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Temperature dependence of the photoquenching of EL2 in semi-insulating GaAs

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A model of the temperature behavior of the photoquenching of EL2 in semi-insulating GaAs is presented. The thermal emission of a hole trapped on an actuator level accounts for the very low photoquenching efficiency above 85 K. This effect is presented in terms of a set of rate equations that reproduce in a reliable way the temperature dependence of the photoquenching of EL2. The activation energy of the actuator level suggests a hole trap level other than Ga_{As} as was previously assumed. © *1997 American Institute of Physics.* [S0003-6951(97)01123-6]

For the last two decades semi-insulating GaAs has received a great deal of attention because of its high performance as a substrate for advanced integrated circuits (ICs). The state of the art of GaAs growth allows one to obtain a semi-insulating material without intentional doping. It is generally thought that a native deep donor, the so-called EL2 level, compensates for residual acceptors, rendering the material highly resistive.[1] Besides its technological interest, this defect level presents unique characteristics since it is transformed by optical excitation at low temperature into a metastable configuration.[1–3] In spite of the work carried out concerning this level, both the microscopic nature and the mechanism driving it to the metastable state remain controversial.

Recently we have presented a new approach to the problem of the metastable transformation of EL2.[4] Upon the basis of several experimental observations we suggested the existence of an actuator level in the metastable state. These experimental views were discussed in earlier papers.[4,5] The most significant of these experimental observations concerns the difference between the temperature dependence of the metastable transformation and the threshold of the thermal recovery of the ground state of EL2. In fact, the first of these transitions is not very efficient above 80–85 K,[6] and the second one is only observed above 110–120 K once the metastable transformation is achieved at low temperature.[5] Along with this thermal hystheresis observation some questions regarding the electrical compensation in the metastable state should be addressed. Within the framework of a conventional electrical compensation scheme, EL2 compensates residual C acceptors. Thus a significant free hole population should be observed after the metastable transformation for temperatures high enough to ionize carbon acceptors, which must be fully ionized above 50 K. This hole population is not experimentally observed, and raises questions about the trapping of such holes. The actual state of the art allows one to grow semi-insulating GaAs with low residual carbon concentration, up to two orders of magnitude below the concentration of EL2.[7,8]

In pursuit of these issues the actuator level of the metastability, labeled *VA*, should play a twofold role, on the one hand it activates the metastable transformation of EL2, which should depend on the charge of the actuator level, and on the other hand it can accommodate the holes released from the ionized $EL2^+$ levels, thus ensuring electric compensation after photoquenching. The main experimental data and the analytical model were presented in previous papers.[4,5,9,10] Herein we will focus our attention on the temperature dependence of the metastable transformation. A set of rate equations was built in order to account for the role of the actuator level in the metastable transformation of EL2. The solution of this set of rate equations was found to accurately fit the experimental aspects of the photoquenching effect. According to this model the metastable state is reached by the photoionization of EL2° after it has transferred one hole to a neighboring actuator level, labeled *VA*.[4]

As we noted prior to this, the quenchability is drastically reduced above 80 K.[5] This is quantified through the representation of the photocurrent quenching transients as a function of the temperature of the quenching excitation. Up to 70 K the quenchability is practically total, while it nearly vanishes at 80 K (see Fig. 1).

This observation was explained in terms of the thermal release of holes trapped at the actuator level, *VA*. The thermal emission probability of a hole trapped in this level is greatly enhanced between 70 and 85 K, resulting in a short lifetime of the quenchable state, $EL2_q \sim$(EL2°, $VA+1$ hole), which should result in a very small photoquenching prob-

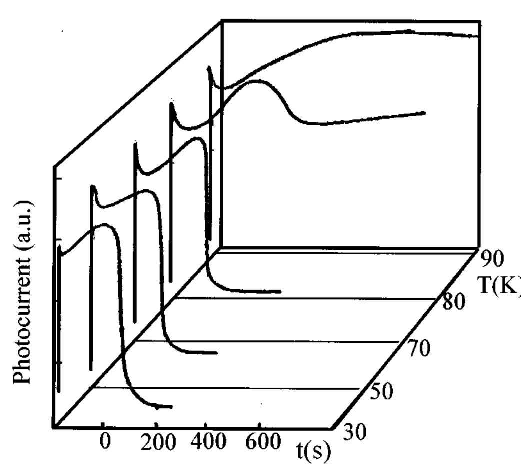

FIG. 1. Experimental photocurrent transients (1.18 eV) at different temperatures.

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ability. It is worth noting that the photoquenching can be observed at such a temperature at very high light intensity, or after very long illumination periods. This temperature dependence of the photoquenching can be described by introducing some modifications into the set of rate equations describing photoquenching at low temperature.[4] A term accounting for the thermal emission of holes from the actuator level shall be introduced. Yet other alternative capture mechanisms must be considered in order to avoid the appearance of a high excess hole population, which is not experimentally observed; in fact, the photocurrent measured is nearly independent of the temperature above 80 K, which does not support the presence of a high free hole concentration.

In relation to the thermal emission of holes a typical Arrhenius term will be considered. Prior of this we have tentatively associated the actuator level with the $(--/-)$ ionization level of the gallium antisite.[4] This energy level is located 203 meV above the valence band.[11] However, this activation energy is higher than expected, when compared to TSC results.[12] Accurate calculations point out an activation energy no higher than 0.18 eV. This thermal emission of holes does not change the photoquenching efficiency at low temperature, but it will dramatically delay photoquenching above 80 K. With such an activation energy a preexponential factor of $10.3\times 10^{8}\ \mathrm{s}^{-1}$ was deduced. The holes that cannot remain in the *VA* at this temperature are captured at EL2° and the additional donor, D, introduced in the three level scheme; the capture rates were obtained from the literature.[13,14] On the other hand, it was assumed that both optical cross sections and capture cross sections remain unchanged in the temperature range under consideration. The set of rate equations including the thermal emission of holes is

$$\frac{dN_{nq}^{+}}{dt}=\sigma_n^0 N_{nq}^0\phi-\sigma_p^0 N_{nq}^{+}\phi+C_{pN}N_{nq}^0 p-C_{nN}N_{nq}^{+}n,$$

$$\frac{dN_{nq}^{0}}{dt}=-\sigma_n^0 N_{nq}^0\phi-C_{pN}N_{nq}^0 p+C_{nN}N_{nq}^{+}n+e_{pA}N_q^0,$$

$$\frac{dN_{q}^{0}}{dt}=\sigma_p^0 N_{nq}^{+}\phi-\sigma_n^0 N_q^0\phi-e_{pA}N_q^0-C_{pN}N_q^0 p,$$

$$\frac{dN^{*+}}{dt}=\sigma_n^0 N_q^0\phi+C_{pN}N_q^0 p-C_{nN}^{*}N^{*+};$$

$$\frac{dD^{+}}{dt}=-C_{nD}nD^{+}+C_{pD}p(D-D^{+}),$$

$$\frac{dn}{dt}=\sigma_n^0(N_{nq}^0+N_q^0)\phi-C_{nN}N_{nq}^{+}n-C_{nN}^{*}N^{*+}n$$
$$-C_{nD}nD^{+},$$

$$\frac{dp}{dt}=e_{pA}N_q^0-C_{pN}p(N_{nq}^0+N_q^0)-C_{pD}p(D-D^{+}),$$

$$N^{*}=N-(N_{nq}^{+}+N_{nq}^{0}+N_q^0+N^{*+}),$$

$$e_{pA}=1.03*10^8T^2e^{-0.18/kT},$$

$$\sigma_n^0=1.17\times 10^{-16}\ \mathrm{cm}^2;$$

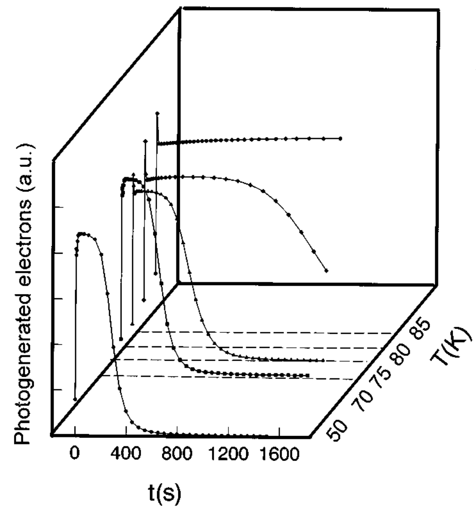

FIG. 2. Calculated photoelectron (1.18 eV) transients at different temperatures.

$$\sigma_p^0=0.11\times 10^{-16}\ \mathrm{cm}^2;$$

$$C_{nN}=2.2\times 10^{-14}\ \mathrm{cm}^3\,\mathrm{s}^{-1};$$

$$C_{nN}^{*}=1.2\times 10^{-13}\ \mathrm{cm}^3\,\mathrm{s}^{-1};$$

$$C_{nD}=1.4\times 10^{-13}\ \mathrm{cm}^3\,\mathrm{s}^{-1};$$

$$C_{pN}=4.4\times 10^{-15}\ \mathrm{cm}^3\,\mathrm{s}^{-1};$$

$$C_{pD}=1\times 10^{-14}\ \mathrm{cm}^3\,\mathrm{s}^{-1};$$

$$\phi=3\times 10^{15}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1};$$

$$[N_{nq}^{+}](0)=1\times 10^{16}\ \mathrm{cm}^{-3};$$

$$[N_{nq}^{0}](0)=1\times 10^{16}\ \mathrm{cm}^{-3};$$

$$[N_q^{+}](0)=0;$$

$$[N^{*+}](0)=0;$$

$$[D^{+}](0)=1\times 10^{16}\ \mathrm{cm}^{-3};$$

$$[n](0)=0;$$

$$[p](0)=0;$$

$$[N^{*}](0)=0.$$

The symbols are defined as follows: N_{nq}^{+}—nonquenchable ionized EL2 concentration; N_{nq}^{0}—nonquenchable EL2 concentration; N_q^0—quenchable EL2 concentration; N^{*+}—ionized metastable EL2 concentration; D^{+}—ionized donor concentration; n—electron concentration; p—hole concentration; σ_n^0 and σ_p^0—optical cross sections; C_{nN}—electron capture rate by the nonquenchable EL2; C_{nN}^{*}—electron capture rate of the ionized metastable EL2; C_{nD}—electron capture rate of the ionized donors; Φ—photon flux; e_{pA}—thermal emission rate of holes.

The photocurrent transients for different calculated temperatures are in very good agreement with the experimental transients (Fig. 2) and with those reported by other authors.[15] The free electron concentration is fully quenched after 400 s of illumination below 70 K, while photoquenching has not

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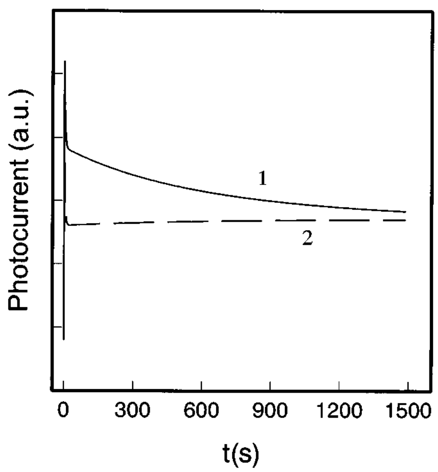

FIG. 3. Calculated transients of the photoelectron concentration and the photocurrent (1.18 eV, 85 K). The photocurrent was calculated from the photoelectron and photohole concentrations assuming a mobility ratio, $m_n/m_p = 10$. (1)Photocurrent and (2) photoelectrons.

even occurred after 2000 s at 85 K. It should be noted that the free hole population does not affect the photocurrent transient below 85 K; above this temperature the influence of the photogenerated holes is limited to the initial part of the transient as it is shown in Fig. 3, where the transients of the electron and hole concentration are shown.

Some authors reported the existence of photoquenching above 80 K;[14,16] this is not incompatible with the results we present herein, since photoquenching depends strongly on the quenching photon flux. This can be easily demonstrated in our calculations when the photon flux is increased; in fact photoquenching is reproduced in such conditions above 80 K (Fig. 4), but the quenching rate is very slow. This is explained in terms of the lifetime of the quenchable state, which is determined by the balance between the optical hole transfer rate to the actuator level and the thermal emission rate of these holes. The equilibrium between capture and emission should depend on both the temperature and the light intensity.

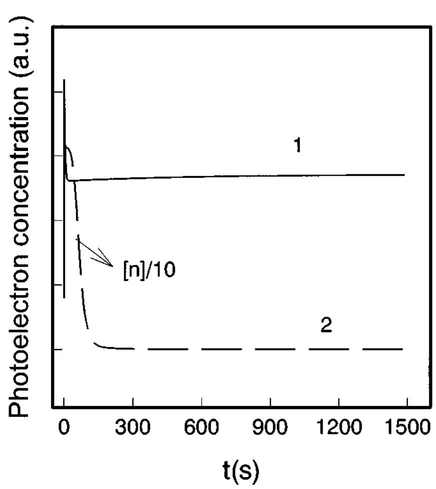

FIG. 4. Calculated photoelectron concentration (1.18 eV, 85 K) transients for two different incident photon fluxes: (1) $3\times10^{15}\ \mathrm{cm^{-2}\,s^{-1}}$; (2) $3\times10^{16}\ \mathrm{cm^{-2}\,s^{-1}}$.

Another experimental point to be noted is the increase in photocurrent quenching at 80 K when a previous excitation with quenching light at low temperature is done.[9] This previous excitation was not long enough to quench the photocurrent. This behavior is also accounted for within the framework of the theoretical model we present herein. In fact, the theoretical analysis demonstrated that photocurrent quenching is only observed when nearly all the EL2 centers have been transformed into the metastable state, and this should occur during the initial part of the photocurrent transition. Also within this framework the above mentioned experiment can be understood, since the illumination at 70 K practically quenches the population of EL2 and only a small population of EL2 levels remained unquenched. Illumination at 80 K only results in the ionization and extinction of the low concentration of remaining unquenched levels, thus, the bleaching time is significantly reduced.

In conclusion, the results presented here allow us to conclude that the thermal hystheresis effect concerning the metastability of EL2 can be accurately reproduced within the framework of our actuator level model. The quenchability of EL2 will be balanced between the rate of the optical charge transfer to the actuator level and the hole thermal emission rate. Such a charge balance should depend on the bleaching photon flux and the temperature, respectively. The previous tentative identification of the actuator level associated with Ga_{As} (Ref. 4) is reconsidered, and a shallower hole trap level (0.18 eV) is identified as the actuator level. The microscopic nature of this level is not known.

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