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Electric-field behavior and charge-density distribution in semi-insulating gallium arsenide Schottky diodes

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The behavior of the electric field and the charge-density distribution in semi-insulating gallium arsenide Schottky diodes have been analyzed by optical-beam-induced current and surface potential measurements. The electric field exhibits three different regions across the detector, the characteristics of which depend on the reverse applied voltage. Furthermore, a positive box-shaped space charge region exists, separated from the Schottky barrier by a neutral space-charge region, and widens and moves towards the Ohmic contact at increasing the reverse bias voltage. This study adds substantial information to the knowledge of the space-charge distribution in semi-insulating Schottky diodes, discriminates between the existing models on the electric field, and provides essential information to understand nuclear detector performance. [S0163-1829(97)04340-3]

In recent years major interest has arisen regarding the distribution of the electric field $\mathcal{E}$ in Schottky barrier particle detectors, since the layer W across which it exists is the region where the free charge carriers are removed, giving rise to the detector output signal.[1] W, therefore, constitutes the detection region of the impinging ionizing particles, hence named ''detector active region.'' Consequently, it is highly desirable to have an electric field possibly extending across the whole detector and high enough to reduce as much as possible carrier trapping phenomena by defects present in the material.

Undoped semi-insulating (SI) gallium arsenide (GaAs) grown with the liquid encapsulated Czochralski (LEC) method, high in atomic number and in resistivity, seems attractive for the fabrication of particle detectors. Due to its very low free charge carrier concentration ($\approx 10^7$ cm^{-3}), for many years Schottky diodes fabricated on SI GaAs were assumed to be fully depleted, also without bias voltage. However, this hypothesis soon proved wrong when experiments carried out with different techniques[2–9] demonstrated that the electric field $\mathcal{E}$, and correspondingly the active region W, has a limited extent in the Schottky diode at null bias and that high reverse biasing V_a is necessary to achieve detector full-depletion conditions. It was also found[2,7–9] that the active layer width W does not increase with the square-root law valid for Schottky junctions on semiconducting materials, even if there is no identity of opinions on the functional relationship between W and V_a. Indeed, there is a controversy between a power-law[2] and a linear[7–9] dependence of W with biasing.

Not even the spatial variation of the nonuniform electric field is unanimously accepted: some authors[6] have shown that the field is tilted with a maximum at the Ohmic contact, while others[7–10] have observed that the maximum value of the electric field occurs at the Schottky side.

The limited extent of the active region was recently explained by modeling the electric field behavior in two different ways.[4,11] McGregor *et al.*[4] included in their model the effect of deep levels that become neutral at high fields due to field-enhanced electron-capture cross section, while Kubicki *et al.*[11] calculated the electric field in terms of the ionization of deep levels and spatial variation of the quasi-Fermi level taking into account the effect of leakage current density. Both models agree on a nearly linear increase of W with bias. On the electric-field behavior, instead, the model given by Kubicki *et al.* predicts a linearly decreasing electric field, while the one of McGregor *et al.* assesses an almost flat field near the Schottky barrier up to some extent into the bulk, followed by a sharp fall to a low-field region.

For a deeper understanding of the aforementioned matter, this paper reports results on the electric-field behavior, charge-density distribution, and reverse bias V_a dependence of the active layer width W, obtained with the optical-beam-induced current (OBIC) method[12] and surface potential (SP) measurements.[7,8] Attention has been paid specifically to the distribution of $\mathcal{E}$ in the range of reverse bias voltages $\leqslant 100$ V since it has been recently demonstrated[13] that detector charge collection efficiency is optimized using detectors with a thickness on the order of 100 μm, where full active conditions are reached at about 100 V.

Samples used in the present work have been prepared by depositing circular Schottky pads (Au/Pt/Ti) (Ref. 14) (diam-

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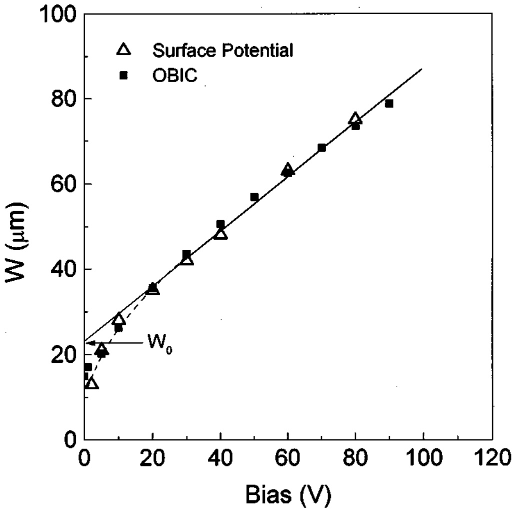

FIG. 1. Active region width of a GaAs diode as a function of the reverse voltage applied. Both dashed and continuous lines are fitting curves to the experimental data.

eter ($\phi = 3$ mm) on Hitachi SI LEC undoped ⟨100⟩-oriented GaAs substrates, with n-type resistivity $\rho = 3 \times 10^7$ Ω cm and thickness equal to about 100 μm. The Ohmic contacts have been realized[10] on the whole back surface of the wafers by implanting Si^+ ions at two different doses and energies, a dose of 7×10^{12} cm^{-2} at 300 keV and a dose of 1×10^{13} cm^{-2} at 40 keV. The wafers, capped with silicon nitride, have been then fast annealed at 850 °C for 30 s. Finally, an e-beam-deposited AuGeNi multilayer has been alloyed at 420 °C for 30 s.

For both OBIC and SP measurements the diodes have been cleaved along a ⟨110⟩ direction to reduce the surface leakage, then have been edge-on mounted. The probe (light beam and tungsten tip in OBIC and SP analyses, respectively) had been scanning across the cleaved surface from the Schottky to the Ohmic contact.

Light-beam-induced currents in the reverse biased diodes are measured by a current amplifier, after conveniently adjusting (i) the light wavelength λ (to the value 700 nm) so as to probe a slab thick enough to be representative of bulk properties and (ii) the photon flux Φ (to the value 9.8×10^{15} cm^{-2} s^{-1}) to work in low injection conditions and thus to avoid plasma effects.[15] The light-beam diameter was 2 μm. To definitely check the in-depth probing of this method, we performed OBIC measurements in different conditions: light beams of different wavelengths, SI GaAs samples of different thicknesses and, finally, Schottky and p-n junctions on high-resistivity silicon.

Surface potential signals have been obtained by connecting the tip to a very-high-impedance voltmeter (Keithley model 6517) and positioning the tip at regular intervals (5 μm) on the freshly cleaved surface of the sample, enabling a plot of potential versus distance from the Schottky barrier to be produced.[7] It has been shown[7,8] that the voltages so measured at the surface reflect those within the material. All measurements have been carried out in air.

From the optical-beam-induced current profiles it is possible to deduce[9] the active layer width W, where the electric field takes place, assumed as the photocurrent profile half-maximum width. The results obtained are shown in Fig. 1. As can be seen, for $V_a < 20$ V W follows the square-root dependence on V_a (dashed line), while for $V_a \geqslant 20$ V it increases linearly with V_a (continuous line). As already reported,[9] for $V_a < 20$ V the value of the net effective charge density due to all (shallow and deep) ionized acceptor and donor levels, N_{eff}, which fits the square-root behavior of Fig. 1 is 2.3×10^{13} cm^{-3}. N_{eff} can be different from the value at the thermal equilibrium conditions because it accounts for the shift of the Fermi energy level due to the pinning at the surface and to the presence of the electric field.

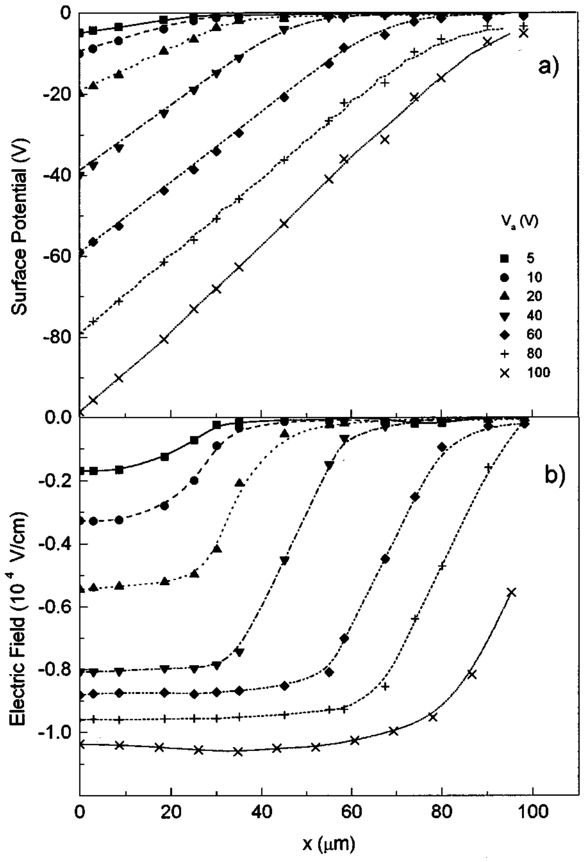

FIG. 2. (a) Surface potential within a GaAs diode versus distance x from the Schottky contact for applied voltages from 5 to 100 V as labeled in the figure. (b) Electric field within the diode. Lines in (a) have been obtained by interpolation of the experimental data, and profiles in (b) by differentiation of the previous lines.

Surface potential measurements have been performed on the same diodes to directly measure electric-field profiles as a function of V_a. Results are reported in Fig. 2(a), where the symbols represent experimental data and the lines the relevant interpolation curves. Data of Fig. 2(a) have been interpolated by means of the function ''interpolate'' of the software package MicroCal Origin, which just minimizes the χ^2 of the interpolating curve to the experimental data. Thus, there is not any *a priori* choice of the fitting functional form. By these interpolating curves, the profiles of the electric field are produced [Fig. 2(b)]. They show that for low applied voltages ($V_a < 20$ V) the maximum value of the electric field $\mathcal{E}$ very rapidly increases in absolute value with V_a while, for voltages $V_a \geqslant 20$ V, the electric-field profile exhibits a nearly rectangular distribution, the plateau of which only slightly

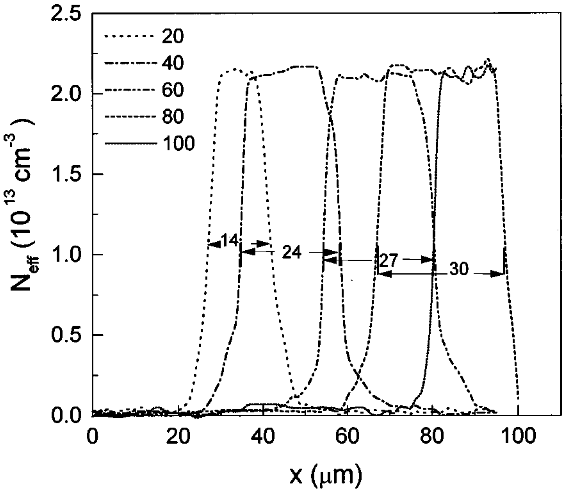

FIG. 3. Density of net ionized charge N_{eff} vs distance x from the Schottky barrier. The biasing voltages are labeled in the figure while the width of each space charge layer (in μm) is reported on the relevant curve.

increases in height by further increasing V_a. At the same time the plateau extent keeps on increasing, going deeper and deeper into the diode bulk towards the Ohmic contact. A transition region of definite size separates the plateau from the nearly zero field region.

Also for the SP measurements the active region W was defined as the half width of full maximum of the electric-field profiles, in accord with what was done with the OBIC profiles. The values obtained are reported in Fig. 1 together with the OBIC data, and show excellent agreement with them. From the slope of the linear region W versus V_a the result is obtained that, for $V_a \geqslant 20$ V, W increases at a rate k equal to ≈ 0.7 μm/V. It is worth noting that W differs from zero at $V_a = 0$ because of the built-in voltage of the Schottky barrier.

According to the Gauss theorem, the derivative of the electric field $\mathcal{E}$ provides the net effective ionized charge density N_{eff}. In Fig. 3 the calculated profiles of N_{eff} are reported for reverse voltages applied $V_a \geqslant 20$ V, for which the electric field exhibits the nearly rectangular distribution and W starts increasing linearly with V_a. Taking into account that tip steps are known with a precision of 0.5 μm and the the error in the high-impedance voltmeter reading is $\leqslant 0.5\%$, an error of 10% relevant to N_{eff} has been calculated using error propagation rules.

The main features on N_{eff} resulting from Fig. 3 can be summarized as follows: (i) N_{eff} is everywhere equal to zero except in the region between the plateau of $\mathcal{E}$ and the nearly zero field region, where it is positive and exhibits a box-shaped distribution; (ii) the height of this distribution remains constant whatever the voltage applied V_a; (iii) it moves towards the Ohmic contact by increasing V_a; (iv) it widens; and (v) consequently, the total positive charge per unit area Q included in the box-shaped distribution increases at increasing V_a. In particular, at increasing V_a from 20 to 80 V the width of the box-shaped distribution of N_{eff} increases from 14 to 30 μm and, correspondingly, Q increases from 5.7×10^{-9} to 1.1×10^{-8} C cm^{-2}. The maximum value of N_{eff} obtained in Fig. 3 gives a result of about 2×10^{13} cm^{-3}, which is in surprisingly good agreement with the charge density N_{eff} obtained by fitting the W data in the region of the square-root regime (Fig. 1).

The above-presented results allow us to achieve a clear understanding of the dependence of the electric field and of the distribution of the space-charge density on the bias applied in diodes made on SI LEC GaAs. At low applied voltages the diode behaves similarly to a standard semiconductor Schottky junction with the active region widening according to the square root of V_a (Fig. 1). The net charge density that determines the detector active layer width is the effective ionized charge N_{eff}. From this regime the diode smoothly moves to a behavior typical of a Schottky junction made on SI GaAs,[4,7–9] which is characterized by a linear dependence of W on V_a described by the expression $W = W_0 + kV_a$ according to the continuous line of Fig. 1, where $W_0 = 24$ μm and $k = 0.7$ μm/V. In this regime the increase of the reverse bias induces several correlated effects: (i) an increase of the strength of $\mathcal{E}$, small but significant, and of the extent of its plateau, (ii) a widening of the active region width W, (iii) the movement and the widening of the box-shaped positive charge region towards the Ohmic contact, and (iv) the increase of the positive charge Q. Obviously, at applied voltages greater than the one required to make the diode fully active (i.e., W equal to the detector thickness T) a further increase of V_a induces an increase of the electric field which, under these conditions, gives the result $\mathcal{E} = V_a/T$.

The space-charge distribution observed in this regime is characteristic of a Mott barrier, where a layer devoid of donors lies just close to the metal.[16] This result can be explained by invoking the neutralization of the ionized charge by the electrons flowing through the reverse biased diode.[2,4,6] At low biasing this neutralization does not occur and the active region is controlled by the net ionized charge density N_{eff} (Schottky barrier). At high biasing, as reported in model of McGregor *et al.*, the deep-level capture cross section is enhanced by the electric field, resulting in the formation of a quasineutral space-charge region that corresponds to the electric-field plateau (Mott barrier). What clearly stems from our results is that this plateau is followed by a transition region where the neutralization extinguishes so that a positive space charge of definite extent takes place. It is noteworthy that the charge density in this region is very close to that which controls the active region extent at low electric fields. Then, a nearly zero field region occurs near to the Ohmic contact.

Consequently, the detector will behave as a ''virtual'' condenser, consisting of two ''plates,'' the negatively charged Schottky metallization and the positively charged box-shaped region, separated by the quasineutral region of high electric field.

In conclusion, we have studied the behavior of the electric field and the distribution of the charge density across semi-insulating GaAs diodes.

The electric-field profiles here reported are consistent with the presence of a plateau in the distribution of $\mathcal{E}$, as explained by McGregor *et al.* with a quasineutral region resulting from the electric-field-enhanced capture cross section of electrons[3,4] from deep levels such as $EL2$. However, while model of McGregor *et al.* predicts that the transition between the high and low electric-field regions is very sharp, we have clearly shown that this transition is actually smooth.

This result reveals that a positive space charge, with a box-shaped distribution of definite extent, exists between the high and low electric-field regions. We also found that this distribution enlarges and moves towards the Ohmic contact when the reverse biasing V_a increases.

Present results, therefore, give a tool for improving the existing models accounting for the electric-field and space-charge features evidenced in this work and to explain the performance of semi-insulating GaAs diodes used as nuclear detectors.

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