5 μs and a multichannel analyser (NUCLEUS-PCA II).

III. SI-VGF GAAS DETECTORS

The detectors developed by I.M.E.-C.N.R. Institute in Lecce (Italy) are 200 μm, 300 μm, 450 μm, 500 μm, 600 μm, 750 μm and 900 μm thick square pixels.

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The thickness of the wafers used for these detectors is 200 μm , 300 μm and 1 mm. So some samples have been obtained by lapping from the 1 mm thick wafer [1].

On the front side the Schottky contacts are square pixels whose side is 200 μm.

Besides another series of detectors have been built with the thickness of 200 μm, 400 μm, 600 μm, 800 μm and 1 mm and with a Schottky contact also on the back side.

A. *Electrical Characterization*

The measures of electrical properties of SI-VGF GaAs detectors have been made at I.M.E.-C.N.R. Institute in Lecce (Italy). Fig. 1 and Fig. 2 show the J-V curves (current density vs. bias voltage) for square pixels of 200 μm side with an Ohmic contact on the back side and with a Schottky contact.

The behavior of the current densities is the correct one and the little differences between detectors with different thickness are in agreement with the little differences in resistivity.

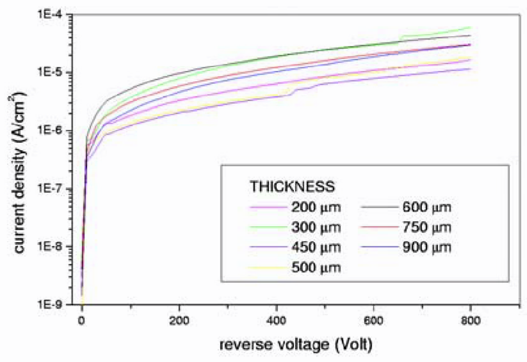

Fig. 1. Current density as a function of reverse voltage for square pixels of 200 μm side with an Ohmic contact on the back side.

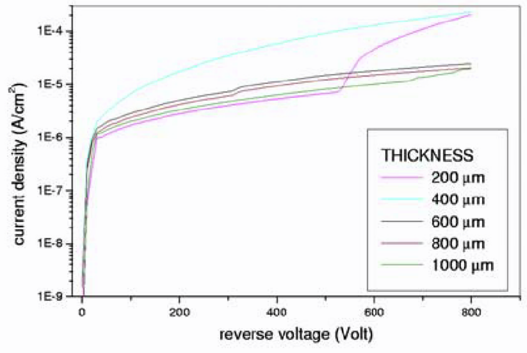

Fig. 2. Current density as a function of reverse voltage for square pixels of 200 μm side with a Schottky contact on the back side.

B. *Spectroscopic Characterization*

The detectors have been irradiated with ^{241}Am (60 keV photons) and the spectra have been acquired increasing the bias voltage with a step of 50 Volt and starting from 50 Volt up to the maximum operating voltages.

For each spectrum we have calculated the c.c.e. (charge collection efficiency) and the energy resolution and we have studied their behavior as a function of the bias voltage.

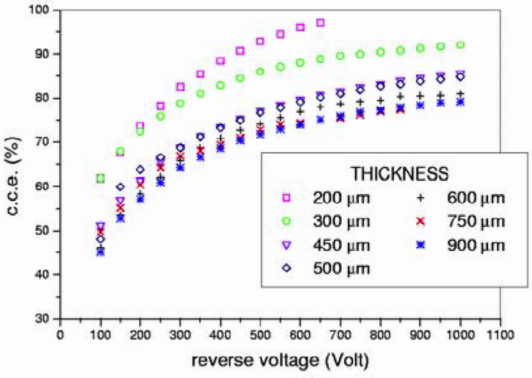

Fig. 3. charge collection efficiency as a function of reverse voltage for square pixels of 200 μm side with an Ohmic contact on the back side.

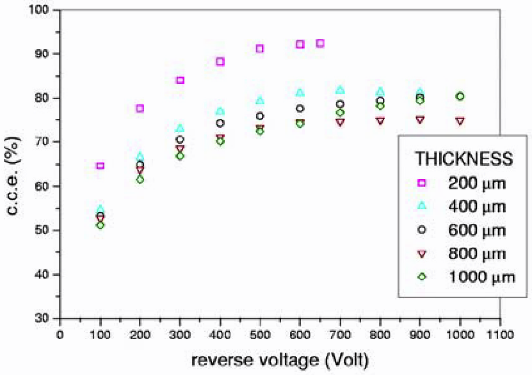

Fig. 4. charge collection efficiency as a function of reverse voltage for square pixels of 200 μm side with a Schottky contact on the back side.

We found that the charge collection properties are related to the thickness of the detector: c.c.e. decreases increasing the thickness, as we can see from Fig. 3 and Fig. 4.

So 200 μm and 300 μm thick detectors reach very high value of c.c.e., of the order of 90 %, while the other detectors reach a value in the range (70-80) %.

The energy resolution decreases increasing reverse bias voltage, because the electric field increases in the detector and this give a better transport and collection of the charge carriers. All detectors show a value of the order of 13 %, at the operating reverse voltage.

IV. MONTECARLO SIMULATIONS

Simulation programs made with Montecarlo methods have been developed to interpret the experimental values of c.c.e., lower than 100 %, associated with a transport affected by trapping.

In SI-GaAs detectors the presence of traps is very important, because these influence the spatial distribution of the electric field and they can capture the generated charge carriers when the detector is irradiated.

The most important traps are those in the midgap region, called EL2 and EL3, because they are present in high concentration, are not completely ionized and have an electron capture cross section higher than the other [2].

Taking into account trapping and field enhancement, that is the dependence of electron capture cross section of the deeper traps from electric field, we have simulated the electric field behavior as function of the thickness. The electric field was calculated resolving the system between the Poisson equation and the transport equation with an iterative method and treating detector as a reverse biased Schottky diode [3].

We found that the active region extension increases with the bias applied for each thickness of the detector and the value of electric field is very small in the ohmic region. Besides, increasing the reverse voltage, the electric field becomes constant in the entire active region reaching a value in the range of 15-20 KVolt/cm for thicknesses lower than 450 μm (Fig. 5), while for thicknesses higher than 450 μm the electric field is 10 kVolt/cm (Fig. 6).

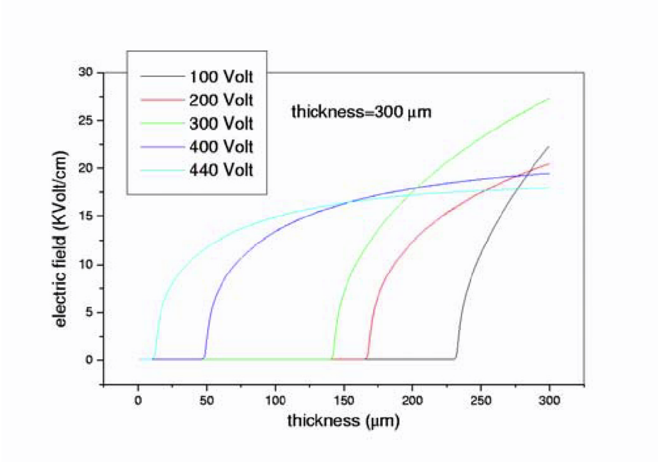

Fig. 5. Electric field as a function of thickness in the case of a 300 μm thick detector.

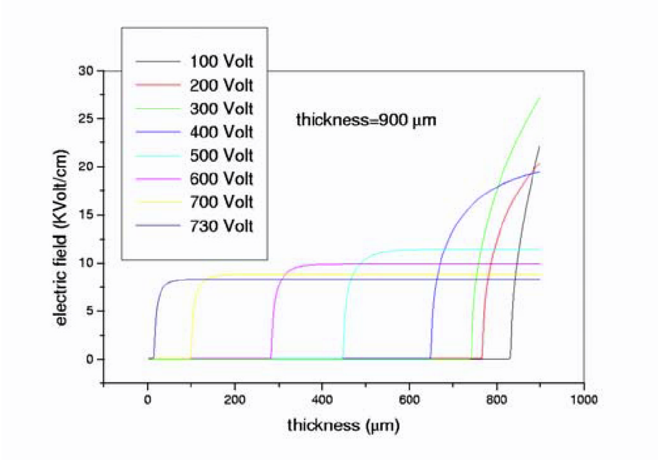

Fig. 6. Electric field as a function of thickness in the case of a 900 μm thick detector.

Then we have used the EGS 4 Monte Carlo code to produce a full simulation of the charge deposition in the crystal induced by an incident 60 keV X-ray beam.

The output from the EGS 4 program are the spatial coordinates, along the beam direction, of each interaction and the correlated charge deposition.

Our program, starting from the EGS 4 output, simulates the transport of the charge carriers in the crystal and the collection of untrapped charges at the electrodes under the action of the electric field, in full depletion condition for the detector.

The charge signal is given by the Ramo's theorem, starting from the elementary contribution due to each photogenerated carrier and induced in the external circuit whitin a time t.

In Fig. 7 and Fig. 8 some examples of charge collection efficiency are presented.

We found that the charge collection efficiency decreases increasing the thickness of the detector. This happens because the space, that the charge carriers have to cross before the collection, increases and the trapping becomes considerable. This behavior is in agreement with the results reached for SI-VGF detectors.

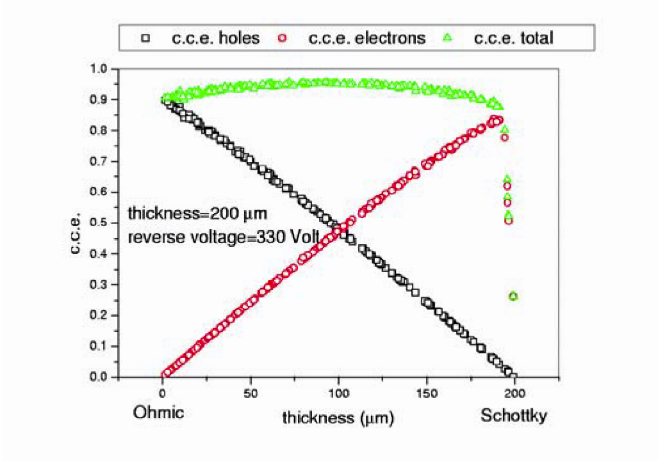

Fig. 7. c.c.e. as a function of thickness in the case of a detector 200 μm thick.

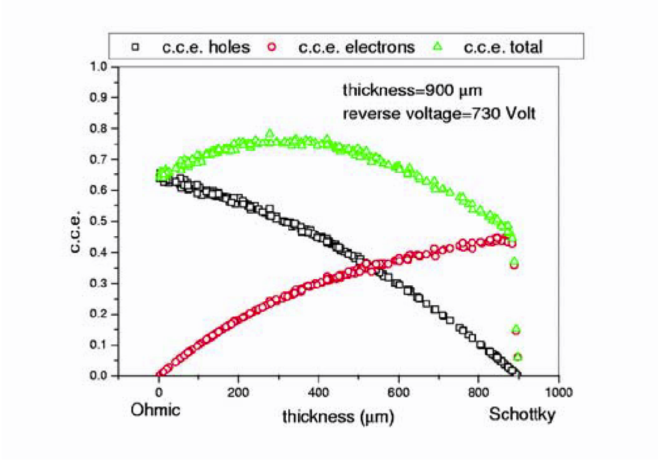

Fig. 8. c.c.e. as a function of thickness in the case of a detector 900 μm thick.

Taking into account also the influence of contact geometry and the small pixel effect for high thicknesses by a 2D dimensional simulation the agreement is very good. For example for a 200 μm thick detector at the reverse voltage of 400 Volt we found a c.c.e. of (86.9±4.2) %, while the experimental value is (88.3±3.8) % [4].

V. SI-LEC GAAS DETECTORS

The SI-LEC GaAs detectors are multidiode structures with thickness of 200 μm and 600 μm.

The 200 μm thick structure contains square pixels with linear dimension of 220 μm with and without a guardring thick 300 μm at a distance of 20 μm from the pixel. The 600 μm structure contains square pixels with side of 170 μm.

A. Electrical Characterization

To evaluate the electrical properties of SI-LEC GaAs detectors the Schottky contact has been reverse biased until 500 Volt and, in the case of structure with guardring, pixel and guardring are biased at the same time.

Fig. 9 shows the J-V curves (current density vs. bias voltage), for square pixels of 220 μm side 200 μm thick with and without guardring and for square pixel of 170 μm side 600 μm thick.

The behavior of the current density is the correct one for a reverse biased diode.

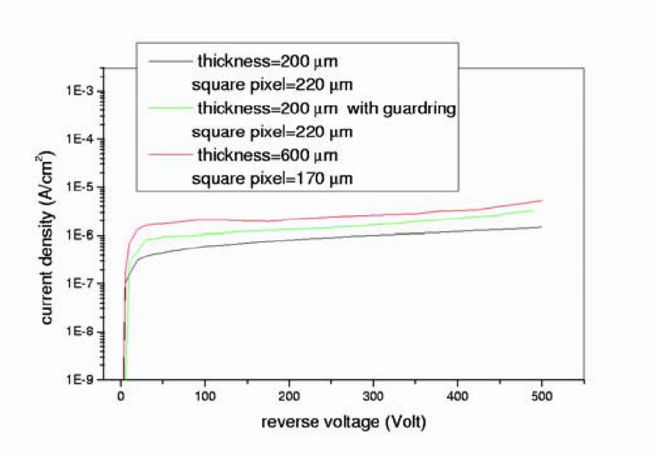

Fig. 9. Current density as a function of reverse voltage for SI LEC GaAs pixels.

B. Spectroscopic Characterization

Square pixels of 220 μm side and 200 μm thick have been irradiated with ^{241}Am (60 keV photons) and ^{109}Cd (22 keV photons) from the Schottky contact, and in the case of structure with guardring also from the Ohmic contact.

In Fig. 10 an example of spectrum is shown.

When we use ^{109}Cd source we have an error on the c.c.e. and an energy resolution bigger than in the case of ^{241}Am source, because the peak is the convolution of the emission at 22 keV with that at 26 keV.

In the plot of c.c.e. as function of reverse bias we can see that the plateau region is reached and that the c.c.e. from Schottky and from Ohmic contact is the same inside the errors (Fig. 11).

Square pixels of 170 μm side 600 μm thick have been irradiated with ^{241}Am (60 keV photons) and ^{99m}Tc (140 keV photons) from the Schottky contact and biased until to 500 Volt. We found that the behavior of c.c.e. is the same as in the case of pixels thick 200 μm.

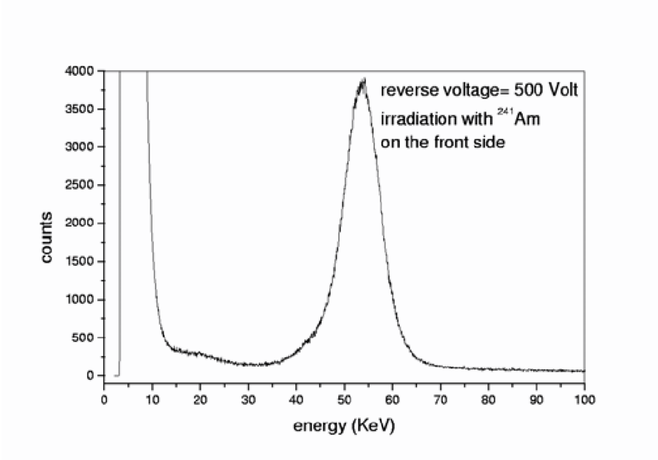

Fig. 10. Spectrum of ^{241}Am source acquired with a pixel of 220 μm side.

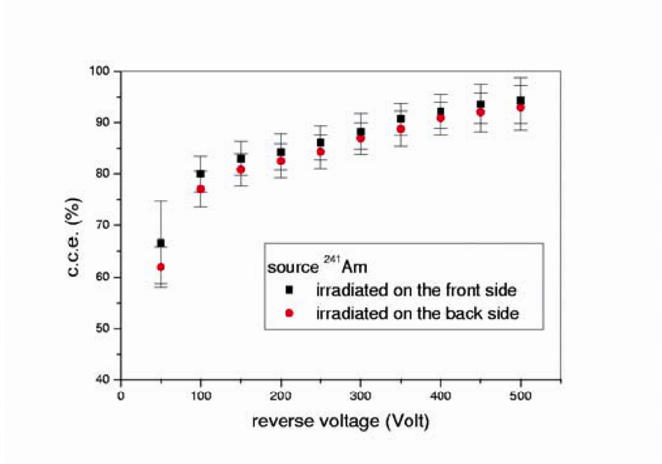

Fig. 11. c.c.e. as a function of reverse voltage for square pixel of 220 μm side with guardring.

VI. SI-GAAS DETECTORS WITH DOOPANTS

The SI GaAs detectors, shown in the previous sections, have been doped with a concentration of Carbon of the order of 10^{15} cm^{-3}, but also detectors, doped with Chromium, have been characterized to compare their performances with that of the other. These detectors are pads of diameter 2 mm and thickness 200 μm.

We studied the detectors doped with Chromium to find their electrical and spectroscopic characteristics. This study has been necessary because we want a detector with the following conditions: breakdown voltage higher than 500 Volt and c.c.e. higher than 75 %.

For each pads the electrical characterization have been made and we have found that these detectors are good because they present a very high breakdown.

Besides the detectors have been irradiated with ^{241}Am source (60 keV photons) and spectra have been acquired varying the reverse bias voltage. In Fig. 12 and Fig. 13 spectra of ^{241}Am source are shown, acquired at the reverse voltage of 200 Volt and 600 Volt respectively.

In the case of doping with Chromium a degrade in the spectroscopic properties have been observed.

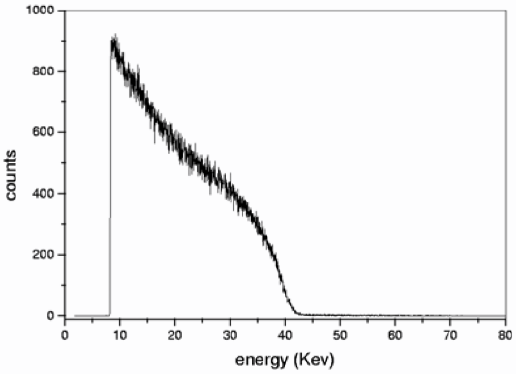

Fig. 12. Spectrum of ^{241}Am source acquired at a reverse voltage of 200 Volt.

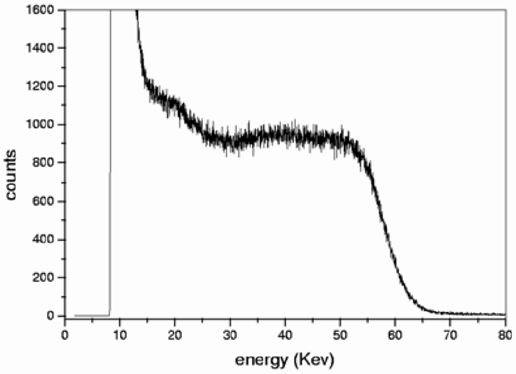

Fig. 13. Spectrum of ^{241}Am source acquired at a reverse voltage of 600 Volt.

VII. CONCLUSIONS

We have compared the results of the spectroscopic characterization of SI VGF GaAs detectors with those of SI LEC GaAs detectors and we have found that, at the actual state of technology, for the best quality production, c.c.e. is independent by the substrate and contact type and decreases increasing the thickness of detector.

The agreement between measurements and simulations, made taking into account also the influence of contact geometry and the small pixel effect for higher thicknesses, is satisfactory.

VIII. ACKNOWLEDGMENT

We would like to thank A. Cetronio, C. Lanzieri and L. Venturelli of Alenia Marconi Systems in Rome (Italy) for making available SI-LEC GaAs detectors and SI-GaAs detectors with dopants and for helpful discussion.

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