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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 \( I_{\text{dark}} \) and 1.1 \( \mu \)m photocurrent \( I_{\text{PC}} \) in semi-insulating (SI) GaAs allows an accurate determination of the electron capture cross section \( \sigma_n \) for the important defect EL2 in GaAs. For 45 SI GaAs samples, from 12 different boules, grown by three different techniques, we find that \( I_{\text{PC}}/I_{\text{dark}}=1.96\pm0.05 \) at 300 K. This relationship gives \( \sigma_n=1.4\pm0.4\times10^{-16} \) 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, \( \sigma_n \) and \( \sigma_p \), respectively. Unfortunately, no direct measurements of \( \sigma_n \) or \( \sigma_p \) 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 literature\(^3\) as \( \sigma_{na}=2\times10^{-13} \) cm\(^2\) for EL2, is only an apparent cross section, because it includes some extraneous factors.\(^4\) Indeed, the above \( \sigma_{na} \) is a factor 10\(^3\) larger than the true \( \sigma_n \) at 300 K, reported here. Other, more careful DLTS studies, involving trap filling by pulse length variations, have given the following relationships for \( \sigma_n \):

1. \( \sigma_n=3\times10^{-15} \exp(-0.075/kT) \) cm\(^2\), from 150 to 245 K;\(^5\) and
2. \( \sigma_n=6\times10^{-15} \exp(-0.066/kT) \) cm\(^2\), from 50 to 275 K.\(^6\)

At 300 K, these two equations give 1.6\(\times10^{-16}\) and 4.7\(\times10^{-16} \) cm\(^2\), respectively, even though neither is presumed valid at 300 K. Thus, an accurate measurement of \( \sigma_n \) at 300 K is needed.

Our method makes use of dark current \( I_{\text{dark}} \) and photocurrent \( I_{\text{PC}} \) measurements on the same sample. Because the photoexcitation is subband gap (1.1 \( \mu \)m), 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 \( T\leq600 \) K:

\[
n = \frac{g_0 N_D - N_A}{g_1 N_D} N_c T^{3/2} e^{\beta T} e^{-E_D/kT},
\]

where \( \beta \) 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 \( N_D^0 (= [EL2]) \) and \( N_A^0 (= [C]) \) were measured independently,\(^7\) we have concluded that

\[
(g_0/g_1)N_c^0 \exp(\beta/kT)=2.0\times10^{15} \text{ cm}^{-3}.
\]

We also note that \( N^0_{EL2}=N_A^0 \), since \( n \approx N_A^0 \), and \( N_D-N_A^0=N^0_{EL2}-N^0_{EL2} = N^0_{EL2} \). Thus, at 300 K, \( n = C N^0_{EL2} / N^0_{EL2} \), where \( C = 2.6\times10^6 \) cm\(^{-3}\). The dark current will obey

\[
I_{\text{dark}}=n e \mu_n V_d = \frac{C N^0_{EL2}}{N^0_{EL2}} e \mu_n V_d,
\]

where \( V \) is the voltage applied across the sample length \( /; \) \( w \) is the sample width; \( d \) is the thickness; and \( \mu_n \) 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 \( I_0 \sigma_{vn} N^0_{EL2} \), where \( \sigma_{vn} \), the optical (photo-ionization) cross section for EL2, is well known.\(^8\) The steady-state concentration of electrons is \( I_0 \sigma_{vn} N^0_{EL2} \), where \( \tau_n \) is the lifetime. Since the photoexcited electron is removed from the conduction band by being trapped at an EL2\(^+\) center, we can write

\[
\tau_n = 1/ \sigma_{vn} v_n N^0_{EL2},
\]

where \( v_n \) is the thermal velocity. By using analogous arguments for holes, the total photocurrent can be written

\[
I_{\text{PC}}=I_0 \left( \frac{\sigma_{vp} N^0_{EL2} \mu_p}{\sigma_{vn} v_n N^0_{EL2}} + \frac{\sigma_{vp} N^0_{EL2} \mu_p}{\sigma_{vn} v_n N^0_{EL2}} \right) e V_d / \tau_n.
\]

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

\[
\frac{I_{\text{PC}}}{I_{\text{dark}}} = \frac{I_0 \sigma_{vn}}{C \sigma_{vn} v_n} \left[ 1 + \frac{\sigma_{vp} \mu_n}{\sigma_{vn} \mu_p} \left( \frac{N^0_{EL2}}{N^0_{EL2}} \right)^2 \right]^{-1}.
\]

For the 45 samples used in this study,

\[
N^0_{EL2}/N^0_{EL2} = C/n = 2.6\times10^6 /n \leq 0.09,
\]

where the \( n \) were measured by the Hall effect. Also, \( \mu_p/\mu_n = 400/8000 = 0.05; v_n/v_p = \left( m_p / m_e \right)^{1/2} = 2.66; \)

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

where \( \sigma_n \) is taken from this work and \( \sigma_p \) is given in Ref. 6, and \( \sigma_{vp}/\sigma_{vn} = 0.320/0.907 \approx 0.353 \), 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
\[ \sigma_n = \frac{I_0 \sigma_{vn}}{C \nu_n (I_{PC}/I_{dark})}, \]  
\[ \mu_n = \frac{\sqrt{8kT}}{\pi n^2} = 4.16 \times 10^7 \text{ cm/s}, \]

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

The samples (45 total) were 3x6 mm² 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 \( \mu m \) was \( I_0 = 3.3 \times 10^{14} \text{ photon/cm}^2 \cdot \text{s} \). 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. 5, 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 \( \sigma_{vn} \); 10% for \( C \); and 5% for \( I_{PC}/I_{dark} \). Thus, the expected accuracy for \( \sigma_n \) is 25% or \( 0.4 \times 10^{-16} \text{ cm}^2 \).

Since the temperature dependences of \( \sigma_{vn} \), \( C \), and \( \nu_n \) are reasonably well known, it should be possible to measure the temperature dependence of \( I_{PC}/I_{dark} \) and determine the activation energy \( E_\sigma \) 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 \( \sigma_n \) 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 \( E_\sigma \).

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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