SI LEC GaAs Nuclear Detectors: Characterization, Performance and Applications

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Abstract

We report on characterization, performance and applications of nuclear detectors fabricated on Semi-Insulating (SI) Liquid Encapsulated Czokralski (LEC) grown GaAs. We have developed a non alloyed and non injecting ohmic contact (NAOC) based on ion implantation to fabricate detectors which can operate at applied voltages greater than the one needed to make them fully depleted. With such a detectors and at high applied voltages, $V_a > 500$ V, a nearly full charge collection efficiency has been achieved for both α particles and X-rays. Furthermore the best energy resolution achieved at room temperature has been 1.1% for 5.48 MeV α particles and 26.1% for 59.5 keV X-rays, while at -30 ^oC the best energy resolution measured for X-rays has been 4.1%.

Introduction

GaAs is a good candidate for the detection of α particles and low energy X-rays at room temperature, thanks to its high Z-value, with consequent high detection efficiency, and to its wide band-gap which allows for its use without cooling [1, 2]. Detectors fabricated from liquid phase epitaxially (LPE) grown high purity GaAs were reported to have 0.3% energy resolution for 5.48 MeV α particles from ^{241}Am and better than 5% energy resolution for 60 keV X-rays from ^{241}Am [3, 4]. Vapor phase epitaxy (VPE) GaAs Schottky contact detectors were reported with similar results [5]. However detectors made from LPE or VPE GaAs material are expensive, limited to thicknesses near 100 µm or less, and difficult to manufacture in large area. On other hand the performance of detectors made with non-epitaxial material is degraded by the presence of defect centers still present even if, due to the demand for high quality GaAs substrates for microwave monolithic integrated circuit, high purity bulk GaAs is now readily available from a number of commercial venders [6, 7].

In this paper we present the substantially better results obtained in α particles and X-rays spectroscopy using 100µm thick semi-insulating (SI) Liquid Encapsulated Czochralski (LEC) GaAs detectors manufactured with an improved ohmic contact based on ion implantation.

Detectors fabrication

The detectors studied in the present work were made by ALENIA SpA on Hitachi (wafer number 2HTC53) SI LEC undoped <100> oriented GaAs. Detectors are 3 mm in diameter, 100 µm thick with circular Schottky pads metallized with Au/Pt/Ti. Two sets of detectors with different kinds of ohmic contacts were realized. In a set A a new, non injecting, ohmic (NAOC) contact has been realized on the whole back surface of the wafer by implanting Si^+ ions at two different doses and energies: 7×10^{12} cm^{-2} at 300 keV and 1×10^{13} cm^{-2} at 40 keV. The wafer, with a reactively sputtered silicon nitride cap, was then fast annealed at 850 ^oC for 30 s. Finally, the ohmic contact was achieved by alloying an e-beam deposited AuGeNi multilayer at 420 ^oC for 30 s. In set B the ohmic contact was obtained by alloying an Au/Ge/Ni metallization (4250Å/500Å/500Å) by a thermal cycle 430 ^oC 20 s in N_2+H_2 (10%) atmosphere [8].

Fig. 1 compares the measured reverse current densities for ALENIA detectors fabricated on the Hitachi substrate with a standard (#B1) and a ion implanted ohmic contact (#A2).

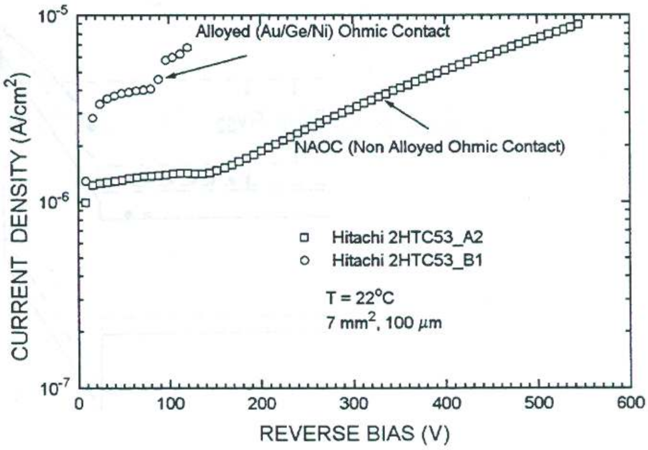

Fig. 1. Room temperature I-V characteristics for a standard Au/Ge/Ni alloyed ohmic (#B1) and the new, ion implanted, (#A2) ohmic contact detectors.

In the case of the ion implanted ohmic contact the current gently increases at increasing the applied voltage from 100

V up to 600 V, while a rapid breakdown of the standard, set B, ALENIA detector occurs at applied voltages around 100V which correspond to full depletion. This comparison shows clearly that the new implanted ohmic contact is much less injecting.

α particles spectra

The cce for the electrons (i.e. α particles irradiate the front contact or negatively Schottky contact) and for holes (i.e. α particles irradiate the back contact or ground ohmic contact), as a function of the applied bias voltage V_a, at room temperature and with a shaping time of the gaussian amplifier-shaper of 0.5 μs, is shown in Fig. 2.

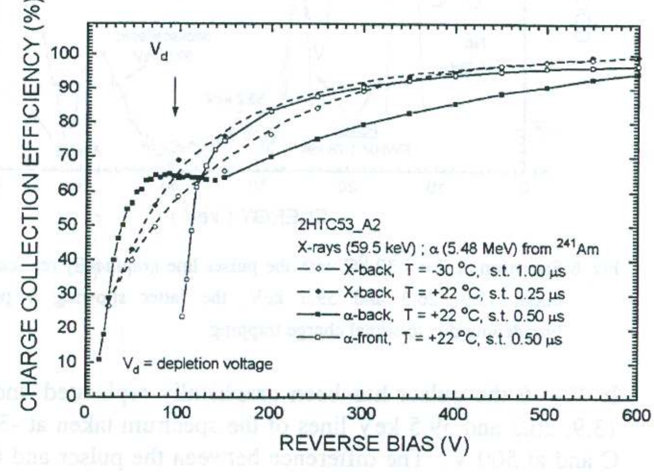

Fig. 2. Charge collection efficiency, cce, for front and back irradiation with 59.5 keV X-rays and 5.48 MeV α particles from ^{241}Am at 22 °C and at - 30 °C as a function of the applied voltage.

The following important comments can be made:

a) the electron collection efficiency, ece, exhibits a linear increase up to V_a = 70 V; with further increase of V_a the ece reaches a plateau and then keeps on growing up to 95% at the very high bias, 600 V;

b) the hole collection efficiency, hce, become visible at a bias of 100 V, which is thus taken as the minimum bias voltage, V_d, necessary to have a fully depleted detector, and increases with V_a up to 97% at 600 V;

c) the hce stays above the ece, thus providing that holes get less trapped than electrons.

Fig. 3 shows two α spectra for front and back irradiation in the same electronics conditions and at the same detector bias of 450 V. It is evident that the front irradiation (electrons drifting across the detector) spectrum has a worse resolution and its peak position falls in a lower channel, again demonstrating less charge collection for front irradiation, i.e. electrons get more trapped than holes.

The energy resolution at FWHM of spectra taken at room temperature from 5.48 MeV ^{241}Am α particles source has been measured for front and back irradiation vs. V_a and is reported in Fig. 4. In the same figure the energy resolution of the electronic system (pulser) and the reverse current are reported vs. V_a. As can be seen the energy resolution reaches optimum values at increasing V_a. For all detectors and in both configurations, front and back irradiation, the applied voltage at which the FWHM reaches its minimum value occurs at the bias voltage required to achieve the maximum cce.

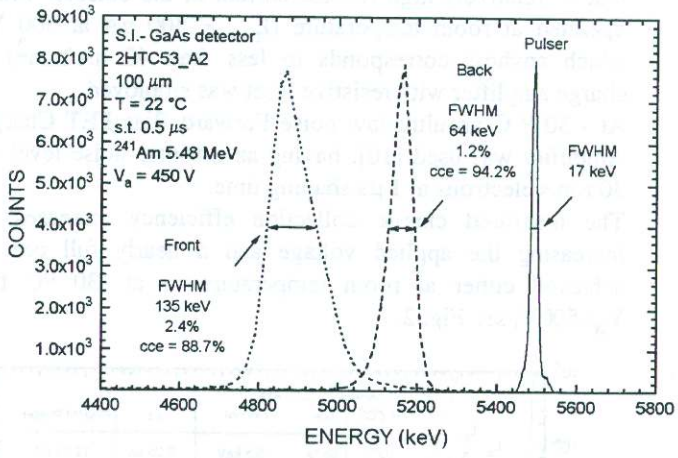

Fig. 3. α particle spectra for front and back irradiation at 22 °C with the same electronic conditions and at the same applied voltage, 450 V.

Furthermore the lowest values of FWHM have been measured for back irradiation, corresponding to hole drift; i.e. for the same configuration where the higher cce has been observed, see Fig. 2. A further evidence that the major limiting factor to the energy resolution is the trapping/detrapping process is given by the comparison between the FWHM and the reverse current behaviour. As shown in Fig. 4 the reverse current increases with V_a while the resolution at FWHM decreases or keeps constant. The contribution to the total resolution FWHM from the electronic chain has been measured by a pulser peak as a function of V_a and it has been found to increase with V_a, being dominated by the reverse current. Finally let us note that these detectors with ion implanted ohmic contact show the best energy resolution of 1.1% so far reported in the literature for α particles [9], in SI LEC GaAs.

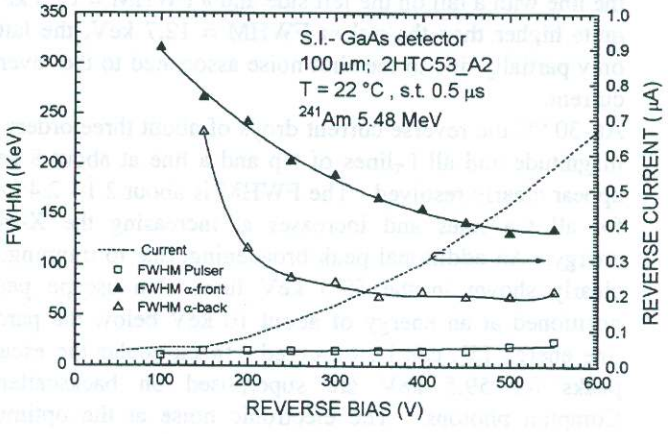

Fig. 4 Energy resolution at FWHM of 5.48 MeV 241 Am α particles measured at 22 °C for front and back irradiation vs V_a. The reverse current and the energy resolution of the pulser are also reported.

X and γ-rays spectra

Detectors have been tested at room temperature (20 ^{o}C) and at - 30 ^{o}C irradiating the ohmic back contact with a ^{241}Am X and γ-ray source and at a reverse bias up to 600 V.

Due to relatively high reverse current of the detector when operated at room temperature ($I_{rev} \approx 300$ nA at 500 V, which anyhow corresponds to less than 40 nA/mm^2) a charge amplifier with resistive reset was employed.

At - 30 ^{o} C an ultra low noise Forward Bias FET Charge Amplifier was used [10], having an intrinsic noise level of 30 r.m.s electrons at 1 μs shaping time.

The measured charge collection efficiency increases at increasing the applied voltage and a nearly full cce is achieved either at room temperature or at -30 ^{o}C for V_a>500V, see Fig. 2.

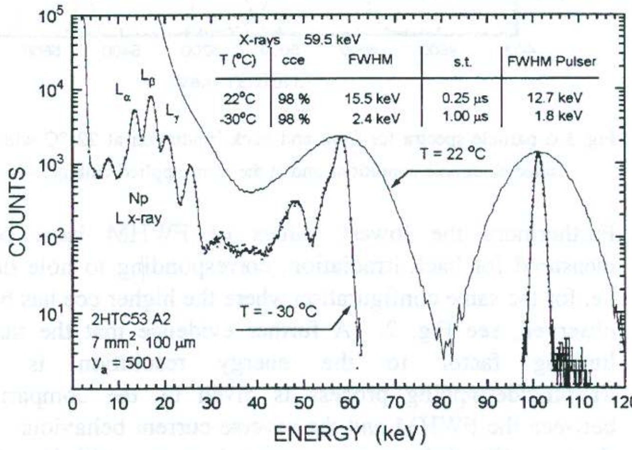

Fig. 5 Spectrum of X-ray from ^{241}Am source acquired at 20 ^{o}C and at -30 ^{o}C with SI LEC GaAs detector biased at 500 V and irradiated on the ohmic contact.

The spectra acquired at V_a = 500 V are shown in Fig 5, whose x-axis has been calibrated in energy by means of a silicon detector. At room temperature only the 59.5 keV line is resolved. It can be observed the asymmetric shape of the line with a tail on the left side and a FWHM = 15.5 keV, quite higher than the pulser FWHM = 12.7 keV, the latter only partially due to the shot noise associated to the reverse current.

At -30 ^{o}C the reverse current drops of about three orders of magnitude and all L-lines of Np and a line at about 8 keV appear clearly resolved. The FWHM is about 2.1 - 2.4 keV for all the lines and increases at increasing the X-rays energy. An additional peak broadening, due to trapping, is clearly shown in the 59.5 keV line. No escape peak, positioned at an energy of about 10 keV below the parent line energy [5], can be observed. In particular the escape peaks for 59.5 keV are superposed on backscattered Compton photons. The electronic noise at the optimum shaping time of 1 μs is 154 r.m.s electrons, partially determined by the high capacitance (≈ 7 pF) and by the non negligible currrent (≈ 300 pA) of the relative large area detector (7 mm^2). To our knowledge this represents the best X and γ-rays spectrum acquired till now using a SI LEC GaAs detector.

The charge collection efficiency on the 59.5 keV line (cce = 98% at T = 22 ^{o}C and cce = 98% at T = -30 ^{o}C) have been determined calibrating the energy axis using a silicon detector and assuming a constant value of 4.27 eV/pair in GaAs [11].

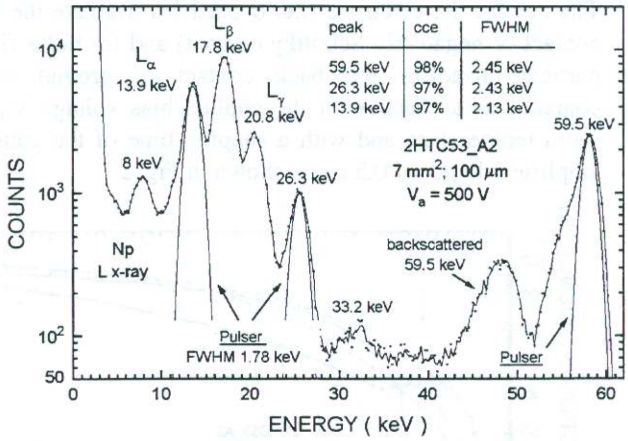

Fig. 6 Spectrum at T = - 30 ^{o}C with the pulser line graphically replicated under 13.9, 26.3 and 59.5 keV, the latter showing a peak broadening due to signal charge trapping.

In Fig. 6 the pulser has been graphically replicated under 13.9, 26.3 and 59.5 keV lines of the spectrum taken at -30^{o} C and at 500 V. The difference between the pulser and the 59.5 keV line clearly quantifies the resolution degradation due to the peak broadening caused by charge trapping (the charge creation statistics can be verified to give a negligible contribution).

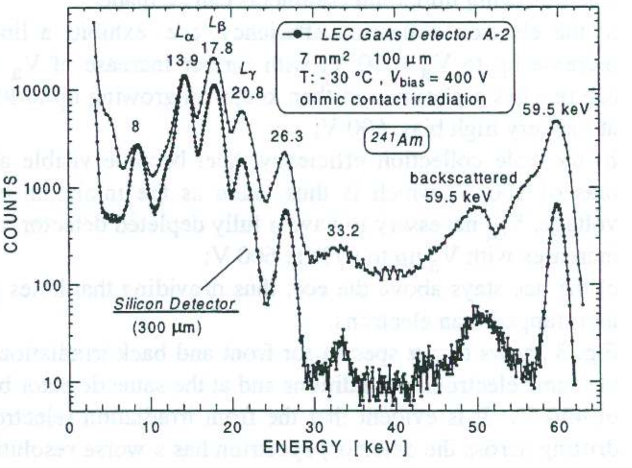

Fig. 7 Comparison of the spectrum obtained with SI LEC GaAs at T = -30 °C with the one obtained with a silicon detector in comparable electronic noise conditions. The x-axis is calibrated in energy independently for Si and GaAs.

Finally in Fig. 7 the spectrum acquired at -30 ^{o}C and at 400V has been superimposed on that obtained using a 300μm thick detector in comparable electronic noise conditions and for an acquisition time such to have the same counts on the L_α peaks of the two spectra. The x-axis has been independently calibrated in energy for GaAs and for silicon by means of the radioactive source peaks.

This comparative plot shows directly the higher detection efficiency of the GaAs detectors to X and γ-rays of energy $\geq$ 17.8 keV, although its thickness is 1/3 with respect to one of silicon detector.

Conclusions

Ion implanted back contacts allow us to operate SI LEC GaAs nuclear detector at applied voltages much greater (6 times) than the one needed to make them fully depleted. A nearly full charge collection efficiency and a satisfactory good energy resolution (FWHM) has been achieved for both α particles and low energy γ-rays.

Trapping from deep levels appear to limit the charge collection efficiency at low applied voltages while trapping and reverse current are the main limiting factors to the energy resolution. Performance of these nuclear detector manufactured with an ion implanted ohmic contact appear to be suitable for application in high energy physics experiments at LHC (Large Hadron Collider) at the CERN laboratory and for medical imaging.

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