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Deep Level Characterization in LEC GaAs

T. Ikoma, M. Taniguchi and H. Noge

Institute of Industrial Science, University of Tokyo

Roppongi, Minato-ku, Tokyo 106, Japan

Mid gap deep levels in liquid encapsulated Czochralski (LEC) GaAs are characterized by the DLTS and photocurrent methods. We have found that at least two kinds of mid gap trap (so far believed to be "EL2") exist in LEC GaAs: One of them distributes highly non-uniformly and the capture cross section varies in depth and in radial direction. This level is considered to be a principal compensator in semi-insulating LEC GaAs.

§1. Introduction

Semi-Insulating LEC GaAs is now of importance as a substrate for very high speed integrated circuits, including HEMT-based LSIs. Uniformity and thermal stability are most important to be clarified from the view point of practical application. To understand these characteristics, the compensation mechanism has to be known in these materials. However, at present there is no straightforward means to measure deep levels in semi-insulating crystals because the conventional deep level transient spectroscopy (DLTS) technique is not applicable to high resistive materials.

As for the compensation mechanism, most people believe without direct experimental verification that the so called "EL2" is a main deep donor which compensates a residual shallow acceptor in non-doped LEC GaAs.[1,2] The authors already showed, however, that the mid gap electron trap, which is almost always considered to be EL2 from its thermal emission rate, has not a unique origin and some different levels appear to be very similar to EL2.[3]

In this paper, non-doped semi-conductive and semi-insulating LEC GaAs are characterized by the DLTS and photocurrent methods in order to elucidate a principal deep level which is responsible for the compensation.

§2. Characterization of Deep Levels in Semi-conductive GaAs

Figure 1 shows typical DLTS spectra from front and tail sections of n-type non-doped GaAs, which was grown from a silica crucible and the carrier concentration ranges from 10^{15} to 10^{16} cm^{-3}. The measurements were carried out using Au Schottky diodes with 700 μm diameter. There are four traps labeled ET3, ET4 and ET5 as shown in the figure. They were found to correspond to EL3, EL5 and EL6 of Martin et al.'s classification[4], respectively. The peak temperature for ETX-1 is the same as that of the so called EL2 detected in HB and VPE GaAs. ET3, ET4 and ET5 are common in both sections, while ETX-1 does not exist in the front section and ETX-2 does not exist in the tail section. The activation energies and the capture cross sections for ETX-1 and ETX-2 are summarized in Table I.

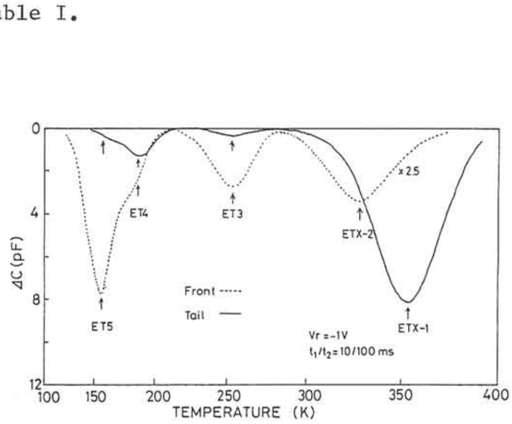

Fig. 1. Typical DLTS spectra in front and tail sections of LEC GaAs.

	E(eV)	$\sigma(cm^2)$
EL2	0.81	1E-13
ETX-1	0.80	4E-13~2E-12
ETX-2	0.77	1.6E-13~3E-12
ETX-3	0.83	4E-13
ETX-4	0.81	~4E-13
ETX-5	0.81	4.7E-12

Table I. Activation energies and capture cross sections for the mid gap levels.

We reported[5] that the peak temperature for ETX-2 gradually shifts to lower temperature and splits into two peaks when the bias voltage is increased. This behavior can be well explained by assuming existence of two levels which are closely located in the band gap: one level has a capture cross section varying continuously in depth with the same activation energy, while the other level (ETX-3) which appears at certain voltage is more stable. In the tail section, very similar characteristic was observed as for mid-gap deep levels.

We also observed that a mid gap trap (ETX-4) dissolved into a new trap (ETX-5) after annealing at 650°C for 40 min. Trap parameters of these mid gap levels are also summarized in Table I. Thus we have shown that the mid gap level (EL2) has a family, which is classified into two groups; ETX-1, -2, -4, -5 and ETX-3, EL2 in HB GaAs.

Figure 2 shows the variation of concentrations for ETX-1 and ETX-2 along radial direction on the same samples as shown in Fig. 2. The profile for ETX-2 is a U-shape with the average density of $1x10^{15}$ cm^{-3}, while ETX-1 has an inverted U-shaped distribution rather than a U-shape. These results would be consistent with the Holmes et al.'s results[6], if both ETX-1 and ETX-2 were considered to be the same as their "EL2".

We have another evidence that ETX-2 and ETX-3 exist simultaneously in some LEC GaAs. Figure 3 shows the DLTS spectra for the mid gap trap measured in another LEC GaAs. As clearly seen in the figure, the spectra is not a single level. By assuming two levels we can fit the theoretical curves (broken line) to the experimental results (solid line) by adjusting the parameters and the

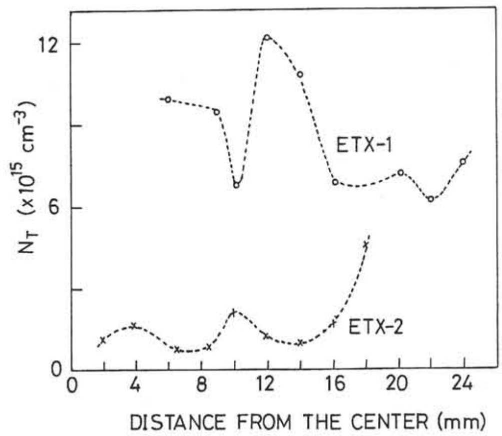

Fig. 2. Profiles of ETX-1 and ETX-2 along radial direction for the same samples as shown in Fig. 1.

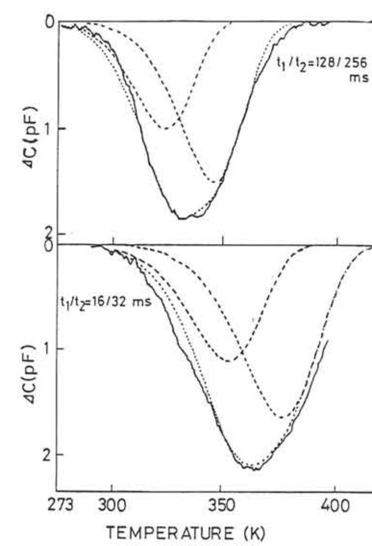

Fig. 3. DLTS spectra for the mid gap level in another LEC GaAs.

concentration ratio of two levels. The activation energy and capture cross section for one level are 0.76 eV and $3.7x10^{-13}$ cm^2 and for the other level, 0.81 eV and $4.3x10^{-13}$ cm^2, respectively. These values are almost the same as those of ETX-2 and ETX-3.

These experimental results show that in LEC GaAs, there is a family of "EL2", which has a large fluctuation in space. One of the group which is rather unstable and highly inhomogeneous, may be introduced by very rapid microscopic growth caused by temperature fluctuation in the melt[7] due to convection. These non-uniformity was also observed in semi-insulating GaAs as shown below.

§3. Characterization of Principal Compensator in Semi-Insulating GaAs

3.1. Photoconductivity in Semi-Insulator[8]

Photoconductivity in semi-insulating materials depends on the compensation mechanism. To analyse photocurrent in semi-insulating GaAs, we assume a two-level compensation model, where a residual shallow acceptor is compensated by a deep donor (presumably "EL2").

Rate equations are set up by assuming the charge neutrality and computationaly solved to obtain the photoconductivity. In the calculation, the parameters for EL2 in Ref. 9 and 10 are used. We considered two cases; the photon energy is less than the band gap (extrinsic) and higher than it (intrinsic). For intrinsic excitation, electron and hole pairs are generated and the generation rate varies with the depth. However, we neglect the lateral diffusion in the present calculation.

Figure 4(a) shows the calculated result of the dark and the photo conductivity as a function of shallow acceptor density at 300 K, where the deep trap density is assumed to be constant of 10^{16} cm^{-3}. Figure 4(b) shows the same quantities as a function of deep trap density where the shallow acceptor density is assumed to be 10^{14} cm^{-3}. The photon flux is 10^{18} $cm^{-2}s^{-1}$ for extrinsic excitation and 10^{14} $cm^{-2}s^{-1}$ for intrinsic excitation. The following important results are deduced; (1) extrinsic photoconductivity varies as dark conductivity, (2) intrinsic photoconductivity reflects the inverse of deep trap density and is not affected by the change of shallow acceptor density.

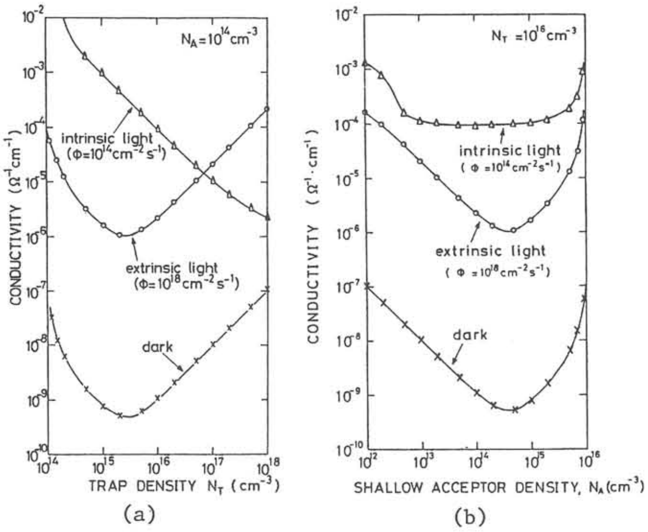

Fig. 4. Calculated photo and dark conductivity in semi-insulating GaAs assuming the two-level model. (a) as a function of shallow acceptor density. (b) as a function of deep trap density.

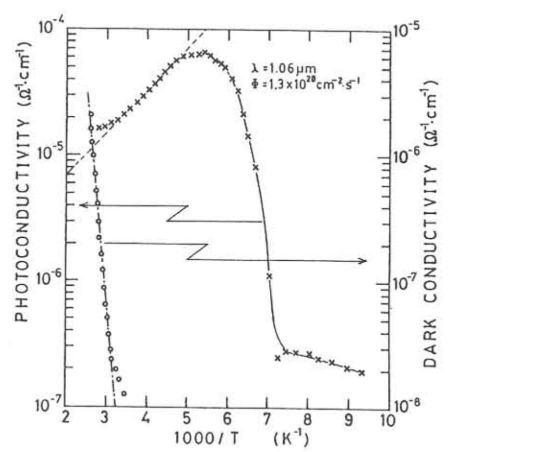

Fig. 5. Temperature dependence of extrinsic photo (YAG laser) and dark conductivity measured for non-doped semi-insulating LEC GaAs.

3.2. Energy Level of Principal Compensator

In the case of extrinsic excitation, excess electron density in the band is given by extrinsic excitation rate at the electron filled traps devided by capture rate at the empty traps. Under low excitation, which is defined as excess carrier density is much less than n_{T0} and p_{T0}, this ratio is proportional to n_{T0}/p_{T0}, i.e., $\exp\{(E_F-E_T)/k_BT\}$. Here n_{T0} and p_{T0} are filled and empty trap densities in thermal equilibrium, respectively: E_F and E_T are Fermi and trap energy levels, respectively: k_B is Boltzmann constant and T is temperature. On the other hand, electron density in dark thermal equilibrium is proportional to $\exp\{(E_F-E_C)/k_BT\}$, where E_C is the bottom energy of conduction band. Therefore we can obtain the activation energy of a principal compensator by measuring the extrinsic photocurrent as a function of temperature if electron is the dominant current flow carrier.

Figure 5 shows the temperature dependence of the dark and the extrinsic photo conductivity measured for non-doped semi-insulating LEC GaAs. From the linear part of the curves, (E_F-E_T) = 0.066 eV and (E_C-E_F) = 0.72 eV are obtained. Consequently, the energy level, (E_C-E_T) is 0.79 eV for a principal compensator.

3.3. Distribution of Photocurrent

We have measured the radial distribution of photocurrent for the sample which is the same as