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Improved Thermally Stimulated Current Spectroscopy to Characterize Levels in Semi-Insulating GaAs

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Deep levels in semi-insulating GaAs were observed at low temperatures by means of improved thermally stimulated current (TSC) spectroscopy. The improvement was done by thinning the specimen and adding a guard ring electrode. The ionization energy of the levels was limited to below 0.7 eV. The concentration of 10^{13} cm^{-3} was easily measured with an electrode area of 5 mm^2. Spectra by electron traps and hole traps were separated by changing the bias polarity.

The importance of III–V compounds for optoelectronic and high-speed devices is well recognized. It is also recognized that structural point defects in these materials affect both their performance and reliability. However, because of their complex nature, identification of these defects is rarely made.

In an element semiconductor such as Si, the vacancy and the interstitial are the sole types of isolated structural point defects, whereas in a compound semiconductor such as GaAs, there can be six types, Ga_I, As_I, V_{Ga}, V_{As}, Ga_{As} and As_{Ga}. Higher residual impurity concentration in GaAs, and the reaction among there defects to form complexes makes it even more difficult to identify a trapping level as a certain type of defect. We therefore believe we should observe the fresh structural defect at very low temperature where reaction among the defects is prohibitive, and follow the successive reaction at higher temperatures. When the material is semi-insulating, especially at low temperatures, the capacitance values are immeasurable because of high series resistance; that is to say, DLTS is useless. Photoluminescence or photoacoustic spectroscopy (PAS) could be employed at low temperatures, but the photoexcitation level is usually high due to sensitivity restriction, so that photo-annealing, i.e., reaction among the defects caused by photo-excitation, could be enhanced. We report here on a method of improved thermally stimulated current (TSC) spectroscopy which is suitable for the above observation.

The schematic diagram of the measurement is shown in Fig. 1. Specimens were of undoped semi-insulating LEC GaAs. The crystals were thinned at the center portion by chemical etching to increase the current collection efficiency of the TSC. The thickness at the center varied from 2 to 300 μm. A small dot of semitransparent ($T \simeq 30\%$) Al was evaporated to cover the etched hole of 5 mm^2 to form the front electrode. The dot was surrounded with a guard ring to prevent surface leakage. The back electrode was a simple Al electrode. As described later the short transit distance was shown to be very effective in obtaining large signal intensity and the guard ring structure reduced the background current.

The measurement of TSC was done as follows. The specimens were cooled down to a starting temperature and initialized by irradiation through the front electrode with a 20 mWcm^{-2} W-lamp light. Both intrinsic and extrinsic excitation were employed. The light was filtered with a Toshiba C-50S to cut the wavelength region longer than 700 nm when intrinsic excitation was desired. A digital electrometer, Keithley Model 616, in series with a voltage supply connected the front and back electrodes. As the temperature of the specimen was increased at a given rate, the thermally stimulated current spectrum was recorded as shown in Fig. 2. The initialization was done with an unfiltered light source for 5 min. at 12 K, without any biasing voltage. The current was measured with +2 V applied to the front electrode in the following experiment. The reproducibility of the TSC spectrum was within a few percent. No peaks were observed without the initialization.

Peaks above 200 K were rarely observed without the

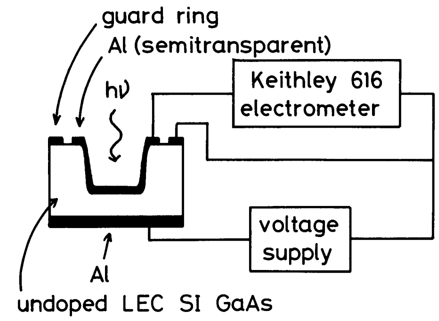

Fig. 1. Schematic diagram of the measurement.

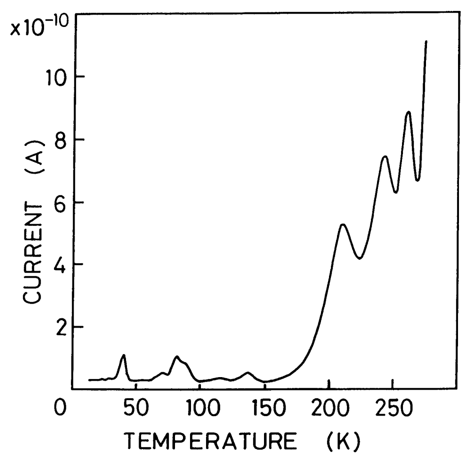

Fig. 2. TSC spectrum of semi-insulating GaAs by the initialization with unfiltered light source (both intrinsic and extrinsic excitation).

guard ring structure because of increase in the background current above 160 K due to surface leakage. In Fig. 3 is shown the effect of the guard ring on the background current. The solid line shows the temperature dependence of the background current with the guard ring. The broken line is the dependence when the guard ring is floated. The difference in the two lines is due to surface leakage. We notice the surface leakage current has two components with activation energies of 0.31 and 0.72 eV, respectively.

The deep levels in semi-insulating GaAs are clearly observed in Fig. 2, however, this observation cannot distinguish the electron trap from the hole trap, which has been cited as one of the disadvantages of TSC.[1] We can easily separate them in the following manner. The specimen was initialized with the filtered light source (intrinsic excitation) for 5 min at 12 K with +2 V bias to the front electrode. The TSC spectrum of this specimen measured with +2 V bias is shown by Curve (A) in Fig. 4. Curve (B) in the same figure is for the same specimen similarly initialized and measured but with the reverse bias polarity, that is, the front electrode was biased at −2 V. Positions of the peaks, (a) to (j) for Curves (A) and (B) in Fig. 4 do not change, while their shapes differ remarkably. We explain the difference between the two curves as follows. Carriers are generated near the front electrode by the intrinsic excitation. When the front electrode is positively biased, holes drifting into the bulk will fill the hole traps in the bulk as well as near the surface. On the contrary, electron traps in the bulk are not filled. Hence, we observe TSC of hole traps under the above condition (Curve (A)) and of electron traps under the other (Curve (B)). Thus, electron and hole traps are distinguishable by TSC in a very simple way.

The ionization energy, E_i, and the concentration, N_T, corresponding to each TSC peak are summarized in Table I. The type of trap deduced from Fig. 4 is also shown here. There are several methods to determine E_i.[2-6] Here, we adopt the simplest form[7] for a rough approximation,

$$E_i = kT_m \ln (Ne\mu/\sigma_m), \tag{1}$$

where T_m is the peak temperature. σ_m, N, and μ are the conductivity, effective density of states, and carrier mobility at T_m. k and e are Boltzmann's constant and the electronic charge, respectively. The values of $\mu(T_m)$ were taken from the literature.[8,9] Values of N and μ were chosen for the effective carrier, i.e., those of electrons for electron traps, and vice versa.

The concentration of level, N_T, is estimated from the total charge of the peak, Q, i.e., temporal integral of the current, and the current collection factor, G, as follows,

$$Q = N_T A L e G, \tag{2}$$

where A and L are the area and the thickness of the specimen, respectively. Assuming a uniform distribution of the electric field throughout the specimen, $G = \mu\tau V/$

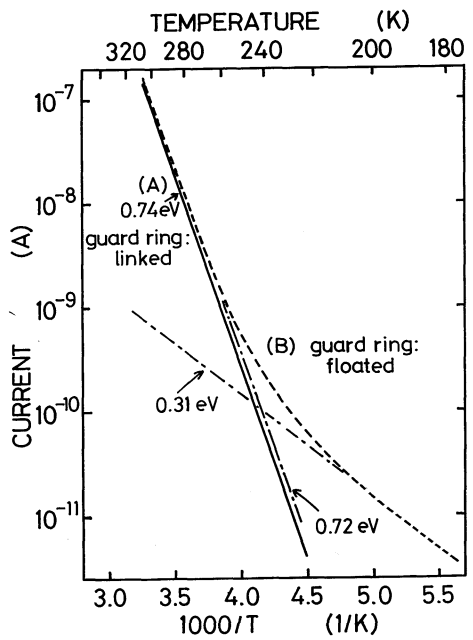

Fig. 3. Arrhenius' plots of the background current. The solid line(A) shows the case when the guard ring is linked; the broken line(B) is when the guard ring is floated.

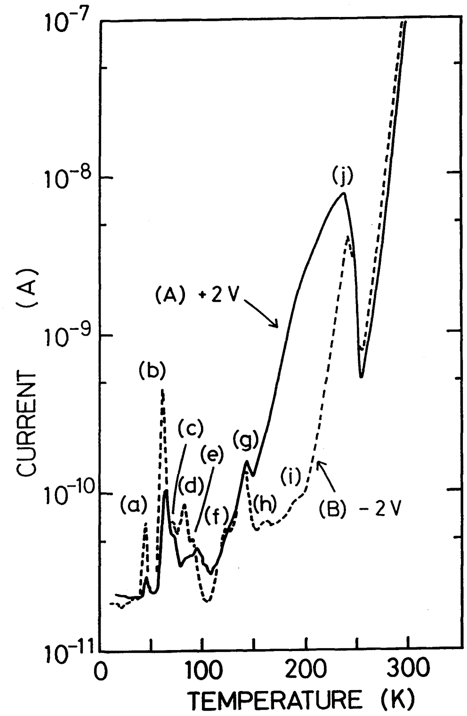

Fig. 4. TSC spectra of semi-insulating GaAs by the initialization with filtered light source (intrinsic excitation) biasing the front electrode at +2 V(A) and −2 V(B).

Table I. Data of TSC analysis for a semi-insulating GaAs specimen (Figure 4).

Peak	T_m (K)	Trap type	σ_m (Ω^{-1}cm^{-1})	E_i (eV)	N_T (cm^{-3})
(a)	45	electron	1.27×10^{-10}	0.12	5.0×10^{12}
(b)	62	electron	8.65×10^{-10}	0.15	1.0×10^{13}
(c)	68	electron	1.29×10^{-10}	0.18	2.4×10^{13}
(d)	83	electron	1.58×10^{-10}	0.22	2.6×10^{13}
(e)	92	electron	9.62×10^{-12}	0.24	1.6×10^{13}
(f)	124	electron	1.13×10^{-10}	0.33	3.1×10^{13}
(g)	141	hole	3.08×10^{-10}	0.35	2.3×10^{14}
(h)	161	hole	4.04×10^{-10}	0.39	6.6×10^{14}
(i)	192	hole	3.64×10^{-9}	0.43	5.6×10^{15}
(j)	238	hole	1.48×10^{-8}	0.50	2.7×10^{16}

L^2, where τ is the lifetime of the carrier and V is the applied bias to the specimen. Therefore,

$$Q = N_T A e \mu \tau V / L. \quad (3)$$

The charge, Q, increases as L decreases. Indeed, Q obtained from the spectrum for the thick ($L \simeq 300\,\mu$m) specimen was much smaller than that for the thinned specimen. However, in the region, $\mu\tau V > L^2$, collection factor G in eq. (2) becomes unity, so that we should be able to estimate the concentration, N_T, independently of the mobility, μ, the lifetime, τ, and the applied bias, V. The specimens were thinned so as to satisfy the condition, $L < (\mu\tau V)^{1/2}$, for all TSC peaks. For example, the maximum thickness is $30\,\mu$m when $V = 2$ V for values of $\mu = 1 \times 10^3$ cm^{2}V^{-1}s^{-1}, $\tau = 2 \times 10^{-9}$ s. When the condition $\mu\tau V > L^2$ holds, the deep level concentration, N_T, is calculated by the following equation,

$$N_T = Q / 2ALe, \quad (4)$$

where the factor 1/2 is added for the correction of the induced current assuming uniform distribution of N_T.

However, there remains uncertainty in the TSC spectrum; the spectral shape changes with the measurement conditions. For example, the total charge of the peak, Q, for the thinned specimen changes with the measuring voltage, which means we cannot use a simple model. Clarification of the reason for this ambiguity will require further examination. In addition, we notice that the electron and hole trap signals are not fully separated in Fig. 4; we should optimize the experimental conditions for better separation. Observable spectral range of the present TSC is limited to 0.7 eV by the increase of the background current. We shall report elsewhere variations of TSC to cover a wider energy range.

In conclusion, we have presented an improvement of thermally stimulated current (TSC) spectroscopy suitable to study semi-insulating GaAs at low temperatures. Deep level concentration on the order of 10^{13} cm^{-3} was easily measured and the detection limit should be well below the present value.

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