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Electrical field enhanced thermal quenching of a prominent thermally stimulated current peak in semi-insulating GaAs

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Detailed experimental results are presented for a “thermal quenching” of thermal stimulated current signals in the most prominent trap in undoped semi-insulating (SI) GaAs, T_5 with an activation energy of 0.27–0.31 eV. A possible model for the thermal quenching of T_5 is discussed, emphasizing the thermally stimulated nature of the quenching process, the effect of electric field and the formation of high-field domains. The thermal quenching of T_5 can frequently be observed in SI GaAs grown by the vertical gradient freeze (VGF) technique, or by the liquid encapsulated Czochralski (LEC) technique under certain conditions. © 1995 American Institute of Physics.

Thermally stimulated current (TSC) spectroscopy has long been used to study deep centers in undoped semi-insulating (SI) GaAs.^{1–6} In the TSC spectrum, six complete TSC peaks are usually observed;⁵ however, we often find a “thermal quenching” (TQ) of TSC signals in the most prominent peak (T_5), i.e., a rapid drop of the TSC signal at a given temperature followed by a slow recovery at higher temperatures, often accompanied by attenuated current oscillations. In this letter, we present more detailed experimental results on the TQ and recovery processes and discuss the possible quenching mechanism.

In the typical TSC measurements, described elsewhere in detail,^{5,6} 1.45 eV light with an intensity of 6×10^{14} photon/cm² s, from a $\frac{1}{4}$ m monochromator, was used to illuminate the sample at 83 K for 2.5 min under a bias of 18 V. As an example, Fig. 1 shows differences in the T_5 signals in three adjacent samples which were cut along the diameter of a 3 in. VGF wafer (sample dimensions of $2 \times 6 \times 0.65$ mm³). In sample No. 27, a complete T_5 peak can be seen, while in sample No. 25, the TSC signals in the peak are quenched, resulting in nearly no observation of T_5 . In contrast to the big difference in trap T_5 among the three samples, the traps T_2 and T_3 are quite similar. Here, we want to point out that although the peak heights of T_2 and T_3 are much lower than that of T_5 , they are still important traps in SI GaAs and have been ascribed to As_{Ga} - and V_{As} -related point defects.⁶ Their lower peak heights are at least partially due to the lower carrier lifetime at their peak temperatures (180–230 K), as indicated by a comparison of the photocurrents (I_{ph}) at 83 and 250 K (not shown), respectively.

To obtain further information on the TQ, we did TSC measurements on a LEC grown and multiple wafer annealed⁷ (MWA) sample, using different heating rates β ($\beta=0.05$ to 0.4 K/s), as shown in Fig. 2. Since we are dealing with the thermal emission of captured carriers from traps, a set of TSC measurements with different heating rates should show a shift in peak temperature for each trap. However, from each TSC spectrum in Fig. 2 we see shifts in both the quenching temperature (T_q) and the recovery temperature (T_r). This result implies that both quenching and recovery processes are controlled by some sort of thermally activated process. To confirm this suspicion, we checked the TQ in a different way. The sample was subjected to the same illumi-

nation, and a thermal scan with $\beta=0.3$ K/s was then performed in such a way that it stopped at a temperature T_w (e.g., 115, 120, or 125 K) below the temperature at which the TQ would have occurred (~ 130 K). The results are shown in Fig. 3(a). This procedure was followed by waiting a time t_w , which depended on the selected T_w , then fast cooling down to 83 K, and finally heating the sample in a regular thermal scan ($\beta=0.3$ K/s); these data are shown in Fig. 3(b). From Fig. 3(a), we note that for each chosen T_w , the initial slow signal decay, which is due to the thermal emission of capture carriers from the region of traps T_5 and T_5^* , is followed by a TQ of more than two orders of magnitude. The initial delay time depends of course on the T_w , since the higher the T_w , the higher the carrier emission rate for the trap. These results indicate that the TQ is indeed partially or fully related to a thermally activated process, i.e., the thermal release of captured carriers from the region of traps T_5^* and T_5 . From Fig. 3(b), we find that after the TQ occurs for each T_w , no TSC signals can be observed at $T < 140$ K, but the other traps at $T > 140$ K, i.e., T_2 , T_3 , and T_4 are not affected at all. This result means that the TQ of T_5 is not associated with other traps, at least not those TSC traps occurring above 140 K.

FIG. 1. TSC spectra for three adjacent samples cut along the diameter of a 3 in. VGF wafer.

FIG. 2. TSC spectra, including TQ of T_5 , as a function of heating rates β ($\beta=0.05$ to 0.4 K/s) for a MWA sample.

Next, we present the bias voltage effect on the TQ. A set of TSC spectra for the MWA sample, using the same excitation conditions at 83 K but various bias voltages from 1.5 to 36 V, is shown in Fig. 4; the photocurrent at 83 K versus bias is shown in the inset. From this figure we see that the TQ of T_5 is closely related to the applied bias or the electrical field $\mathcal{E}$; i.e., at $\mathcal{E} < 7.5$ V/cm, a complete T_5 can be measured, whereas at $\mathcal{E} > 15$ V/cm the TQ occurs, with the threshold temperature T_q decreasing as $\mathcal{E}$ increases. For this sample we can find a threshold electrical field $\mathcal{E}_{th}$ of about 13 V/cm, at which the TQ of T_5 begins to appear. The photocurrent shows a non-ohmic behavior at $\mathcal{E} > 15$ V/cm, which is very similar to the results of earlier studies on the photoelectric properties of high-resistivity GaAs:O and GaAs:Cr by Lin *et al.*^{8,9} In contrast to the photocurrent, the TSC for all traps, except for T_5 , and the dark current (at $T > 250$ K where it is measurable) show good ohmic behavior. Thus, the TQ of T_5 is evidently connected with the photocurrent saturation.

Before we proceed further, it is helpful to summarize what we know about T_5 . T_5 is closely related to EL2 or As_{Ga} , based mainly on its IR quenching behavior⁴ and its thermal recovery, with a rate $r = 2.0 \times 10^8 \exp(-0.26 \text{ eV/kT}) \text{ s}^{-1}$.⁵ From TSC measurements, using a Schottky contact and surface absorbed light (1.96 eV), T_5 is judged by its variation with bias to be a hole trap,¹⁰ but it might also trap electrons. From a study of molecular beam epitaxial GaAs grown at 200–250 °C, which is thought to have abundant concentrations of As_i , As_{Ga} , and V_{Ga} , it was concluded that T_5 must involve V_{Ga} , because, of these three primary defects, only V_{Ga} is expected to have acceptor levels below midgap.¹¹ The trapping and recombination of free carriers by T_5 , studied by Desnica *et al.*,¹² indicates that T_5 (labeled T_3 in Ref. 12) behaves more like a recombination center than an ordinary electron trap, since its capture cross section for holes can be larger than that for electrons. Thus, we can infer that T_5 is probably a V_{Ga} -related hole trap.

The thermal quenching (TQ) model for T_5 must explain the following observations: (a) the abruptness of the drop in TSC at temperature T_q ; (b) the dependence of T_q on heating

FIG. 3. Observation of TQ in T_5 on a MWA sample using an alternative method: (a) TQ begins at a certain decay time depending on the waiting temperature (T_w), as shown in the thermal scan schedule in the inset; (b) TSC spectra measured after the waiting time and after fast cooling the sample to 83 K; also shown is a regular TSC spectrum with TQ of T_5 as in Fig. 2.

rate β and electric field $\mathcal{E}$; (c) the small value of the threshold electric field $\mathcal{E}_{th}$ necessary to cause the TQ; and (d) the saturation of photoconductivity at $\mathcal{E} > \mathcal{E}_{th}$. Observation (a), the abruptness of the TSC drop, suggests a cooperative process, i.e., one in which the process rate increases as the process continues. Such an event can occur in SI GaAs because $EL2^+$ and probably other As_{Ga} -related defects have barriers for electron capture, so that higher-energy electrons are more easily captured. Then, if part of a sample somehow attains a higher electric field $\mathcal{E}$, perhaps due to an instability, more of the electrons in that region will be captured, leading to a higher resistivity. The higher resistivity will now produce an even higher electric field (greater voltage drop) and the process will speed up, eventually creating a high-field, high-resistivity domain that will greatly decrease the sample current. This charged domain will eventually drift to the opposite electrode and there be annihilated, thus increasing the current. Current oscillations, commonly seen in SI GaAs, are usually attributed to the periodic formation and annihilation

FIG. 4. TSC spectra, including TQ of T_5 , as a function of applied bias (V_b) for a MWA sample, with I_{ph} at 83 K vs V_b shown in the inset.

tion of domains. However, it should be noted that the domain drift may be slow, and the domain may appear to be stationary over a certain time period. The data in this report are consistent with the formation of domains. For example, we would expect such a formation to take longer at lower current levels, as indeed is seen in Fig. 2. For $\beta=0.05$ K/s, there are approximately 340 s from the current minimum at $T=97$ K to the quenching temperature $T_q=114$ K, while for $\beta=0.4$ K/s, the time from the minimum to T_q is about 70 s. This ratio of quenching times is close to the inverse of the ratio of the currents at T_q . The same qualitative picture holds in Fig. 3(a), in which a lower current (as well as a lower electron energy) at the lower waiting temperature would lead to a longer time before quench. The dependence on electric field is seen in Fig. 4, which illustrates that higher $\mathcal{E}$ leads to an earlier quench. In spite of these aspects of the present quenching process, which appear similar to those previously observed in SI GaAs,^{13,14} there are also some differences. For example, threshold fields for both photocurrent¹³ and TSC¹⁴ were found to be at least 500 V/cm in the previous works, whereas we see TSC quenching effects at threshold fields as low as 15 V/cm. It is perhaps significant that most of the previous studies were performed at temperatures above 140 K, so that As_{Ga} -related defects were always in their normal states. However, we believe that the data in Fig. 3(b) indicate that the defects involved in our field-enhanced trapping process may be As_{Ga} -related defects in their metastable states. The reason is that the recovery of the thermally quenched TSC exactly follows the recovery of the optically quenched TSC, and the latter is known to have the same kinetics as the EL2 (or As_{Ga}) recovery from metastability. Thus, As_{Ga} metastability seems to be involved in the present TQ. Note also, from the inset of Fig. 4, that the photocurrent (PC) at 83 K saturates at electric fields that are high enough to cause TSC quenching. The PC does not itself quench, probably because 1.45-eV excitation continuously provides electrons from the valence band, rather than just from EL2 and traps such as T_5 . The PC saturation could be

caused by a reduced lifetime τ due to the increased ability of the photoexcited electrons to surmount the As_{Ga}^+ capture barrier. For example, if $\tau \propto \mathcal{E}^{-1}$ for $\mathcal{E} > \mathcal{E}_{th}$, then the PC would saturate at $\mathcal{E}_{th}$. However, the saturation could also be explained by a high-field, high-resistivity region which increases in size as $\mathcal{E}$ increases, as, e.g., occurs in a field-effect transistor.

In summary, we suggest that the thermal quenching of the TSC in the region of T_5 can be explained by the formation of a current-limiting, high-field domain that is nearly stationary (since large oscillations do not appear until T_5 has recovered). The domain could form when a high-electric-field instability in a particular region begins to cause field-enhanced trapping of the TSC electrons in that region, thus causing even higher fields and further trapping. The high-field, high-resistivity domain thus formed could quickly limit current, as is observed. Because the recovery of the TSC follows a temperature dependence exactly the same as that found for metastable EL2 and other As_{Ga} -related defects, it is likely that the trapping centers are themselves As_{Ga} related. We have previously proposed that T_5 itself is an As_{Ga} -related defect, perhaps $As_{Ga}-V_{Ga}$.¹¹ This defect could trap an electron during the illumination at 83 K and then release that electron to the conduction band at higher temperatures, i.e., the normal TSC process. However, at high electric fields, it might be possible for the electron to immediately be recaptured at the As_{Ga} component of the defect, and cause a metastable transition of the As_{Ga} . Above 140 K, the As_{Ga} would return to its normal state, and the electron could finally be emitted to the conduction band. This model is consistent with the thermal quenching being triggered by an emission process with an activation energy close to that of T_5 , as is found from an analysis of the T_q vs β data in Fig. 2. However, further evidence is necessary before a microscopic TQ model can be firmly established.

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- ¹D. I. Desnica, J. Electron. Mater. **21**, 463 (1992).
- ²J. P. Fillard, J. Bonnafe, and M. Castagne, Solid State Commun. **52**, 855 (1984).
- ³U. V. Desnica, D. I. Desnica, and B. Santic, Appl. Phys. Lett. **58**, 278 (1991).
- ⁴Z-Q. Fang and D. C. Look, Appl. Phys. Lett. **59**, 48 (1991).
- ⁵Z-Q. Fang and D. C. Look, J. Appl. Phys. **73**, 4971 (1993).
- ⁶Z-Q. Fang and D. C. Look, J. Appl. Phys. **69**, 8177 (1991).
- ⁷M. Mori, G. Kano, T. Inoue, H. Shimakura, H. Yamamoto, and O. Oda, in *Semi-insulating III-V Materials, Toronto, 1990*, edited by A. G. Milnes and C. J. Miner (Adam Hilger, Bristol, 1991), p. 155.
- ⁸A. L. Lin, E. Omelianovski, and R. H. Bube, J. Appl. Phys. **47**, 1852 (1976).
- ⁹A. L. Lin and R. H. Bube, J. Appl. Phys. **47**, 1859 (1976).
- ¹⁰Z-Q. Fang, L. Shan, T. E. Schlesinger, and A. G. Milnes, Mater. Sci. Eng. **5**, 397 (1990).
- ¹¹Z-Q. Fang and D. C. Look, Appl. Phys. Lett. **63**, 219 (1993).
- ¹²U. V. Desnica, B. Santic, D. I. Desnica, and M. Pavlovic, J. Electron. Mater. **22**, 403 (1993).
- ¹³D. A. Johnson, R. A. Puechner, and G. N. Maracas, J. Appl. Phys. **67**, 300 (1990).
- ¹⁴M. Kaminska, J. J. Parsey, J. Lagowski, and H. C. Gates, Appl. Phys. Lett. **41**, 989 (1982).