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Simple measurement of 300 K electron capture cross section for EL2 in GaAs

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A simple experiment involving only the measurement of dark current I_{dark} and 1.1 μm photocurrent I_{PC} in semi-insulating (SI) GaAs allows an accurate determination of the electron capture cross section σ_n for the important defect EL2 in GaAs. For 45 SI GaAs samples, from 12 different boules, grown by three different techniques, we find that $I_{\text{PC}}/I_{\text{dark}} = 1.96 \pm 0.05$ at 300 K. This relationship gives $\sigma_n = 1.4 \pm 0.4 \times 10^{-16} \text{ cm}^2$, which is compared to previously estimated values. © 1996 American Institute of Physics. [S0021-8979(96)07818-8]

The defect EL2 in GaAs has been widely studied because of its importance in the production of semi-insulating (SI) material.¹ Not only is EL2 important in the compensation process, but it also is relevant with regard to carrier trapping and recombination dynamics. For example, in molecular-beam-epitaxial GaAs grown at very low temperatures, the subpicosecond carrier lifetimes are attributed to the EL2-like, As-antisite centers.² Thus, it is highly desirable to have accurate values of the electron and hole capture cross sections, σ_n and σ_p , respectively. Unfortunately, no direct measurements of σ_n or σ_p have ever been performed at 300 K, to our knowledge. Often a rough cross section is derived from the intercept of a deep level transient spectroscopy (DLTS) Arrhenius plot; however, this value, given in the literature³ as $\sigma_{na} = 2 \times 10^{-13} \text{ cm}^2$ for EL2, is only an apparent cross section, because it includes some extraneous factors.⁴ Indeed, the above σ_{na} is a factor 10^3 larger than the true σ_n at 300 K, reported here. Other, more careful DLTS studies, involving trap filling by pulse length variations, have given the following relationships for σ_n :

- (1) $\sigma_n = 3 \times 10^{-15} \exp(-0.075/kT) \text{ cm}^2$, from 150 to 245 K;⁵ and
- (2) $\sigma_n = 6 \times 10^{-15} \exp(-0.066/kT) \text{ cm}^2$, from 50 to 275 K.⁶

At 300 K, these two equations give 1.6×10^{-16} and $4.7 \times 10^{-16} \text{ cm}^2$, respectively, even though neither is presumed valid at 300 K. Thus, an accurate measurement of σ_n at 300 K is needed.

Our method makes use of dark current I_{dark} and photocurrent I_{PC} measurements on the same sample. Because the photoexcitation is subband gap (1.1 μm), these measurements involve the full sample volume, in contrast to the more restricted near-surface, space-charge region seen by the DLTS (or any diode capacitance) technique. Consider first the carrier concentration n in SI GaAs, which is given by the following well-known formula, for $T \lesssim 600 \text{ K}$:

$$n = \frac{g_0}{g_1} \frac{N_D - N_A}{N_D} N_C' T^{3/2} e^{\beta/k} e^{-E_{D0}/kT}, \quad (1)$$

where β is a temperature coefficient defined by $E_D = E_{D0} - \beta T = 0.75 - \beta T$; g_0/g_1 is a degeneracy factor; and $N_C' T^{3/2}$ is the effective conduction-band density of states.

By analyzing a large number of samples in which $N_D (= [\text{EL2}])$ and $N_A (= [\text{C}])$ were measured independently,⁷ we have concluded that

$$(g_0/g_1) N_C' \exp(\beta/k) = 2.0 \times 10^{15} \text{ cm}^{-3}.$$

We also note that $N_{\text{EL2}}^+ = N_A$, since $n \ll N_A$, and $N_D - N_A = N_{\text{EL2}} - N_{\text{EL2}}^+ = N_{\text{EL2}}^0$. Thus, at 300 K, $n = C N_{\text{EL2}}^0 / N_{\text{EL2}}^+$, where $C = 2.6 \times 10^6 \text{ cm}^{-3}$. The dark current will obey

$$I_{\text{dark}} = n e \mu_n V \frac{wd}{\ell} = C \frac{N_{\text{EL2}}^0}{N_{\text{EL2}}^+} e \mu_n V \frac{wd}{\ell}, \quad (2)$$

where V is the voltage applied across the sample length ℓ ; w is the sample width; d is the thickness; and μ_n is the mobility. If we now apply IR light of intensity I_0 , electrons and holes will be excited from EL2^0 and EL2^+ , respectively. The concentration of electrons excited per unit time is $I_0 \sigma_{vn} N_{\text{EL2}}^0$, where σ_{vn} , the optical (photo-ionization) cross section for EL2, is well known.^{8,9} The steady-state concentration of electrons is $I_0 \sigma_{vn} N_{\text{EL2}}^0 \tau_n$, where τ_n is the lifetime. Since the photoexcited electron is removed from the conduction band by being trapped at an EL2^+ center, we can write $\tau_n = 1/(\sigma_n v_n N_{\text{EL2}}^+)$, where v_n is the thermal velocity. By using analogous arguments for holes, the total photocurrent can be written

$$I_{\text{PC}} = I_0 \left(\frac{\sigma_{vn} N_{\text{EL2}}^0 \mu_n}{\sigma_n v_n N_{\text{EL2}}^+} + \frac{\sigma_{vp} N_{\text{EL2}}^+ \mu_p}{\sigma_p v_p N_{\text{EL2}}^0} \right) e V \frac{wd}{\ell}. \quad (3)$$

Then, from Eqs. (2) and (3),

$$\frac{I_{\text{PC}}}{I_{\text{dark}}} = \frac{I_0 \sigma_{vn}}{C \sigma_n v_n} \left[1 + \frac{\sigma_{vp}}{\sigma_n} \frac{\sigma_n}{\sigma_p} \frac{v_n}{v_p} \frac{\mu_p}{\mu_n} \left(\frac{N_{\text{EL2}}^+}{N_{\text{EL2}}^0} \right)^2 \right]. \quad (4)$$

For the 45 samples used in this study,

$$N_{\text{EL2}}^+ / N_{\text{EL2}}^0 = C/n = 2.6 \times 10^6 / n \leq 0.09,$$

where the n were measured by the Hall effect. Also, $\mu_p / \mu_n \approx 400/8000 \approx 0.05$, $v_n / v_p = \sqrt{m_p^* / m_n^*} \approx 2.66$,

$$\sigma_n / \sigma_p \approx 1.4 \times 10^{-16} / 2 \times 10^{-18} \approx 70,$$

where σ_n is taken from this work and σ_p is given in Ref. 6, and $\sigma_{vp} / \sigma_{vn} \approx 0.320/0.907 \approx 0.353$, from Ref. 8. Thus, the square bracket in Eq. (4) represents less than a 3% correction for all samples and can be neglected. The final result is then

FIG. 1. Photocurrent I_{PC} vs dark current I_{dark} for 45 SI GaAs samples from 12 different boules.

$$\sigma_n = \frac{I_0 \sigma_{vn}}{C v_n (I_{PC}/I_{dark})}, \quad (5)$$

independent of sample dimensions, applied voltage, mobility, EL2 concentration, or Fermi level (which determines N_{EL2}^+/N_{EL2}^0). The known quantities are $\sigma_{vn} = 0.907 \times 10^{-16} \text{ cm}^2$ for $1.1 \mu\text{m}$ light,^{8,9}

$$v_n = \sqrt{8kT/\pi m_n^*} = 4.16 \times 10^7 \text{ cm/s},$$

and $C = 2.6 \times 10^6 \text{ cm}^{-3}$, all valid at 300 K.

The samples (45 total) were $3 \times 6 \text{ mm}^2$ pieces cut from the center, ring, and edge portions of one wafer each from four different boules grown by the high-pressure liquid-encapsulated Czochralski (LEC) technique, seven different boules grown by the low-pressure LEC method, and one boule (four different wafers) grown by the vertical gradient freeze technique. The boules were subjected to many different annealing schedules, which produced a spread in the various values of I_{dark} and I_{PC} . The light intensity at $1.1 \mu\text{m}$ was $I_0 = 3.3 \times 10^{14} \text{ photon/cm}^2 \text{ s}$. The I_{PC} vs I_{dark} data for the 45 points, presented in Fig. 1, are well fitted by the relationship $I_{PC}/I_{dark} = 1.96 \pm 0.05$. Thus, from Eq. (5) $\sigma_n = 1.4 \times 10^{-16} \text{ cm}^2$ at 300 K. This value is about a factor of 3

below the quantity predicted from the formula in Ref. 6, but is quite close to that predicted in Ref. 5. The estimated accuracies for the various quantities in Eq. (5) are: 20% for I_0 ; 10% for σ_{vn} ; 10% for C ; and 5% for I_{PC}/I_{dark} . Thus, the expected accuracy for σ_n is 25% or $0.4 \times 10^{-16} \text{ cm}^2$.

Since the temperature dependences of σ_{vn} , C , and v_n are reasonably well known, it should be possible to measure the temperature dependence of I_{PC}/I_{dark} and determine the activation energy E_σ in the relationship $\sigma_n = \sigma_{n0} \exp(-E_\sigma/kT)$. Among other things, this energy is of interest in analyzing the microscope nature of EL2. A preliminary activation energy, $E_\sigma \approx 0.08 \text{ eV}$, can be obtained by combining the present value of σ_n at 300 K with that recently obtained at 377 K ($\sigma_n = 2.7 \times 10^{-16} \text{ cm}^2$) by an analysis of capacitance changes during trap-filling processes.¹⁰ However, a detailed study of $I_{PC}(T)/I_{dark}(T)$ will have to be carried out in order to get an accurate value of E_σ .

Finally, it should be pointed out that Eq. (5) can be applied to any system with a deep center that behaves like EL2. In particular, EL2 itself belongs to a “family” of As-antisite related centers,¹¹ and it would be quite interesting to compare the factor $\sigma_{vn}/C\sigma_n$ for each of these centers by a simple measurement of I_{PC}/I_{dark} .

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