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Strongly anisotropic field ionization of a common deep level in GaAs

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Résumé. — Nous observons une très forte anisotropie de l'ionisation, par effet de champ, du défaut « EL2 » (un niveau profond usuel, attribué dans le passé à l'oxygène) dans GaAs. Le taux d'ionisation est maximum lorsque le champ électrique est orienté $\overline{111}$ (de As vers Ga) et minimum dans la direction opposée 111. Des conclusions concernant la structure microscopique du défaut peuvent être déduites de ce comportement. Cette nouvelle méthode d'investigation des propriétés de symétrie des défauts peut être plus généralement appliquée à tous les niveaux profonds qui émettent dans la bande de conduction de GaAs, composés ternaires apparentés et de tout autre semi-conducteur à grande mobilité.

Abstract. — We observe a very strong anisotropy of the internal field effect for defect « EL2 » (a well-known deep level, assigned in the past to oxygen) in GaAs. The ionization rate is maximum when the electric field is $\overline{111}$ oriented, pointing from As, to Ga and is minimum for the opposite 111 field orientation. Conclusions concerning the microscopic defect structure can be deduced from this behaviour. This new method of investigation of the symmetry properties of deep level defects can be more generally applied to all the levels emitting into the conduction band of GaAs, its related compounds and any other high-mobility semiconductor.

The anisotropic effects in the bulk of III-V semiconductors are rare and deserve particular attention. Such effects may be intrinsic (characteristic of the perfect crystal) or extrinsic, related to particular defects; in this case, their study can provide a unique source of information about the microscopic physical structure of the defect. We report below the observation of strong anisotropy of the electric field-induced ionization rate of a deep level which is commonly present in GaAs crystals. In the discussion of the experimental results we shall try to show that they are uniquely compatible with a definite microscopic structure of the corresponding defect. To our knowledge, this is the first time that such an effect is observed and interpreted in this way. Recently, T. P. Pearsall *et al.* [1] reported the observation of strong anisotropy of the coefficient of impact ionization by electrons, α , in GaAs but this is an intrinsic effect related to the structure of the conduction bands. The interesting, recent theoretical treatments and experimental investigations of electric field-induced ionization of impurity levels [2] do not easily lend themselves to immediate generalization for the consideration of anisotropic effects.

Our samples were cut from a single piece of bulk GaAs crystal, Czochralski grown in a (100) direction, n-type Si doped. Wafers with surfaces normal to the

vectors 111 (As surface), 100, 110 and $\overline{111}$ (Ga surface) were obtained and polished mechanically and chemically. On each wafer, Schottky barriers were made by Au evaporation through a metallic mask and the samples were mounted in a cryostat for characterization by barrier capacitance measurements under reverse bias. The equipment used for this purpose has been already described [3].

As a first step we measured the internal potential barrier V_b and the free carrier (electron) concentration n at 300 K for each orientation (Fig. 1). One can

Fig. 1. — Doping profiles of the four Schottky barriers with different orientations. The built-in potential V_b can be calculated from the minimum depleted layer width which corresponds to zero applied bias.

appreciate that these parameters are essentially the same in all samples, indicating that the initial crystal piece was homogeneous and that the barrier height Φ ($\Phi = V_b + E_F$, E_F = Fermi level in the bulk) does not strongly depend on the semiconductor surface orientation. The V_b and n values thus obtained are listed in table I. They can be used for calculating the electric field in the depleted region of the Schottky barrier as a function of position and reverse bias.

The second step consisted in recording the spectrum of deep levels in each sample by the transient capacitance method called Deep Level Transient Spectroscopy (D.L.T.S.) [4]. A small value of the reverse bias was used in order to minimize the effect of cold ionization due to the electric field. We obtained (Fig. 2) a single peak, whose position and amplitude are essentially identical in all samples of different orientations. The peak is quite symmetrical, indicating that the cold ionization effect is indeed weak. This peak corresponds to a deep level which is well known for a long time, is commonly found in melt-grown GaAs, and in the past has been attributed to oxygen impurity. According to a recent compilation [5] we call this defect by the conventional name « EL2 » since in fact its physico-chemical origin is not established. The common occurrence of this defect, as well as some very peculiar physical properties (persistent photo-conductivity self-quenching [6-10]) specific to it, confer a particular interest to experiments which, like the one we are now going to describe, permit description of its microscopic structure.

Fig. 2. — D.L.T.S. spectra at low electric fields (reverse bias = -1 V). Dotted line : 100, full-line : 110, dot-dashed line : $\bar{1}\bar{1}\bar{1}$ (Ga), dashed line : 111 (As). The same symbols are used in figures 2 and 3. The emission rate window is 7.5 s^{-1} in both cases.

When the D.L.T.S. spectra were taken, while using a larger value of reverse bias, very strong differences appeared as a function of the crystalline orientation (Fig. 3). In all cases, the peak is distorted on the low temperature side and its amplitude is smaller than the value which can be calculated using the results already obtained at low electric fields. This is due to the fact that some of the defects, instead of emptying by

Fig. 3. — D.L.T.S. spectra at high electric fields (reverse bias = -4 V).

thermally activated emission, empty much faster under the influence of the large electron field, essentially by tunnelling [2, 11].

In order to characterize quantitatively the cold emission process we recorded the capacitance transients at a fixed temperature, which was chosen low enough so that the thermal emission could be neglected. Moreover, the bias pulse used for filling the deep levels before the transient was chosen of such an amplitude and duration that only a thin sheet of the depletion layer was filled during the pulse.

A detailed calculation (omitted here), which takes into account the partial refilling effects which occur at the edge of the depleted layer as discussed in [12], indicates that, with the pulse characteristics mentioned in the legend of figure 4, the electric field in the sheet varies only between 1.75×10^7 and $2 \times 10^7 \text{ V/m}$ approximately, so that it was possible to obtain reasonably sharp transients which are displayed in figure 4. The 110 transient, not shown, was similar to the 100 one.

Strictly exponential transients, fitted to the central parts of the experimental transients, are shown in dashed lines. The fits for $\bar{1}\bar{1}\bar{1}$ (Ga) and for 100 indicate that at least 60 percent of the deep level population in the sheet empties at the same rate in each case. The corresponding rates are 2 s^{-1} for $\bar{1}\bar{1}\bar{1}$ Ga and 0.7 s^{-1} for 100.

In the case of 111 As orientation the situation is slightly more complex. As seen in figure 4, not all of the « EL2 » levels empty out. In competition with the electron emission process, a hole emission one is present and the final stationary occupation ratio in the sheet is about 0.5. Both processes are extremely slow ; the effective emission rate ($e_n + e_p$) which can be deduced from figure 4 is about 0.024 s^{-1} and again it affects more than 50 percent of the variable part of the occupation ratio.

To summarize, the cold ionization effect is strongly anisotropic. Most important, there is a very large difference of emission rates for the opposed $\bar{1}\bar{1}\bar{1}$ and

Fig. 4. — Capacitance transients recorded at 253 K after a bias pulse of duration 100 μ s from -4 V to -2 V and back to -4 V. Prior to the bias pulse the deep levels were emptied by heating the samples at 300 K. Dashed lines are pure exponential variations fitted to the experimental transients and corresponding to time constants of 0.5 s, 1.4 s, and 41 s respectively.

111 orientations. For 100 and 110 the emission rates take intermediate values. The observed emission rates are listed in table I.

The detailed interpretation of these observations is not clear to us at the time of writing. We think that the ionization anisotropy might be related to a corresponding anisotropy of the defect potential [13] and of the defect-bound electron wave-function. The (111) direction would become, in the presence of the external field, an axis of symmetry and of electrical polarization (i.e., from Ga to As). However, the defect structure cannot be a complex (such as, for instance, an impurity coupled to a vacancy) involving two neighbouring sites, since in that case, the defects being

equally distributed along the four equivalent (111) directions, when the electric field is applied along one of those the cold ionization effect would affect at most one fourth of the total number of defects ; while in reality the effect shown in figure 4 is much stronger, involving *all* the defects.

It seems to us that, to be compatible with the experimental observations, the defect structure must initially have (nearly) tetrahedral symmetry. When the bias is applied, field emission will occur along the direction of the electric field. The emission rate anisotropy would correspond to different values of the effective potential barrier height and/or width along the different directions. A simple structure like, e.g., an isolated vacancy could satisfy these requirements [14].

To conclude, we have observed a strong anisotropy in the electrical properties of a deep level in GaAs and tentatively deduced from these experiments unique information about the microscopic structure of the defect. It would be interesting first to study similar effects on other deep levels, and second to obtain a deeper theoretical understanding of the interaction between electrons captured in a deep level and the applied electric field.

This method of investigation could find application in studying the symmetry of all the defects which cannot be observed by electron paramagnetic resonance or piezospectroscopic experiments, but which are observed as deep levels emitting into the conduction band of GaAs, related compounds, and any other high-mobility semiconductor.

Table 1. — Summary of experimental results.

Sample n°	Orientation of the surface	Net doping n , cm^{-3}	Built-in barrier potential V_b , V	Field-effect emission rate, s^{-1} ($E \simeq 1.9 \times 10^7$ V/m, $T = 253$ K) (*)
1	100	1.6×10^{17}	0.83	0.7
2	110	1.55×10^{17}	0.81	1
3	111 (As)	1.4×10^{17}	0.91	0.024
4	$\overline{111}$ (Ga)	1.5×10^{17}	0.88	2

(*) The low-field, thermal emission rate at $T = 253$ K is approximately $6 \times 10^{-5} \text{ s}^{-1}$.

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