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Rapid Note

Influence of acceptor impurities on semi-insulating GaAs particle detectors

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Abstract. GaAs Schottky diodes, made on semi-insulating liquid encapsulated Czochralski grown material with concentrations of acceptor dopants N_a varying from 10^{14} to 10^{17} cm^{-3}, were investigated as alpha particle detectors. The charge collection efficiency (CCE) was found to decrease dramatically with increasing N_a. Optical spectra in transmittance and reflectance were accurately measured to determine the concentrations of both neutral and ionised EL2 defects as a function of N_a. The concentration of ionised EL2$^+$ centres was shown to increase with N_a, and to be quasi inversely proportional to the CCE values. This behaviour strongly supports the hypothesis that the EL2 defects play the main role in the compensation of the material and in limitation of the detection properties.

PACS. 29.40.Wk Solid-state detectors – 78.70.-g Interactions of particles and radiation with matter – 71.55.-i Impurity and defect levels

1 Introduction

Radiation detectors for room temperature operation based on GaAs have been widely studied in recent years [1,2]. Liquid Phase Epitaxy has permitted the growth of GaAs material which confers good performances on devices, but not the production of thick layers of adequate purity to achieve sufficient depletion for detection of charged particles or gamma radiation [3].

Semi-insulating (SI) GaAs [2,4] has been used as an alternative, because it has the advantages of being readily available with thicknesses of several hundred microns and of having a high resistivity ($\sim 10^7$ ohm cm). The SI nature of GaAs results from the compensation of residual acceptor impurities, typically carbon and chromium, by intrinsic deep donor levels [5,6]. One of these electron levels, the so-called EL2, which is associated with an arsenic antisite As$_\mathrm{Ga}$ defect, in its ionized state (EL2$^+$) is dominant: although it occurs in concentrations comparable to all other electron trapping centres, its capture cross section increases with the electric field to far exceed that of the other ones [7,8]. Since the detrapping time of EL2$^+$ is of the order of seconds, the trapped electrons are lost for detection [9].

Detectors based on these SI materials suffer, then, from losing some of the charge signal [2,10], and it has been found that this degradation in performance, as a result of electron trapping, is more evident in high resistivity materials [11].

In the present paper, we present a systematic study by means of optical and electrical techniques of detectors fabricated on GaAs wafers with different concentrations of acceptor dopants (N_a) in an attempt to alter the compensation mechanism. In particular, we determined the EL2$^+$ concentration by optical spectroscopy, which we had previously used successfully to evaluate the effect of proton irradiation on GaAs based devices [12], and the charge collection efficiency (CCE) by electrical techniques. We will give experimental evidence of the tight correlation between N_a, the EL2$^+$ defect concentration and CCE values.

2 Experimental details

The detectors were made on 200 μm thick 3$''$ SI-Liquid Encapsulated Czochralski (LEC) GaAs wafers grown with different contents of acceptor dopants, mainly carbon (C) and chromium (Cr), by several manufactures (Freiberger, Nippon-Mining and Sumitomo). The C and Cr nominal concentrations and the manufacturers of the SI GaAs substrates are reported in Table 1.

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Table 1. Nominal carbon and chromium concentration of the SI GaAs wafers, supplied by the indicated manufacturers.

#	Manufacturer	Acceptor Dopant Concentration
1	FREIBERGER	[C] = 3×10^{14} cm^{-3}
2	"	[C] = 8×10^{14} cm^{-3}
3	NIPPON-MINING	[C] = 1.3×10^{15} cm^{-3}
4	"	[C] = 5×10^{15} cm^{-3}
5	"	[C] = 1×10^{16} cm^{-3}
6	SUMITOMO	[C] < 1×10^{15} cm^{-3}, [Cr] = 1×10^{17} cm^{-3}

The detectors were Schottky diodes: the ohmic contact covered the whole back side of the detector, whereas the front side was patterned with circular Schottky contacts of 2 mm in diameter. The details of the electrical contact formation are described elsewhere [10].

The samples for optical evaluation, with plane parallel surfaces both optically polished, were derived from the same wafers and had a thickness of 200 ± 3 μm, as determined by a mechanical stylus and by interference fringes in the mid-IR high resolution spectra. The optical quality of the samples was checked by spectroscopic ellipsometry in the visible-ultraviolet region.

The detectors were tested, as usual [13], by standard I/V and C/V measurements and by irradiating them with 5.48 MeV alpha particles from an ^{241}Am source on the Schottky and ohmic contacts.

Reflectance (R) and transmittance (T) spectra at room temperature and at near-normal incidence were measured with high accuracy by a Varian Cary 5E spectrophotometer in the photon energy interval 0.6-1.4 eV. More details are reported in reference [12]. For the typical value $T = 0.5$, the absolute accuracy in T was better than 0.0015 and in R better than 0.005.

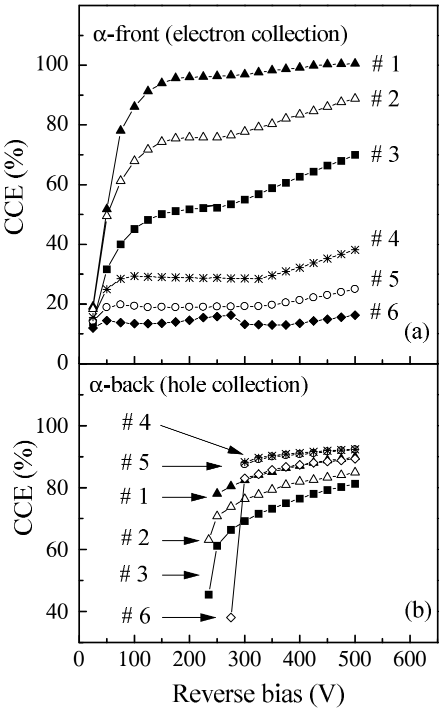

Fig. 1. Charge collection efficiency (CCE) *vs.* reverse bias for α-particles of GaAs detectors with different concentrations of acceptor dopants. The CCE values refer to front (a) and back (b) exposure. The numbers from #1 to #6 refer to samples in Table 1.

3 Results and discussion

The CCE values for electrons (*i.e.* alpha particles irradiate the Schottky contact) and for holes (*i.e.* alpha particles irradiate the ohmic contact) as a function of the reverse bias $V_{\rm a}$, measured at room temperature, are shown in Figures 1a and b, respectively.

The following important remarks can be made:

i) the CCE for electrons depends strongly on the acceptor concentration, decreasing monotonically with increasing $N_{\rm a}$;
ii) the CCE for holes does not display a clear dependence on $N_{\rm a}$, and is almost independent of $N_{\rm a}$ at high $V_{\rm a}$.

The optical absorption coefficient $\alpha(E)$ and the reflectivity $\rho(E)$, where E is the photon energy, were derived from the inversion of the T and R spectra through the well-known relationships (1, 2) [14], which take into account multiple reflection effects:

$$T = (1-\rho)^2 \exp(-\alpha t)\left[1-\rho^2\exp(-2\alpha t)\right]^{-1} \quad (1)$$

$$R = \rho + \rho(1-\rho)\exp(-2\alpha t)\left[1-\rho^2\exp(-2\alpha t)\right]^{-1}. \quad (2)$$

We observed that within the experimental uncertainty the ρ spectra of all samples coincided with the reference spectrum of GaAs reported by Palik *et al.* [15]. In addition, the accuracy of ± 0.0015 in T produces a systematic uncertainty in α of ± 0.07 cm^{-1} over the entire spectral range.

The total absorption coefficient $\alpha(E)$ in the near IR region can be expressed as:

$$\alpha(E) = N^0\sigma^0(E) + N^+\sigma^+(E) + \alpha_0 \quad (3)$$

where $\sigma^0(E)$ and $\sigma^+(E)$ are the absorption cross sections at room temperature for EL2^0 and EL2$^+$, respectively; N^0

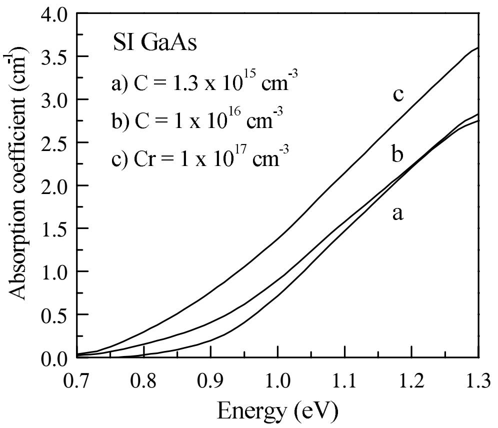

Fig. 2. Absorption coefficient spectra at room temperature of samples from SI GaAs wafer, with different dopant acceptor concentrations.

and N^+ are the corresponding concentrations, while α_0 is the background absorption accounting for any process unrelated to EL2 defects. In our case, for $E < 0.7$ eV α_0 values are constant and quite small, and their differences can be attributed to the different quality of the GaAs wafers.

Figure 2 shows the EL2 absorption spectra $\alpha(E) - \alpha_0$ of three typical samples with different nominal concentrations N_a of impurities (C or Cr). It is evident that the absorption connected to the EL2 centers increases with N_a: a quantitative evaluation of N^0 and N^+ was obtained by fitting the experimental α spectra in the energy range 0.7-1.3 eV with equation (3) and $\sigma^0(h\nu)$ and $\sigma^+(h\nu)$ cross sections taken from Silverberg *et al.* [16].

The N^+ values and the EL2 ionized fraction $P_i = N^+/(N^0 + N^+)$, as obtained from the least-square fits (standard deviation less than 2×10^{-2} and maximum standard error 5×10^{-3} on both parameters), are shown in Figure 3a. We note that N^+ increases monotonically with N_a, regardless of the dopant element, and the same is true for P_i: in particular $N^+ \approx N_a$ at low N_a values ($\leq 5 \times 10^{15}$ cm^{-3}), as is usually assumed in SI materials. Instead, at high N_a values, N^+ seems to saturate: it reaches a maximum value of 10^{16} cm^{-3}, corresponding to $P_i \sim 0.3$ and only to 10% of N_a.

It is now interesting to compare the dependence of the N^+ and of the CCE values as a function of N_a. Because CCE is expected to decrease with increasing N^+, we plotted the $1/N^+$ quantity compared to the CCE α-front values at 300 volts (Fig. 3b). This value of the reverse bias V_a guarantees that all the detectors are fully depleted and the measurements for electrons are not affected by extrinsic effects like those due to the undepleted region [17]. Moreover the electric field, defined by the ratio V_a/W, where W is the thickness of the detector, takes the same value for all the examined samples [18]. The similar behavior of the $1/N^+$ and CCE plots gives the experimental evidence (to our knowledge never previously reported) of the dependence of both the EL2$^+$ content and the charge collection efficiency on N_a, due to the trapping of electrons by EL2$^+$ levels. We note that our results are in qualitative agreement with those previously reported [11,19]; our data extend over a wider range of N_a concentrations, producing a more significant comparison between CCE and N_a values, while in the previous works CCE values are reported as a function of the resistivity ρ, which in turn should depend on different compensation mechanisms.

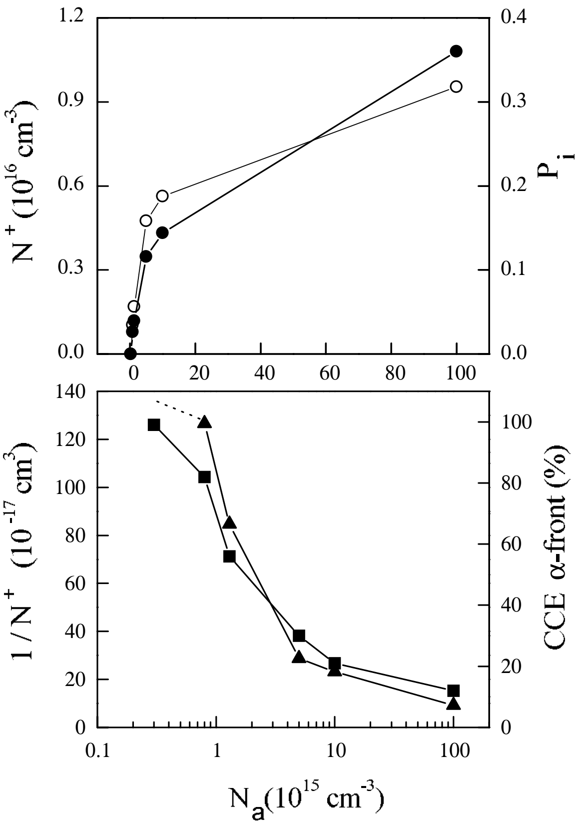

Fig. 3. (a) Density of EL2 defects in the ionized state (N^+, full circles) and ionized EL2 fraction P_i (open circles) as a function of the acceptor concentration N_a in SI GaAs wafers; (b) $1/N^+$ values (triangles) and CCE α-front values at 300 volts (squares) as a function of N_a in the same wafers.

4 Conclusions

We measured accurately the optical absorption due to neutral and ionized EL2 defects on a series of semi-insulating GaAs wafers with acceptor concentration N_a varying from 10^{14} to 10^{17} cm^{-3}. It was shown quantitatively that the concentration N^+ of ionized centers EL2$^+$ increases with N_a; at the same time the electron collection efficiency (CCE) of the Schottky-barrier detectors, based on the same wafers, decreases. In addition, the CCE values turned out to be quasi-inversely proportional to the N^+ values. These results support the hypothesis that the EL2$^+$ donor levels, which participate with the impurity acceptor levels to the compensation of the material, are the most effective electron traps, and play a fundamental role in the limitation of the detection properties.

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