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Quenching and recovery characteristics of the *EL*2 defect in GaAs under monochromatic-light illumination

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Quenching of the normal state and recovery from the metastable state of the *EL*2 defect in semi-insulating GaAs grown by the liquid-encapsulated Czochralski technique were studied under monochromatic-light illumination in the energy range $0.7 \leq h\nu \leq 1.51$ eV. The photoquenching data show two peaks at 1.125 and 1.30 eV. In addition, light with energy $h\nu = 1.46$ eV is found to photoquench the normal state of *EL*2 in unannealed doped samples within 25 min. On the other hand, the photoinduced recovery data from the metastable state show a complex structure consisting of a broad band around 0.9 eV and multiple sharp peaks between 1.4 eV and the band edge. The magnitude as well as structure of recovery were found to be sample dependent. Both quenching and recovery data are in conflict with the available calculations and predictions reported for the isolated-arsenic-antisite model. The recovery peaks are coincident with the calculated arsenic vacancy (V_{As}) energy levels. Thus, the present results support the complex models involving V_{As}. The optical recovery from the metastable state suggests that *EL*2 is a charge-controlled bistable defect. The sample dependence of most of the data indicates the existence of interactions between *EL*2 and other defects and traps.

I. INTRODUCTION

The atomic structure of the midgap defect known as *EL*2 in GaAs and how its constituent atom(s) rearrange during the transformation of this defect from the normal state ($EL2^0$) to the metastable configuration ($EL2^*$) in response to photoexcitation at low temperatures ($T \leq 100$ K) are issues which have initiated some very active controversies in recent years. The presence of an optically induced metastable configuration is the most unusual aspect of this defect. Several effects such as conductivity-type change,[1] neutralization of shallow acceptors,[2–4] persistent photoconductivity,[5,6] and excitation of traps[7–9] appear to accompany the $EL2^0 \rightarrow EL2^*$ transformation. The key to reaching a clearer understanding of the nature of the *EL*2 defect is therefore to understand its metastable state which apparently exhibits no experimentally observed properties of its own. Thus, we are reduced to constructing our knowledge of this state by indirect methods. One approach is to observe its recovery back to the normal state ($EL2^* \rightarrow EL2^0$) under photon irradiation. It is well known that recovery can also occur thermally by heating the sample to about 140 K or higher for a short period of time.

A few attempts have been made recently to transform the *EL*2 defect from $EL2^*$ to $EL2^0$ by photon irradiation. Such photoinduced recovery has been reported for photoluminescence,[10] photoconductivity,[11] photocapacitance,[12] infrared (ir) absorption,[13–16] and electron paramagnetic resonance[17] (EPR). Even though all these studies have established that the optical recovery of $EL2^*$ can be induced, they disagree on some important aspects such as the amount of optical recovery and the spectral dependence of the recovery. The reasons for these disagreements are usually not obvious, but it is known that in at least some cases the results are highly dependent on parameters such as temperature, the history of the sample, the technique employed to study the recovery, and the intensity of the irradiation.[16] There is also a general consensus that photons with an energy of 1.1 eV quench $EL2^0$. This has led many authors to speculate that the $EL2^0 \rightarrow EL2^*$ transformation occurs through an internal transition that leaves the electrons localized within *EL*2. This transition is believed to be responsible for the broad peak observed at 1.18 eV in the ir-absorption spectrum of $EL2^0$ (see, for example, Refs. 18 and 19).

In this article we extend the previous studies of the photoquenching and photoinduced recovery properties of the *EL*2 defect.[20] Both photoquenching of $EL2^0$ and optical recovery from $EL2^*$ were found to be sample dependent, indicating the existence of interactions between *EL*2 and other defects and traps present in the samples. The current results will be tested against the isolated arsenic antisite model as well as other more complex models. The recovery data are in good agreement with the calculated arsenic vacancy energy levels lending support for models containing this point defect.

TABLE I. Characteristics of the GaAs samples used in the present study. The Fermi level (E_F) was obtained with respect to the conduction-band minimum. n denotes electron concentration and μ mobility. The annealing conditions of the boules from which the samples were cut were 850 °C for ~18 h.

Sample no.	Dopant	[Dopant] (10^{19} cm^{-3})	[$EL2^0$] (10^{16} cm^{-3})	[C] (10^{15} cm^{-3})	n (cm^{-3})	$-E_F$ (eV)	μ (cm^2/V s)	Annealed
1			1.55	<0.1	3.88×10^7	0.77	4690	yes
2			1.50	2.8	3.00×10^7	0.77	6000	yes
3			1.55	4.3	1.90×10^7	0.77	5500	no
4	Sb	~1	0.72	0.6	3.03×10^{10}	0.48	4750	no

II. EXPERIMENTAL TECHNIQUE

Several semi-insulating GaAs samples (doped and undoped) grown by the liquid-encapsulated Czochralski (LEC) technique and obtained from several manufacturers were investigated. In this paper we report measurements obtained for selected samples that show noticeable differences in the $EL2$ properties. The characteristics of these samples are presented in Table I. The $EL2$ concentrations in these samples were estimated from Martin's calibration curve,[21] while the carbon concentrations were estimated from the localized vibrational modes[22] (LVM's) recorded with an FTS-20E Digilab interferometer. Infrared-absorption measurements were made with a Cary 2300 spectrometer. Its probing light was weak enough that no observable photoquenching or photoinduced recovery occurred during long sample exposure times in the beam (~18 h). A separate monochromator with an external 100-W quartz-halogen lamp provided the secondary irradiation. A wide range of photon energies (0.7–1.51 eV) was available with this monochromator. A cutoff filter with 50% transmittance at 1.46 eV was placed at the output of the monochromator to prevent illumination with photon energies larger than the band gap. The intensity of the monochromator output was measured with a calibrated thermopile and it was kept constant (~1.9 mW/cm^2) by adjusting the voltage on the light source at each photon energy over the range 0.7–1.4 eV. The intensity decreased from 1.9 mW/cm^2 at 1.4 eV to ~0.4 mW/cm^2 at 1.50 eV, as shown in Fig. 1.

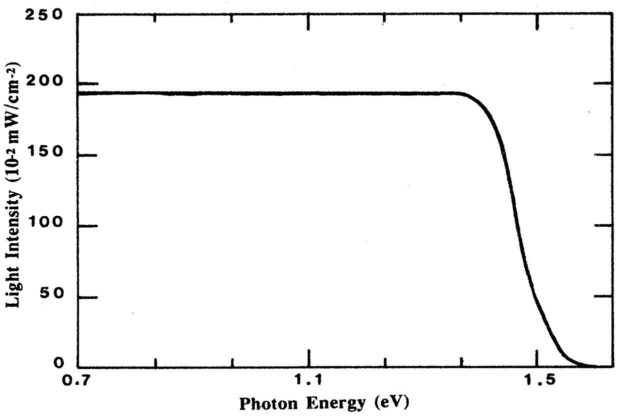

FIG. 1. Light intensity at the monochromator output as a function of photon energy. A cutoff filter with a 50% transmission at 1.46 eV was placed at the monochromator output to prevent any illumination by photons with energies larger than the band gap.

III. RESULTS AND DISCUSSIONS

The photoquenching data were collected as follows. The sample was cooled in the dark to 9 K using a closed-cycle refrigerator. The ir-absorption spectra were taken before (S_1) and after (S_2) photoquenching of $EL2^0$ using light of energy $h\nu=1.125$ eV. The residual absorption, S_2, was subtracted from S_1 and from all other spectra taken during either the quenching or recovery process. The difference between S_1 and S_2 was taken in order to calculate the absorption coefficient, α_0, at 1.18 eV, from which the $EL2^0$ concentration, [$EL2^0$], was calculated using Martin's criterion.[21] Then the sample was heated to 150 K for several minutes to regenerate $EL2^0$. The sample was again cooled to 9 K, and $EL2^0$ was photoquenched with various monochromatic light energies in the range $0.7\leq h\nu\leq 1.51$ eV for different periods of time depending on the samples. The absorption coefficient, α, was calculated from the ir spectrum at 1.18 eV for each photon energy and compared to α_0. The sample was again heated to 150 K and then cooled to 9 K for each run cycle. The quenching factor defined as

$$Q=100(\alpha_0-\alpha)/\alpha_0\ \% \tag{1}$$

is plotted in Fig. 2 for samples 1 and 3, where α_0 and α are the absorption coefficients taken at 1.18 eV before and after quenching. Sample 3 was found to photoquench completely within 30 s. Two points should be mentioned here. First, the quenching time is found to be strongly sample dependent. Second, Q was found to be smaller for sample 1 (annealed) as compared to sample 3 (unannealed) above $h\nu\geq 1.4$ eV. From other samples, we found that the larger the carbon concentration, the smaller the photoquenching time.

There have been recent theoretical developments toward identifying $EL2$ with the isolated $\mathrm{As_{Ga}}$ defect. Exciting results were reported by Dabrowski and Scheffler[18] (DS), who performed parameter-free, self-consistent Green-function calculations of the electronic structure, total energy, and forces of $\mathrm{As_{Ga}}$, and found that the defect can, in fact, possess a metastability. According to Fig. 2 of the DS, electrons can be promoted from the normal state (F) to an excited state (E) within $\mathrm{As_{Ga}}$ and can then decay to the metastable state (M). The $F\rightarrow E$ transition was calculated to be 0.97 eV, and DS made an at-

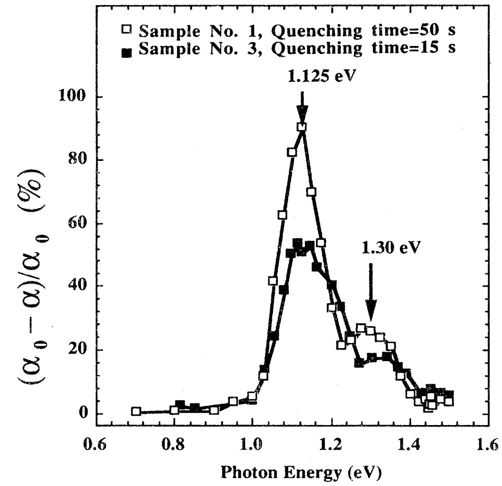

FIG. 2. Infrared-absorption photoquenching data for LEC-grown semi-insulating GaAs as a function of photon energy for both samples 1 (□) and 3 (■). Both absorption coefficients α and α_0 were obtained from the $EL2^0$ ir-absorption spectrum at 1.18 eV. The spectra were collected at 9 K, and $EL2^0$ was thermally regenerated at 150 K before each run.

tempt to identify this transition with the broad peak (BP) observed at 1.18 eV in the $EL2^0$ ir-absorption spectrum.[23] This attempt was made under the assumption that the zero-phonon line (ZPL) observed at 1.039 eV and the BP belong to the same transition, i.e., the $F \rightarrow E$ transition. The quenching data in Fig. 2 seem to be in conflict with the DS model for the following reasons. First, two peaks were observed at 1.125 and 1.30 eV, suggesting that the $EL2^0 \rightarrow EL2^*$ transformation occurs through two paths. Second, the 1.125-eV peak is not identical to the BP or ZPL energies. This disagreement may suggest that the $EL2^0 \rightarrow EL2^*$ transformation does not occur through the BP. Third, the calculated energy of 0.97 eV is in good agreement with the ZPL energy, but a wide range of monochromatic-light energies can photoquench $EL2^0$ in such a way that the calculated energy of 0.97 eV is meaningless when one compares it to the experimental observation as shown in Fig. 2. Fourth, $EL2^0$ was found to be photoquenched by using 0.8- or 1.4-eV light after an illumination time longer than 25 min. The photoquenching of $EL2^0$ at the above energies and illumination time was found to be complete, especially for unannealed doped or undoped semi-insulating GaAs (see Table I). It is also noted that the latter samples were found to photoquench completely with $1.4 \leq h\nu \leq 1.5$ eV monochromatic light, as we will see in the following discussion. Fifth, the 1.30-eV peak in Fig. 2 was observed in all samples tested. The quenching time at this energy was found to be sample dependent. There is also experimental evidence that the ZPL and BP belong to two different transitions.[24,25]

Optical recovery from $EL2^*$ was monitored as follows. After a complete photoquenching of $EL2^0$ at 9 K using 1.125-eV light, the sample was heated to 77 K and illuminated with 1.457-eV light for specific periods of time. The results are shown in Fig. 3 for sample 1. In this sample, an almost complete recovery (96%) has been achieved within 60 min. This is a rather surprising result because the optical recovery observed previously[10–17] was found to peak at approximately 0.8–0.9 eV. The optical recovery from $EL2^*$ was checked in the monochromatic-light range 0.7–1.51 eV, and it was found that the recovery factor

$$R = 100\alpha/\alpha_0\ \% \qquad (2)$$

shows a very complex structure, as in Fig. 4. Here, α is the absorption coefficient measured at either the 1.18- or 1.40-eV position after photon irradiation, and α_0 is the initial absorption coefficient measured after cooling the sample in the dark to 9 K and before photoquenching.

A few points should be noted here. First, the 1.18- and 1.40-eV positions were chosen to calculate the absorption coefficient because two broad absorption peaks were obtained at these positions when a baseline correction was made (see Refs. 26 and 27). Second, thermal recovery is insignificant[28] (< 1%) at 77 K for the illumination period of 25 min used in this study. Third, an illumination time of 25 min for sample 1 (Fig. 4) was used because it was long enough to permit significant optical recovery, but still short enough to collect a reasonable number of data points in a day's time. Fourth, optical recovery was observed at 9 K, but with a slower rate compared to the recovery rate at 77 K using 1.46-eV monochromatic light (see Ref. 16). Fifth, the recovery factor, R, may be larger than reported in the region above 1.4 eV in Fig. 4 because the light intensity is not constant in this region (see Fig. 1). Sixth, according to Fig. 4, we found that R is only about 16% [Fig. 4(a)] when using photons of about 0.9 eV

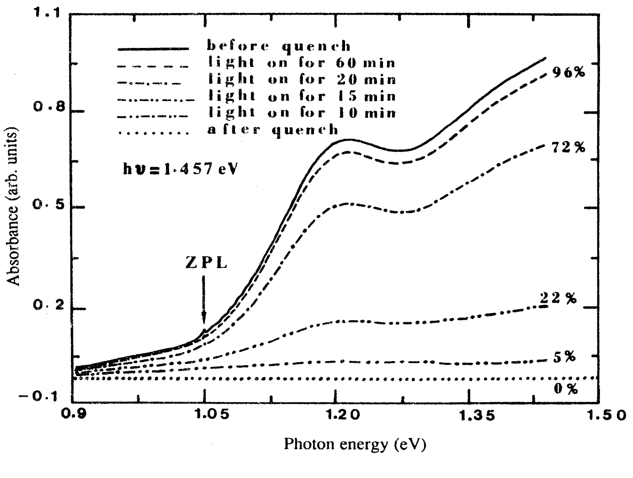

FIG. 3. Infrared-absorption spectra of $EL2^0$ in sample 1 before (——) and after (· · · ·) photoquenching and after illumination with 1.457-eV light at 77 K for different periods of time. A 96% recovery was achieved by illumination for 60 min. The residual absorption remaining after $EL2^0$ is completely photoquenched is subtracted from all spectra. Hence, the spectra indicated by a dotted line is the residual absorption subtracted from itself, i.e., the zero line.

energy, and that the band seems to be composed of two peaks. On the other hand, R in Fig. 4(b) is about 96% at 1.457 eV. The latter point can be understood in terms of competition between Q and R [Eqs. (1) and (2)]. It was reported[14] that competition between the quenching and recovery processes at 1.17 eV exists. Tajima *et al.*[13] also demonstrated that significant quenching (recovery) competition is present at 0.94 eV and concluded that the partial recovery they observed at this energy is the result of a dynamic balance between $EL2^0 \rightarrow EL2^*$ and $EL2^* \rightarrow EL2^0$ transformations. The existence of this quench (recovery) competition, however, does not seem to adequately answer, by itself, the question of why only partial photoinduced recovery is observed in most experiments. The amount of recovery obtained at any given photon energy also appears to depend on the experimental technique employed, the sample, the type of irradiation and its intensity, and the temperature. A temperature dependence is observed in the photoinduced $EL2^* \rightarrow EL2^0$ recovery of the ir absorption.[16] It was shown that there is a significant increase in the amount of optical recovery obtained (using light of energy $h\nu = 0.90$ eV) when the temperature is increased over the $60 \leq T \leq 100$ K range.[16] The pure thermal recovery at these temperatures is almost negligible, indicating that the photoinduced recovery process itself is thermally activated. A photoinduced recovery was also observed in a photocurrent experiment[29] where the maximum is centered around 0.94 eV with a profile identical to Fig. 4(a).

The recovery factor [Eq. (2)] was found to exhibit more complex structure in unannealed samples. Sample 3, which was used in previous studies,[15,28] is taken as an example (see Table I) for which R is plotted as a function of photon energy as shown in Fig. 5. It should be pointed out that the same conditions were applied to both samples 1 (Fig. 4) and 3 (Fig. 5), except that the illumination time used for sample 3 was 50 min. Despite the fact that a longer illumination time was used, the amount of R in Fig. 5 is smaller than that obtained in Fig. 4. The complex structure in Fig. 5 consists of a peak and two shoulders [Fig. 5(a)] around 0.9 eV and a number of multiple sharp peaks between 1.38 and 1.51 eV [Fig. 5(b)].

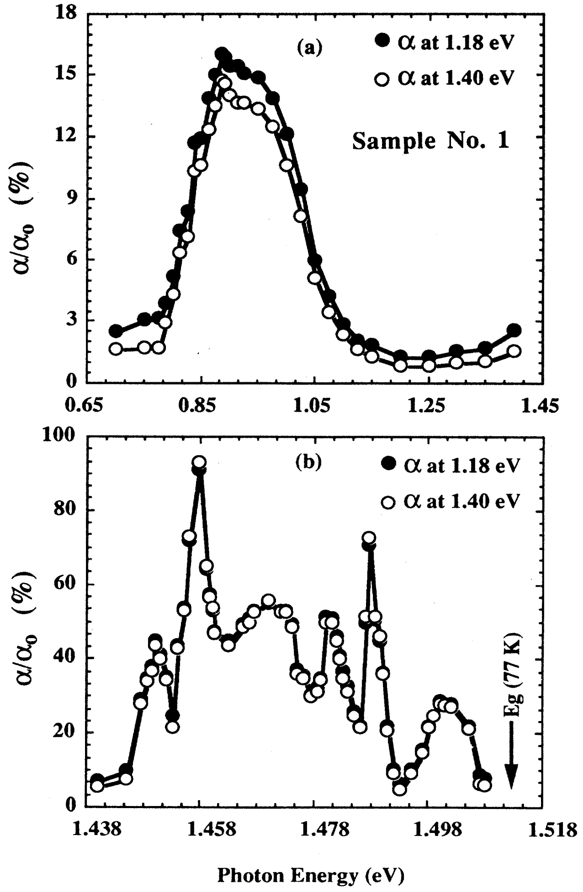

FIG. 4. Photoinduced $EL2^* \rightarrow EL2^0$ recovery for sample 1 as a function of photon energy (a) in the 0.7–1.4-eV range and (b) in the 1.44–1.51-eV range. The optical recovery was determined at both the 1.18- (●) and 1.40-eV (○) energy positions in the ir-absorption spectrum after illumination for 25 min with monochromatic light of energy indicated by each pair of data points. Sample was illuminated at 77 K and then cooled to 9 K to measure the absorption coefficients.

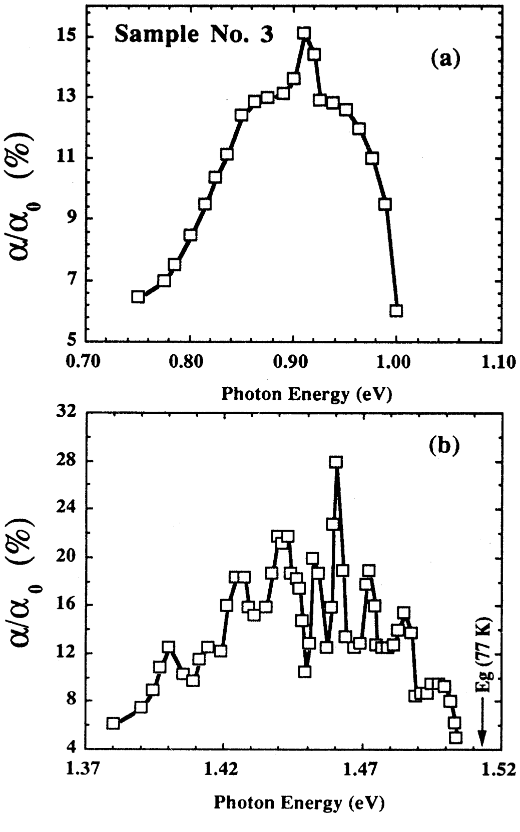

FIG. 5. Same key as in Fig. 4, but for sample 3. The illumination time was 50 min. Here we have shown only the recovery factor at 1.18-eV position.

The recovery factor R was also studied as a function of time at 77 K using 1.461-eV light for three different samples, as shown in Fig. 6. The data in this figure were found to be fitted by the following analytical expression,

$$R = A[1 - B\exp(-t/\tau)]\ , \tag{3}$$

where A and B are constants depending on the initial and final concentrations of $EL2^*$, t is the illumination time, and τ is a time constant which is inversely proportional to the cross section of the $EL2^* \rightarrow EL2^0$ transformation. A, B, and τ were all used as fitting parameters in Fig. 6, and it was found that τ is 111.8 ± 17.4, 56.6 ± 4.2, and $27.9 \pm 2.1\ \mathrm{s}^{-1}$ for samples 3, 2, and 1, respectively. Such sample dependence of *EL*2-related data has certainly been noted by others. It is well known that LEC-grown GaAs can exhibit variations in properties due to variations in growth conditions and thermal history. The conditions under which crystallization and thermal stress occur can introduce other midgap levels with activation energies similar to the *EL*2 defect,[30,31] complexes of unidentified traps with acceptor- and donorlike properties,[7-9,32-40] and other intrinsic defects[41] such as *EL*3 and *EL*6. These various defects and traps may interact with *EL*2. If so, sample dependences observed for some *EL*2 properties such as photoquenching and optical recovery characteristics should not be surprising.

The isolated $\mathrm{As_{Ga}}$ model[18] provides a good description of Auger-type recovery under electron injection,[42] but it does not give any information about the photoinduced recovery from $EL2^*$, a process that was found to occur with various techniques, as mentioned in the Introduction. The optical recovery as shown in Figs. 3–5 is still unexplained. One possible interpretation is that the peaks in Figs. 4 and 5 represent energy levels of a defect (or defects) that is not part of *EL*2, from which free electrons were excited and then captured by $EL2^*$, causing an Auger-type recovery. If this is the case, then photons within the $1.4 \le h\nu \le 1.51$ eV range should not cause any quenching. Sample 4 (see Table I) was chosen to test the above premise. The Fermi level in this sample is pinned at 0.48 eV and the free-carrier concentration is about 3 orders of magnitude larger than other samples, as shown in Table I. Light of energy $h\nu = 1.46$ eV was used to check the photoquenching of $EL2^0$. It was found that this light quenches $EL2^0$ completely within 25 min, as shown in Fig. 7. The same behavior was observed in other samples, but the quenching time was sample dependent. The results of Fig. 7 clearly demonstrate that an Auger-type recovery cannot explain the observed photoinduced recovery, and therefore the peaks in Figs. 4 and 5 are related to *EL*2.

The recovery data in Figs. 4 and 5 were evaluated with respect to some well-known models proposed for the metastable *EL*2 defect, namely arsenic antisite–gallium vacancy,[18] arsenic split interstitial,[43] arsenic antisite–arsenic vacancy,[44] and arsenic antisite–divacancy[45-47] (gallium vacancy–arsenic vacancy). The optical recovery was also compared with the energy levels of point defects reported in the literature[48-61] for GaAs (see Table II). It appears that the one point defect that has electronic energy levels which coincide with the peaks observed in the recovery data (Figs. 4 and 5) is the arsenic vacancy (V_{As}). According to Table II, the V_{As} was found[52,56-60] to possess an *S*-like energy level near midgap and a *P*-like energy level close to the conduction band. These energy levels may be shifted due to other point defects, such as the arsenic antisite,[44,62] present in its vicinity (see Table II). It is not the purpose of this paper to show how much the levels shift or in which direction this shift may occur, but rather to show qualitatively that the present optical recovery data support the models that involve V_{As}. The

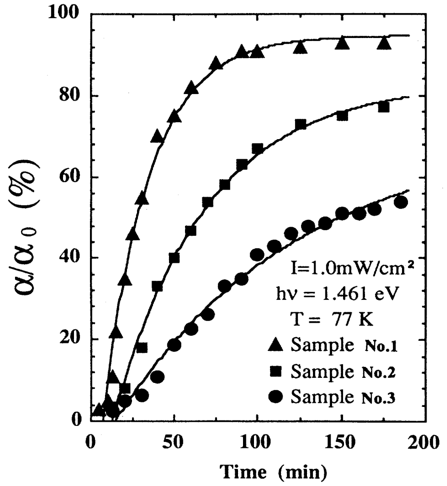

FIG. 6. Photoinduced $EL2^* \rightarrow EL2^0$ recovery as a function of time at 77 K for samples 1 (▲), 2 (■), and 3 (●). The solid lines are the results of fitting the experimental data by using Eq. (3), where A, B, and τ are the fitting parameters.

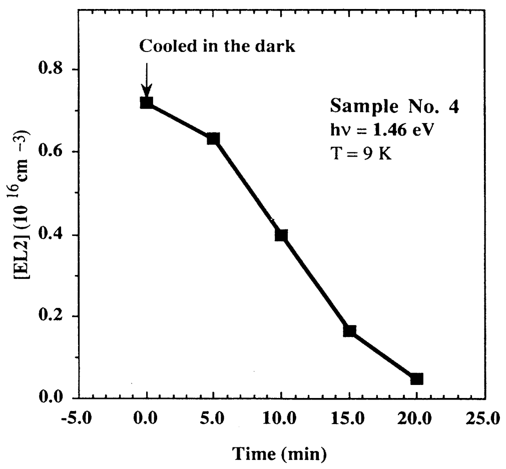

FIG. 7. $EL2^0$ concentration in sample 4 as a function of photoquenching time using 1.46-eV light at 9 K. This photon energy was also found to quench $EL2^0$ in other samples.

optical recovery (Figs. 4 and 5) is in an excellent agreement with the calculations of Myles and Sankey,[62] who found that the As_{Ga}-V_{As} pair defect possesses an energy level at 1.4 eV when it is occupied by one electron, and another energy level at 0.8 eV when it is occupied by two electrons. From the above discussion, V_{As} may act as an actuator for the $EL2^* \rightarrow EL2^0$ transformation. The EPR measurements, however, seem to be in conflict with the As_{Ga}-V_{As} model. von Bardeleben *et al.*[63–65] found that $g=1.97$ and $A=6.8\times10^{-2}$ cm^{-1} for the As_{Ga}-V_{As} pair defect, in disagreement with $g=2.04$ and $A=8.9\times10^{-2}$ cm^{-1} of $EL2$. It should be pointed out that the EPR measurements were performed only on electron-irradiated GaAs materials and a definitive identification of the As_{Ga}-V_{As} defect requires additional measurements using different materials (for example, as-grown LEC-grown GaAs) and techniques. The above disagreement can be resolved as follows. $EL2^*$ can be represented by $V_{As}+X$, where X could be As_{Ga}, while $EL2^0$ has a different atomic structure. The metastable state, $EL2^*$, is inaccessible by direct EPR, because it is not a paramagnetic state, and is also inaccessible by the ir-absorption technique, because of the presence of a large lattice relaxation, but its energy levels nevertheless exist in the gap and are V_{As}-derived states,[44,62] as supported by the present measurements. The fact that $EL2^0$ can be optically recovered from $EL2^*$ (see Figs. 3–5) strongly suggests that $EL2$ is a charge-controlled bistable defect, i.e., $EL2^0$ and $EL2^*$ have different charge states. Transport properties measurements[26] also indicate that $EL2^*$ may not be neutral. A charge-controlled bistability has been observed for other defects such as the M center in InP and an Fe-acceptor pair defect in Si (for a review, see Ref. 66).

TABLE II. Electronic energy levels of point and As_{Ga}-V_{As} pair defects in GaAs as measured from the top of the valence band. T denotes theory and E experiment.

Defect	Symmetry		Position (eV)	Method	Ref.
$As_{Ga}^{0/+}$	A_1		1.5	T	48
			1.10	T	49
			0.75	E	50
			0.70	E	51
			0.87	T	52
	T_2		1.74	E	51
			1.97	T	49
$As_{Ga}^{+/2+}$	A_1		0.5	E	50
			0.69	T	49
			1.25	T	48
			0.64	T	52
	T_2		1.82	T	49
			1.57, 1.81	E	53
$Ga_{As}^{0/-}$	A_1		0.078	E	54
			0.063–0.0929	E	55
	T_2		0.25	T	52
$Ga_{As}^{-/2-}$	A_1		0.203	E	54
			0.155–0.200	E	55
	T_2		0.55	T	52
V_{As}	A_1		0.57	T	52
			0.61	T	56
			0.71	T	58
			0.86	T	59
			0.65–0.70	T	60
	T_2		1.47	T	52
			1.46	T	56
			1.21	T	57
			1.47	T	58
			1.33	T	59
			1.52–1.54	T	60
V_{Ga}	A_1		−0.73	T	52
			<0	T	56
			−0.74	T	57
	T_2		0.01	T	52
			−0.03	T	56
			0.44	T	57
			0.02	T	58
			0.55	T	59
			0.05	T	61
As_{Ga}, V_{As} pair	A_1	0[a]	CBE[b]	T	62
	E	1[a]	1.4	T	62
	A_1	2[a]	0.8	T	62
As_{Ga}, V_{As} pair[c]	A_1		0.87	T	44
	E		1.75	T	44
	A_1		1.87	T	44

[a] Electron occupancy.

[b] Conduction-band edge.

[c] Energy level calculated at zero displacement of As_{Ga}.

The self-interstitial energy levels were not included in Table II because information about them is scarce. However, the arsenic interstitial (As_i) was predicted[48] to have an energy level at ~1.48 eV, and the energy level of the gallium interstitial is found to be ~0.56 eV above the valence-band maximum.[44,67] The As_{Ga}-As_i model is excluded in the present discussion because of the conflicting theoretical calculations reported by Baraff *et al.*,[68–73] on one hand, and by Dabrowski and Scheffler,[18,74] on the other. In addition, this model has been revised to an arsenic split interstitial for $EL2^*$, such that its energy levels lie outside the band gap,[43] in disagreement with the present optical recovery results.

The question of whether the peaks observed in Figs. 4 and 5 are due to splitting in the V_{As} energy levels or to the fact that $EL2$ is a family of slightly different levels[30,31,75] is still open. However, the presence of what appears to be two peaks around 0.9 eV in Fig. 4(a) and three peaks in Fig. 5(a), and the fact that an S-like energy level (A_1) does not split under crystal or strain fields, may suggest that the data in Figs. 4 and 5 are due to both splitting in the p-like levels (T_2) and to the existence of a family of energy levels.

IV. CONCLUSIONS

We have shown some new and different photoinduced $EL2^* \rightarrow EL2^0$ recovery data obtained by the ir-absorption technique. Various features of this recovery have been discussed and are summarized as follows.

(a) For the first time, optical recovery has been shown to occur in the 1.4–1.51-eV region.

(b) The recovery in the 1.4–1.51-eV region is more efficient and more complex than that previously reported for the 0.9-eV region.

(c) The peaks observed in the optical recovery are $EL2$-related energy levels.

(d) The small magnitude of the recovery factor around 0.9 eV as compared to that in the 1.4–1.51-eV region can be understood in terms of competition between quenching and recovery around 0.9 eV.

(e) Optical recovery is temperature dependent.[16] In general, the lower the temperature, the smaller the recovery.

(f) The peaks observed in the optical recovery were interpreted as being V_{As}- (which is part of the $EL2^*$ complex) related energy levels, in good agreement with the available theoretical calculations.[44,62]

(g) The fact that the $EL2^* \rightarrow EL2^0$ transformation occurs under photon illumination may strongly suggest that $EL2$ is a charge-controlled bistable defect.

(h) The photoinduced recovery data strongly support the concept of a "family" of $EL2$ defects.

Two peaks were observed in the photoquenching data of the normal state of $EL2$, indicating that $EL2^0 \rightarrow EL2^*$ transformation occurs through two paths. Neither the photoquenching nor the photoinduced recovery data can be explained in terms of the available predictions and calculations reported for the isolated arsenic antisite model.[18,19] The sample dependence of most of the data indicates the existence of interactions between $EL2$ and other defects and traps present in the sample.

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