A number of different deep traps has been detected up to now in semi-insulating (SI) GaAs, where they play an important role either positive (helping compensation mechanism) or negative (detrimental effects on substrate quality and performance of devices). It has been demonstrated recently that some of these traps influence dramatically the photosensitivity, persistent currents, and photoconductivity\(^*\) of SI GaAs. A detailed picture of defects responsible for deep traps is generally unknown; some of them are tentatively attributed either to native defects, or to residual impurities (Fe, Zn, Cu, Cr, O, ...) or to some complexes involving both impurities and native defects. The purpose of this letter is to demonstrate that some of these deep traps are complex defects which might include as their main constituent the well known defect EL2.

The high quality liquid-encapsulated Czochralski (LEC) SI GaAs, described earlier,\(^7\) has been used in this study. The EL2 concentration (determined by standard absorption measurements in near infrared) was \(2 \times 10^{16} \text{ cm}^{-3}\). Six other deep traps have been detected and analyzed with thermally stimulated current (TSC) method.\(^7\)\(^-\)\(^9\)

The illumination with photons in 1.0–1.2 eV energy range was provided by a tungsten lamp and a combination of long-pass filter (1.2 eV cutoff energy) and 2-cm-thick H\(_2\)O filter, enabling a wide range of applied photon flux densities (10\(^{11}\)–10\(^{16} \text{photons/cm}^2 \text{s}\)). To further increase the intensity, in some cases only the cutoff filter was used, transmitting photons in 0.5–1.2 eV range. The photoconductivity (PC) was determined by measuring the photo-induced current \(I_{pc}\) at 10 V applied bias, where contacts show good Ohmic behavior.

Although photon energy used in this study is lower than the energy gap of GaAs (1.5 eV), a strong PC response is observed, as electrons are transferred from valence to conductive band via a two-step process, involving midgap level EL2. The time evolution of PC during 86 K illumination with below-gap photons is presented in Fig. 1 for a variety of light intensities. For about 10\(^{14} \text{photons/cm}^2 \text{s}\) photon flux density PC quickly reaches a constant value (curve 3), which does not change even after prolonged illumination. For stronger light intensities, however, a quenching is observed down to four orders of magnitude. (Transient phenomena observed for low-light intensities were analyzed in detail elsewhere,\(^10\) and will not be examined here).

In different points of time evolution of PC curves (i.e., after different low-temperature illumination times with the same photon flux density of 4 \times 10^{15} \text{photons/cm}^2 \text{s}\), TSC spectra were taken. Several representative curves are presented in Fig. 2. Curve 1, which was recorded after short illumination time before practically any quenching of PC occurs (point A in Fig. 1), shows a maximal TSC signal. Prolonged illumination, which causes the quenching of PC, also leads to a monotonous decrease of six TSC peaks. On the other hand, a new TSC signal emerges with longer illumination around 250 K.

Previous investigation of PC bleaching and recovery processes\(^11\) proved that the PC signal can be fully recovered to nonquenched value if the bleached sample was heated over 125 K. Therefore possible recovery of a bleached TSC signal was analyzed in 86–300 K range. These experiments involved several steps: (1) bleaching at

![Fig. 1](image-url)  
**FIG. 1.** Time evolution of the photoconductivity at 86 K, for illumination with photons in the 1.0–1.2 eV energy range, for different photon flux densities (photons/cm\(^2\) s): (1) \(1 \times 10^{14}\), (2) \(5 \times 10^{14}\), (3) \(7 \times 10^{13}\), (4) \(5 \times 10^{14}\), (5) \(2 \times 10^{15}\), (6) \(6 \times 10^{15}\). For the comparison, bleaching of EL2 with wide range, 0.5–1.2 eV, photon energies are presented (dashed curve; light intensity being \(5 \times 10^{16} \text{photons/cm}^2 \text{s}\)). In that case the photoconductivity can be bleached for almost four orders of magnitude. Inset: temperature dependence of photoconductivity for unbleached sample (solid curve) and bleached sample (dashed curve).
The effect of quenching of PC at low temperature with high-intensity below-the-gap photons (depicted in Fig. 1) has been observed earlier by several groups. The generally accepted explanation for quenching of PC is optically induced transformation of EL2 defects into their metastable states, EL2*. As EL2* very weakly interacts with light, the EL2 to EL2* transformation interrupts the main path of electron transfer from valence to conduction band, resulting in a decrease of generation rates of free carriers and consequent quenching of PC. For the same reason the quenching of optical absorption, photocapacitance, photoluminescence, and photoelectric paramagnetic resonance has been observed as well. Similarly, the sharp and well defined recovery of PC and other EL2-related signals observed at about 125 K (inset in Fig. 1) is considered to be caused by the recovery of EL2 from its metastable state EL2*. Therefore, one can conclude that observed quenching of PC in Fig. 1 corresponds to the EL2-EL2* transition. On the other hand, results presented in Figs. 1–3 clearly show that quenching of PC and quenching of a number of TSC peaks are closely associated. Quenching of TSC peaks, which for some traps exceeded three orders of magnitude, is the monotonous function of EL2-related PC-signal quenching. Similarly, the full recovery of quenched TSC signals was obtained in the same temperature range as the recovery of PC. The dynamics of thermal recovery of PC and all six TSC's signals was exactly the same (Fig. 3). This result indicates a close relation between EL2 and the defects responsible for these deep traps.

It is not quite clear why bleaching does not affect peaks T3 and T6 as strongly as it does shallower peaks T1–T3, which are bleached completely (Fig. 3). One possible explanation would be that T3 and T6 are actually emptier after 86 K bleaching, but that they retrap some of the charge during the TSC run, when some electrons are released due to the EL2-EL2* transition when the temperature crosses 125 K.

A very important question is whether the connection between EL2 defects and these deep traps is direct, caused by the physical proximity of two defects, or indirect, via some sort of indirect interaction. Here we propose a model which can explain experimental data presented in this letter, and is compatible with other published results related to the subject. In this model, six deep traps, detected in TSC experiments and observed to be in some way related to the EL2 defect, are assumed to be complex defects which include EL2. In this case any change in the status of EL2 changes properties of these complex defects as well. This explanation is consistent with all observed phenomena: The illumination with photons in the 1–1.3 eV range transfers EL2 (and the whole complex) into its metastable state, which brings along the electrical deactivation of these complexes and quenching of TSC signals. The recovery of the normal EL2 state by thermal treatment also restores original complex defects and related TSC signals once again.

Any alternative model which would assume the contrary, i.e., that EL2 and defects acting as deep traps are not directly connected at the microscopic level, has to explain how the transition of EL2-EL2* and back would influence properties of a distant trap. One possible explanation in that direction would be that the quenching of EL2 effectively removes electrons from the system because the fraction of EL2 defects become effectively neutral during transfer into the metastable state EL2*. This process could involve electrons from deep traps, affecting traps' occupancy. The other possibility would be that the transfer of
EL2 to the metastable state EL2* does not influence the starting occupancy of observed deep traps but their filling rates. Namely, the EL2–EL2* transfer, induced by 0.95–1.3 eV photons, cuts off the path through which EL2 absorption of below-the-gap photons generates free electrons and holes, lowering the availability of free carriers for trapping. To check these two possibilities we illuminated samples with above-the-gap photons, directly creating an abundance of free electrons and holes, giving ample opportunities for filling of all deep traps. With this procedure it was possible to fill up completely all traps in unbleached samples. However, in bleached samples the same procedure could not restore the TSC signals, which gives a strong indication that observed bleaching of TSC peaks was not caused by incomplete trap filling but by actual trap deactivation.

The consequences of these experimental results and proposed explanation are many. The most important conclusion is that some of the defects observed as deep traps might be complexes involving EL2 defects. As some of these deep traps have been tentatively identified to be associated with impurities, these results would indicate that EL2 can serve as an internal gettering center for these impurities. Furthermore, as it is also well known that some of the deep traps are connected with native defects, it might be also possible that EL2 serves as a nucleation point for more complex native defects. Altogether, it seems that EL2 tends to make pairs with other defects in GaAs.

The influence of IR illumination on some peaks in TSC spectra has also been observed previously, leading to the conclusion that these TSC peaks are shallower levels of the EL2 defect. Nevertheless, this claim was soon refuted on the basis that the concentration of EL2 defects was considerably larger than concentration of defects responsible for TSC peaks. However, this argument is proving that EL2 is not a complex defect having shallower levels as assumed in Ref. 22, but the same argument is not speaking against the opposite assumption, i.e., that defects with shallower levels could involve EL2 as their constituent. In our model the concentrations of observed deep levels would be determined by concentrations of additional constituents (impurities or native defects) complexing with EL2, while the larger fraction of EL2 defects would remain unperturbed, giving its usual, characteristic “signature.”

Additional evidence about the connection between EL2 and some of other deep traps (EL3, EL5, EL6, and EL14) can be derived from experiments in which EL2 concentration was modified by thermal treatment: annealing at 1000 °C followed by thermal quenching destroys EL2 defects, while subsequent annealing at 650 °C restores them back. However, the same 1000 °C annealing procedure also destroys a number of other deep traps (see Fig. 9 in Ref. 22), while annealing at 650 °C restores them back, together with EL2 levels. Furthermore, our assumption that EL2 tends to pair with other defects may also be used to explain small variations observed in some of the EL2 properties usually referred to as the EL2 family of defects. This might be especially true if pairing interaction is weak and only slightly perturbs EL2 properties. Variations were observed in the EL2-related deep-level transient spectroscopy signal, in peak position and half width in luminescence signal, in electron paramagnetic resonance signal, etc. In addition, annealing-induced transformation of EL2 into defects EX2 and EX1, with similar but distinct energies, also fits well in our model. The proposed model invokes further experiments, interesting both from the fundamental and practical standpoints. Especially interesting would be the intentional doping with fast diffusers (Cu, Fe, ...) or intentional introduction of native defects with electron irradiation or thermal treatments with consequent monitoring of influence of these treatments on both TSC peaks and EL2 related signals.

In conclusion, we presented the experimental results and an analysis which indicates that some of the observed deep traps in GaAs are complex defects, which might include the EL2 defect as their constituent. It means that EL2 can serve as a gettering center for other native defects and/or impurities in Si GaAs.

20 Incomplete filling of traps would decrease TSC signal in the same manner as annihilation of traps—TSC detects only the charge actually trapped in deep traps during low-temperature illumination.