Analysis of the near-intrinsic and extrinsic photocapacitance due to the EL2 level in boron implanted GaAs

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A detailed analysis of the photocapacitance signal at the near-band and extrinsic energetic ranges in Schottky barriers obtained on horizontal Bridgman GaAs wafers, which were implanted with boron at different doses and annealed at several temperatures, has been carried out by using the optical isothermal transient spectroscopy, OITS. The optical cross sections have been determined as well as the quenching efficiency of the EL2 level which has been found to be independent of the annealing temperature. Moreover, the quenching relaxation presents two significant features: (i) a strong increase of the quenching efficiency from 1.35 eV on and (ii) a diminution of the quenching transient amplitude in relation with that shown by the fundamental EL2 level. In order to explain this behavior, different cases are discussed assuming the presence of several energy levels, the existence of an optical recuperation, or the association of the EL2 trap with two levels located, respectively, at $E_v + 0.45$ eV and $E_c - 0.75$ eV. The theoretical simulation, taking into account these two last cases, is in agreement with the experimental photocapacitance data at low temperature, as well as at room temperature where the EL2 filling phototransient shows an anomalous behavior. Moreover, unlike the previous data reported for the EL2 electron optical cross section, the values found using our experimental technique are in agreement with the behavior deduced from the theoretical calculation. The utilization of the OITS method has also allowed the determination of another level, whose faster optical contribution is often added to that of the EL2 level when the DLOS or standard photocapacitance is used.

INTRODUCTION

The midgap EL2 level at $E_c - 0.75$ eV, is created by a native donor defect in GaAs except when it is grown by LPE. It can also be created by means of plastic deformation, ionic implantation, or neutron irradiation. In these cases, the DLTS (deep level transient spectroscopy) spectra of the untreated samples do not show the normal peak corresponding to the EL2 center, but they show the presence of the U band. It is necessary to anneal at temperatures higher than 450 °C to obtain the EL2 peak in the DLTS spectra.[1] Initially, this was explained assuming that the formation of the EL2 center does not occur below such temperatures. On the contrary, several recent works have reported the association between the EL6 and EL2 native defects, in order to justify the origin of the U band and to prove the direct EL2 creation by means of those processes. Moreover, this allows us to reconcile again the EL2 level with the data obtained from EPR (electronic paramagnetic resonance), attributed to the As_{Ga} defect.[2,3] Nevertheless, considering theoretical calculations, this antisite appears as a double charge donor, whose higher energy state would be the EL2 level and whose second level has recently been identified by Wosinski[4] and Lagowski *et al.*,[5] as a level located at about 0.5 eV above the top of the valence band.

The main characteristic of the EL2 level is the quenching of its photoresponse. The fundamental EL2 level relaxes to a new state, labeled EL2 metastable state, which does not show the optical response. This photoelectric fatigue or quenching has been analyzed by Vincent *et al.*[6] These authors reported that quenching efficiency begins at about 0.9 eV, passes through a maximum located at about 1.12 eV and goes to zero before reaching 1.35 eV. More recently, Taniguchi and Ikoma[7] have carried out measurements which indicate further increases of the quenching efficiency from about 1.35 eV, depending on the samples used.

The fundamental EL2 state can again be recuperated in a thermal or electrical way. Thus, when the light is off, the unquenched state can be recuperated with a temperature dependent rate. This thermal recuperation is consistent with a single diffusion like atomic displacement process. Alternatively to the thermal recuperation, the presence of free electrons gives rise to the electrical recuperation of the unquenched states.

The existence of an excited state near the conduction band, or the participation of a donor shallow level in the process, has been claimed[8] in order to explain this last mechanism. Likewise, several works have reported experimental data which suggest such a possibility. Shanabrook[9] found that the above gap excitation photoluminescence spectra exhibit an oscillatory behavior, which is attributed to resonant cooling of hot electrons by emission of LO phonons. This indicates that the energy transfer or capture process is dominated by a shallow donor state, whose capture cross section is sensitive to the free electron energy before capture. Analo-

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gous results have been found by Leyral *et al.*[10] Recently Jiménez *et al.*[11] have found that, after excitation with photons of about 1.15 eV, another quenching phenomenon takes place, which is the optical quenching of the photocurrent in the near band-edge spectral region. It has been explained on the basis of a two-step mechanism: (i) the EL2 level electrostatically associates with shallow levels, when it is optically ionized at low temperatures; (ii) afterwards the shallow level relaxes to a quenched state. Furthermore, Nojima[12] has reported the existence of an optical slow-relaxation phenomenon, or a slow optical fatigue in the photoconductivity measurements on undoped semi-insulating liquid encapsulated Czochralski GaAs, which has been attributed to an optical transition from the quenched to the fundamental EL2 state.

In the present paper, we report the experimental results of the near-band and extrinsic photocapacitance related with the EL2 level. The measurements were obtained from the new method, labeled OITS, recently reported[3] which allows a more spectroscopic analysis of the photocapacitance signals than the standard photocapacitance or DLOS techniques. The analyzed samples were Au:GaAs Schottky barriers which were boron implanted at different doses and, afterwards, annealed at different temperatures. The data analysis carried out has allowed us to do the following:

(1) to explain both the increase of the quenching efficiency and the diminution of the expected EL2 quenching amplitude, at energies greater than about 1.2 eV;

(2) to deduce the exact EL2 electron optical cross section, σ_n^0 in the near-band energetic range which, unlike the data previously reported by other authors,[13] has been found to show a good agreement with the results of its theoretical calculation;

(3) to identify the presence of another level whose optical response appears to be mixed with the EL2 level one;

(4) to show that the EL2 quenching efficiency and optical cross sections are independent of the annealing temperature;

(5) on the basis of the above results, to report a model assuming an optical recuperation between the metastable and fundamental states and the presence of a second level associated with the EL2 center. This level would be located at about 0.45 eV above the valence band, according to the values previously proposed by Wosinski[4] and Lagowski *et al.*[5] The kinetic equations developed from this model confirm the experimental results found at low temperatures, as well as the anomalous photocapacitance behavior at room temperature.

EXPERIMENT

The measured samples were obtained using, as starting material, horizontal Bridgman *n*-GaAs with a free electron concentration of about 8×10^{16} cm^{-3}. The polished surface was capped with a 1000-Å CVD Si_3N_4 layer and annealed at 870 °C for 15 min in order to decrease the native electron trap concentration in a 1-μm-thick layer below the surface. After removing the Si_3N_4 capping layer, the samples were implanted with boron except for the testing sample. The dose was 10^{10} and 10^{11} ions/cm^3 and the ion kinetic energy 100 keV. The annealing treatments were carried out in an open furnace, using the close-contact technique under H_2 flux during 15 min at a temperature range between 300 and 800 °C. Finally, the Schottky diodes were obtained by evaporating gold electrodes on the surface of the implanted and nonimplanted samples.

The defect concentration for the boron dose used is adequately small to facilitate the capacitance transients interpretation. However, we find a strong nonexponential photocapacitance response. Its analysis presents a greater difficulty than in the usual case. This is due to the addition of exponential transients of different levels whose optical response, concentration, and optical cross sections are not well known *a priori*. Accordingly, the standard photocapacitance and the DLOS experimental techniques[6] are rather unsuitable for characterizing the samples with possible nonexponential transients.

We have used a new experimental method based on the time analysis of the isothermal phototransients (optical isothermal transient spectroscopy).[3] Once the phototransient is stored in the computer and normalized to its initial value, the OITS signal is generated by sampling the photocapacitance at different times t_i and t_iK, where $K>1$ is a fixed parameter. For each t_i, the OITS signal is

$$S(t_i\sqrt{K},T)=[C(t_iK)-C(t_i)]/\ln(K). \tag{1}$$

For each level with optical response, straightforward calculations show the existence of a maximum of the OITS signal. These maxima are characterized by their height $H_{\max}$ and their position at the time logarithm axis $t_{\max}$, which are given, respectively, by

$$H_{\max}=\frac{e_n^0}{e_n^0+e_p^0}\frac{N_T}{2N_D}\frac{K-1}{\ln K}K^{-K/(K-1)}, \tag{2a}$$

$$t_{\max}=(e_n^0+e_p^0)^{-1}\frac{\sqrt{K}\ln K}{K-1}, \tag{2b}$$

where e_n^0 and e_p^0 are the electron and hole optical emission coefficients, N_T is the trap level concentration, and N_D the shallow donor density. From these equations, when the minority optical emission coefficient is smaller than that of the majority carriers, the level concentration and the majority optical emission can be directly deduced. In the other cases, one can only obtain a magnitude proportional to the majority optical emission coefficient and the concentration at a fixed photon energy.

Figure 1 shows representative photocapacitance transients together with their OITS spectrum at low temperatures, $T=80$ K, for two samples annealed at different temperatures. The dashed lines correspond to the fitting, assuming the addition of different exponential transients. Figure 2 shows the experimental setup which is the standard one used for the photocapacitance measurements.

RESULTS

The DLTS spectra of our samples show the existence of the EL6 and EL2 levels together with the *U* band, Fig. 3. As the annealing temperature increases the EL6 and *U*-band concentrations become smaller, being negligible from 500 °C on. Then, the DLTS spectra show only the EL2 peak. There-

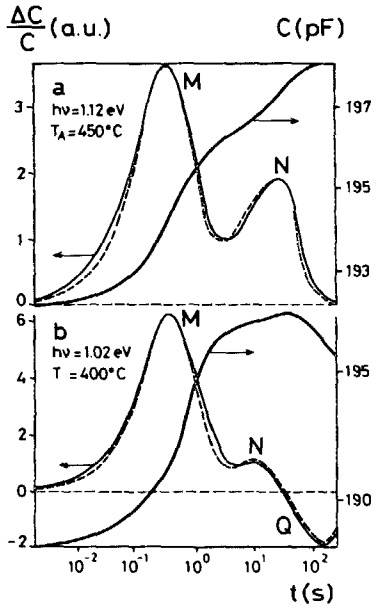

FIG. 1. OITS spectra at different excitation energies and annealing temperatures. The thick lines are, respectively, the photocapacitance transients.

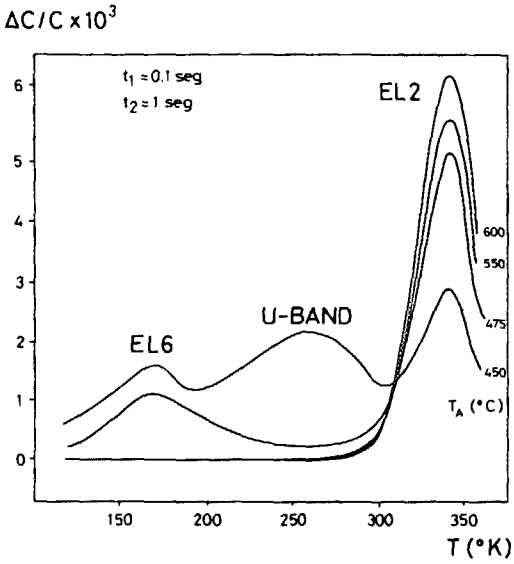

FIG. 3. DLTS spectra of the gold Schottky barriers obtained on the horizontal Bridgman GaAs afterwards implanted with boron and annealed at different temperatures.

fore, we have used basically the samples annealed at a temperature of 600 °C for the photocapacitance measurements of the EL2 level.

Figure 4 shows a photocapacitance transient obtained from the sample annealed at 600 °C and its corresponding OITS spectrum, together with other OITS spectra at different annealing temperatures with an illumination energy of 1.44 eV. The dashed line represents the theoretical fitting of the 600 °C OITS spectrum, assuming the superposition of two exponentials. It should be noted that at this photon energy, the samples annealed at temperatures greater than 475 °C show a new peak, which we have named *P* peak. In Fig. 5 we show OITS spectra at different photon energies for the samples annealed at 600 °C. In Fig. 6 we present the quenching efficiency versus the photon energy. These values have been deduced from each OITS spectrum according to Eqs. (2a) and (2b). The dashed line corresponds to values reported by Vincent *et al.*[6]

Several points about the negative quenching peak *Q* should be noted:

(i) The quenching efficiency increases from 1.35 eV (Fig. 6).

(ii) Its amplitude is much smaller than that measured in the usual quenching range, where the amplitude of the *Q* and *M* peaks are equal when the recuperation is negligible in front of the quenching efficiency.[6] This behavior begins at

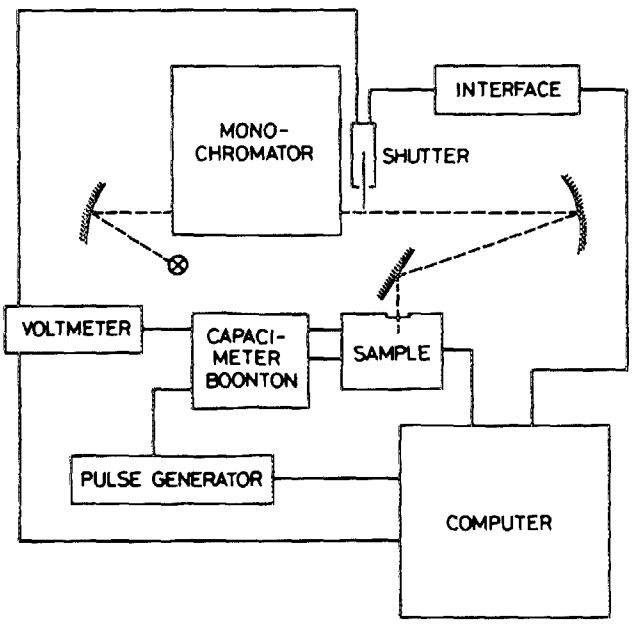

FIG. 2. Experimental setup.

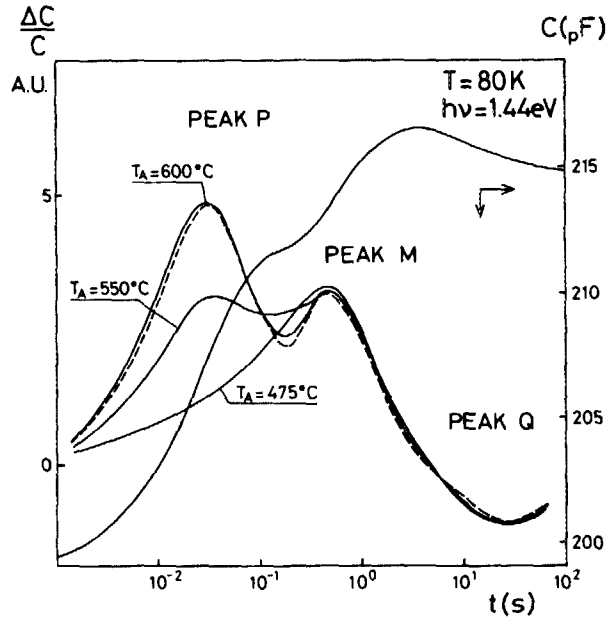

FIG. 4. OITS spectra at different annealing temperatures with $h\nu = 1.44$ eV. The thick line corresponds to photocapacitance transient of the sample annealed at 600 °C and the dashed line is the fitting carried out assuming the contribution of several exponential transients.

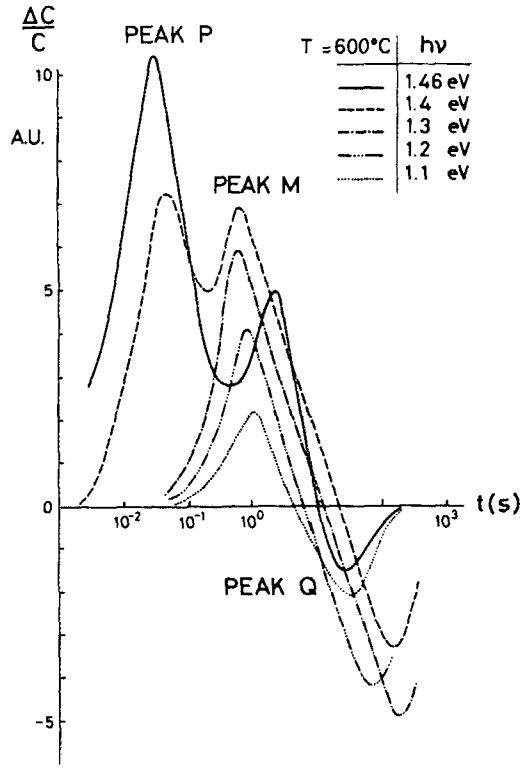

FIG. 5. OITS spectra at different photon energies for the samples annealed at $T_A = 600$ °C.

about 1.2 eV and becomes larger in the near intrinsic region, as is shown in Fig. 7.

A similar increase of the quenching efficiency from about 1.35 eV has also been reported by Taniguchi *et al.*[7] Their samples were obtained from different technological processes or subjected to implantation. They assumed the existence of a multilevel family associated with EL2 level.

The *P* peak level has never been noticed by DLTS or DLOS. Its optical response begins to be detected at about

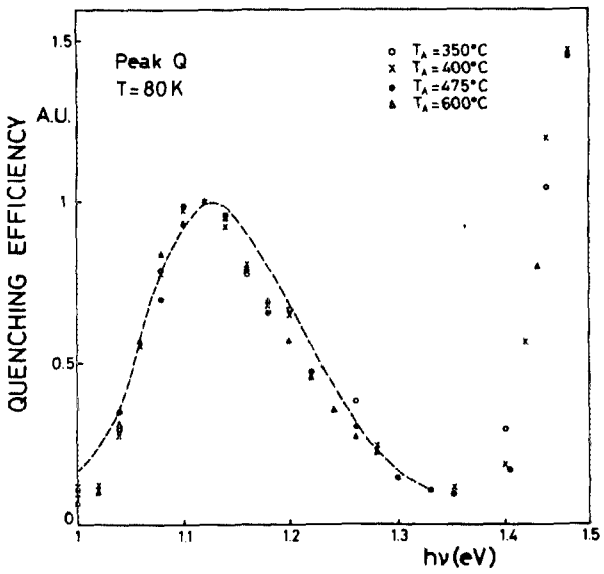

FIG. 6. Quenching efficiency for the Schottky diodes obtained on boron implanted GaAs at 10^{10} ions/cm^2 having 100 keV of energy and at different annealing temperatures. The dashed line corresponds to the values found by Vincent *et al.*[6]

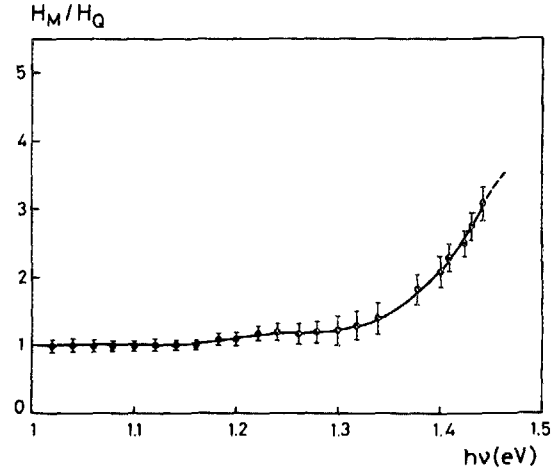

FIG. 7. Amplitude ratio of the EL2 and quenching OITS peaks.

1.15 eV and can be exactly separated from the *M* peak contribution by the OITS method from 1.28 eV.

In Fig. 8 we present the electron optical cross-section values, deduced from the *M* and *P* peaks with the same arbitrary units. We attribute the *M* peak to the EL2 level, according to the behavior of its optical cross section with the photon energy. The dashed line corresponds to the theoretical model of Chantre[14] and the crosses are the values previously reported by other authors.[6,12] Figure 9 shows the *M* peak σ_n^0 versus the photon energy for different annealing temperatures. The observed variation has been attributed to the interaction between the EL2 and the EL6 levels analyzed elsewhere.[3] Likewise, the EL2 σ_p^0 values have been deduced from the OITS spectra, taking into account the N_T/N_D ratio deduced by means of the DLTS spectra. The obtained data present an increase after energies greater than 1.3 eV, Fig. 10, whose theoretical fitting excludes any possibility of its being due to the transition between the Γ_7 valence band maximum and the EL2 level. Moreover, our values and those

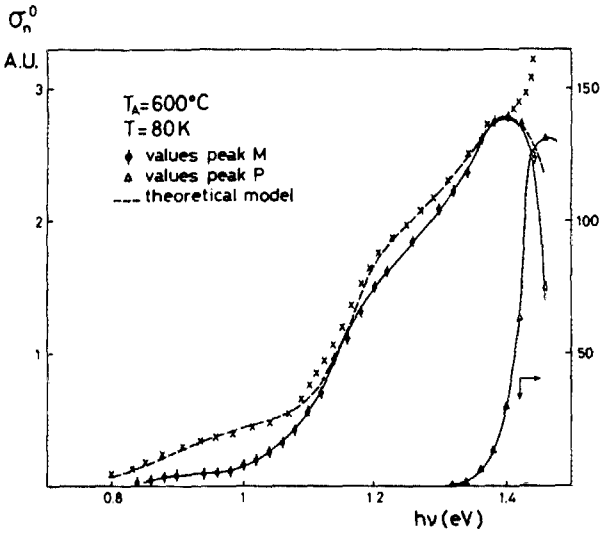

FIG. 8. Electron optical cross section of the *M* peak attributed to EL2 level vs the photon energy measured using the sample annealed at $T_A = 600$ °C. The dashed line is the theoretical model and the symbols (×) are the experimental values according to Refs. 6 and 13. The triangles are the electron optical cross section associated with the peak *P* expressed with the same units.

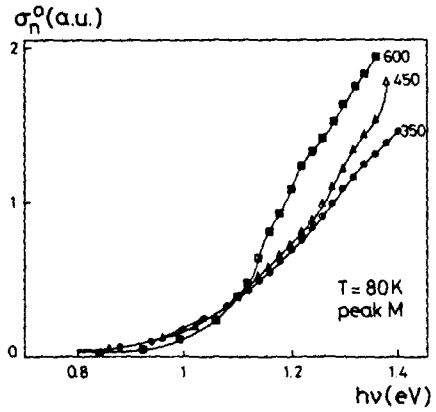

FIG. 9. Electron optical cross section of the M peak attributed to the EL2 level vs the photon energy taking the annealing temperature as a parameter.

found in previous work at different temperatures[14] suggest that the σ_p^0 increase is caused by the absorption due to the presence of another donor level D associated with the EL2 center. This level would be the associated state located near the conduction-band maximum which has been determined from photoluminescence excitation measurements[9,10] or Hall measurements.[15]

Also, it must be noted that the σ_n^0 data present a diminution from about 1.4 eV, in agreement with the theoretical calculation. The previously reported values deduced from DLOS do not show this diminution. However, it has been pointed out from photoluminescence measurements.[9,10] We think that this disagreement is due to the presence of the P peak whose contribution cannot be separated using the DLOS method, but it can be measured correctly using our OITS method.[3] This strong diminution, together with the σ_p^0 increase, contributes to increase the quenching efficiency according to its expression deduced from the Vincent *et al.* model.[6] It should be noted that the increase of σ_p^0 must depend on the origin of the D defect. This would explain the different values of the quenching efficiency obtained in samples from different starting materials.

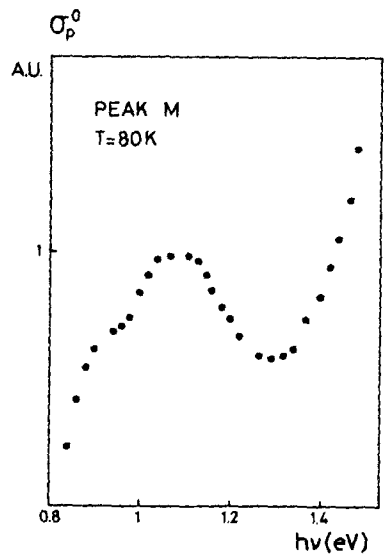

FIG. 10. Hole optical cross section of the M peak attributed to EL2 level vs the photon energy.

DISCUSSION

The presence of this P peak brings about the question of its origin. Wosinski,[4] and more recently Lagowski *et al.*,[5] have reported the existence of a level located at about 0.45 eV above the valence band, which was attributed to a paramagnetic state of the As_{Ga}^{4+} while the usual EL2 level should be the nonparamagnetic state As_{Ga}^{3+}.[16] However, a detailed analysis of the EL2 and P concentrations at different annealing temperatures, Fig. 4, allows us to reject the possibility that the P peak is due to the level found by Wosinski or Lagowski *et al.* Our experimental data rather suggest that the P peak appears with the annealing process in a different way than the EL2 level. This peak might be related to the defects created by the boron implantation, B_{As} or Ga_{As}, as reported by Dansas.[17]

Interesting features about the photocapacitance behavior appear when the energy of the illumination is changed. Figures 11 and 12 show the evolution of the photocapacitance versus the time, under the consecutive illumination with photons of different energies. The final value of the photocapacitance does not show any dependence on the alternative order of the illumination. Thus, the change of the photon energy gives rise to a sudden photocapacitance variation which is followed by a slower relaxation. These features can be summarized as follows:

(i) The photocapacitance variations caused by the change of the illumination energy are steplike. This is due to the photocapacitance being related to the sum of the populations of electrons at levels related with the EL2, or other center. In the photocurrent case, the illumination change should give a spikelike variation which is in agreement with the previous work of Jiménez *et al.*[11] and Nojima.[12] Like the results of these authors, the photocapacitance step depends on the application time of the second illumination, i.e., depends on the EL2 occupancy.

(ii) The switch-off illumination after reaching the steady value of the photocapacitance gives rise to a transient, but the following illumination with photons of energy $h\nu$ regenerates, again, the steady value for this energy.

(iii) The steplike photocapacitance variation shows two

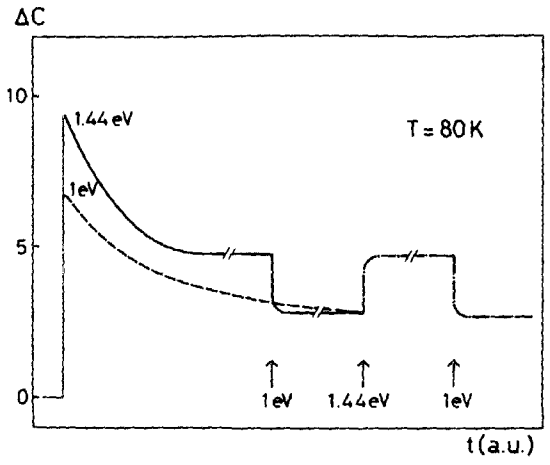

FIG. 11. Experimental evolution of the photocapacitance corresponding to the application, consecutively, of different photon energies.

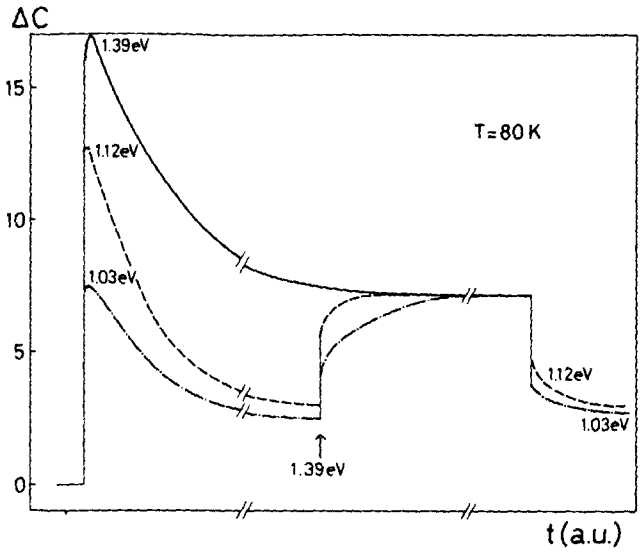

FIG. 12. Experimental evolution of the photocapacitance corresponding to the application, consecutively, of different photon energies.

components, fast and slow, which depend on the illumination energy.

The existence of these two different relaxation processes suggests that there are two mechanisms. On the one hand, given the large values of the electron optical cross section of the P level, it is reasonable to think that the fast variation of the photocapacitance can partially be due to the contribution of this level. On the other hand, the only contribution of the EL2 level cannot explain the slow relaxation, unless the metastable EL2 shows an optical response. We have two options to explain the second mechanism:

(i) There is another level X which generates the slow relaxation.

(ii) The metastable EL2 level presents optical response.

In the first case, the time constants associated with the X level should correspond to the quenching efficiency to justify the diminution of its expected amplitude in relation with that of the EL2 peak in the OITS spectra. Moreover, this amplitude should be similar to that of the EL2 to explain the quasi-extinction of the quenching. Thus, under these conditions, once all the EL2 center are in the metastable state, the photocapacitance changes would be only due to the X level.

In the second case, the optical response of the metastable EL2 level leads to two new possibilities:

(a) The existence of a direct optical recuperation process;

(b) The existence of a second level associated with the EL2 center together with the optical recuperation process, on the basis of the results of the Wosinsky[4] and Lagowski *et al.*[5]

Both possibilities can be analyzed together taking into account that the first one is a particular case of the second one, assuming null values for the second level optical cross sections. Thus, in the (b) case, we can suppose that the EL2 level corresponds to the neutral charge state which presents a first ionization energy threshold about 0.75 eV and a second about 1.05 eV. Therefore, according to this assumption, the new kinetic equations governing the persistent photocapacitance quenching become

$$\begin{aligned}
\frac{dN_1}{dt} &= -\sigma_n^0\theta N_1 - qN_1 + \sigma_p^0\theta \\
&\quad \times (N_T - N_1 - N^* - N_3) + \bar{q}N^*, \\
\frac{dN^*}{dt} &= qN_1 - \bar{q}N^*, \qquad (3a) \\
\frac{dN_3}{dt} &= -\sigma_p'\theta N_3 + \sigma_n'\theta(N_T - N_1 - N^* - N_3),
\end{aligned}$$

with the condition

$$N_T = N_1 + N_2 + N_3 + N^*, \qquad (3b)$$

where N_1, N_2, N_3, and N^* are, respectively, the number of neutral, simple ionized, double ionized, and quenched states. σ_n^0 and σ_p^0 are the electron and hole optical cross section associated to the $E_c - 0.75$ eV level and σ_n' and σ_p', the $E_v + 0.45$ eV level ones. $q = \sigma^*\theta$ is the quenching rate corresponding to the transformation of the EL2 level into its metastable state, $\bar{q}$ is the total recuperation and θ is the photon flux. The general solution is now given by the linear combination of three exponentials, with coefficients A_1, A_2, and A_3, whose time constants are the inverse of the roots of the following equation:

$$\begin{aligned}
0 = \lambda^3 &+ [\bar{q} + q + (\sigma_n^0 + \sigma_p^0 + \sigma_n' + \sigma_p')\theta]\lambda^2 \\
&+ [(\sigma_n^0\theta + q + \sigma_p^0\theta)\bar{q} + q(\sigma_p^0\theta - \bar{q}) \\
&+ (\sigma_n' + \sigma_p')\theta(\bar{q} + q + \sigma_n^0\theta + \sigma_p^0\theta) - \sigma_n'\sigma_p^0\theta^2]\lambda \\
&+ \sigma_p'\theta[(\sigma_n^0 + \sigma_p^0)\theta\bar{q} + q\sigma_p^0\theta] + \sigma_n^0\sigma_n'\theta^2\bar{q}. \qquad (4)
\end{aligned}$$

Under illumination, the steady-state value of the positive charge can be expressed by

$$P(\infty) = 1 + \frac{\sigma_n^0\sigma_n'\theta^2\bar{q} - \sigma_p^0\sigma_p'\theta^2(q + \bar{q})}{\sigma_p'\theta(\sigma_n^0 + \sigma_p^0)\theta\bar{q} + q\sigma_p^0\theta + \sigma_n^0\sigma_n'\theta^2\bar{q}}. \qquad (5)$$

According to the value of $\bar{q}$ the values of $P(\infty)$ can change from zero, for $\bar{q} = 0$, to

$$P(\infty) = 1 + \frac{\sigma_n'\sigma_n^0 - \sigma_p'\sigma_p^0}{(\sigma_n^0 + \sigma_p^0)\sigma_p' + \sigma_n'\sigma_n^0} \qquad (6)$$

for $\bar{q} \rightarrow$ infinite. It should be noted that σ_n' also acts exactly as a recuperation process; the smaller the σ_p' is, the more effective the process will be.

Taking into account the values of the optical cross section, as well as those of the quenching efficiency and optical recuperation that will be used later to carry out the fitting of the experimental photocapacitance, the solutions of Eq. (4) can approximately be given by

$$\begin{aligned}
\lambda_1 &\simeq (\sigma_n^0 + \sigma_p^0)\theta, \\
\lambda_2 &\simeq (\sigma_n' + \sigma_p')\theta, \qquad (7) \\
\lambda_3 &\simeq \frac{\sigma_p'[(\sigma_n^0 + \sigma_p^0)\bar{q} + q\sigma_p^0] + \sigma_n'\sigma_n^0 q}{(\sigma_n' + \sigma_p')(\sigma_n^0 + \sigma_p^0)}.
\end{aligned}$$

Usually, λ_2 is larger than λ_1, but the amplitude of the associated exponential A_2 is negligible. Moreover, λ_3 and the amplitude A_3 show a direct dependence on the optical parameters. The increase of σ_p^0 and $\bar{q}$, and the diminution of σ_n^0 give rise to an increase of the quenching efficiency.

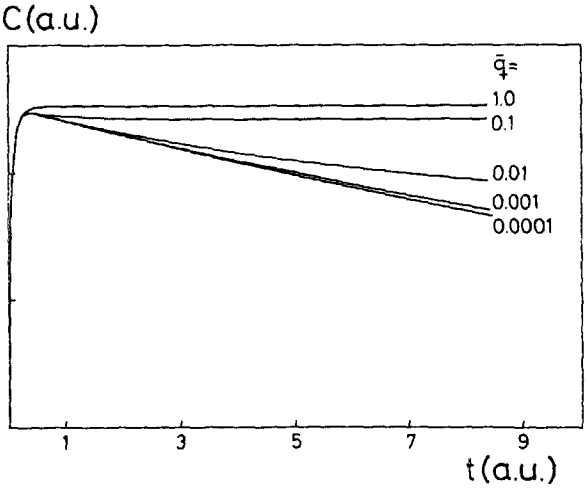

FIG. 13. Theoretical photocapacitance transients calculated from the model of a second ionization level for the EL2 center assuming different values of recuperation from the metastable state to the fundamental state. $\sigma_n^0 = \sigma_p^0 = 1$ a.u., $\sigma^* = 10^{-2}$ a.u., $\sigma_n' = 10^{-3}$ a.u., and $\sigma_p' = 10^{-1}$ a.u.

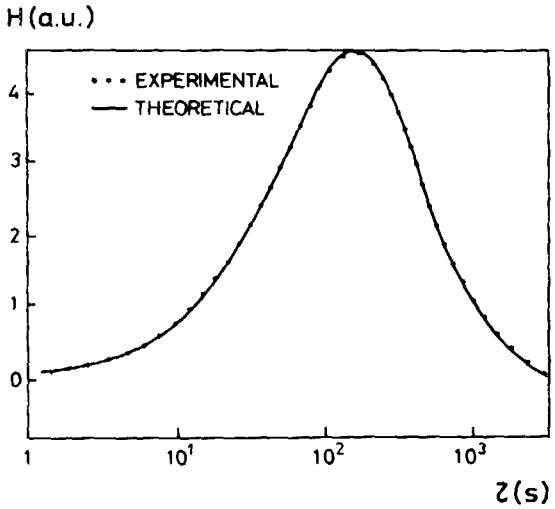

FIG. 15. OITS spectra of the photocapacitance transient carried out at $T = 140$ K with $h\nu = 1.18$ eV using the sample annealed at 600 °C. The continuous line is the theoretical fitting using three time constants and the dots correspond to the experimental photocapacitance transient.

Figure 13 shows the numerical calculation of the above kinetic equation for different values of the recuperation $\bar{q}$, assuming that $\sigma_n^0 = \sigma_p^0 = 1$, $\sigma_n' = 0.001$, $\sigma_p' = 0.01$, and $\sigma^* = 10^{-2}$ a.u. Recuperation values as small as $q/10$ are enough to give rise to the diminution of the quenching amplitude.

The numerical simulation of the consecutive application of two photon energies is shown in Fig. 14. We have also included the variation due to the P level, according to the amplitude variation of the P peak in the OITS spectra. The qualitative agreement with the experimental results is excellent. Thus, this model allows us to explain the detailed behavior of the photocapacitance.

On the contrary, the possible existence of other levels, besides the P level, which could also justify the photocapacitance variations, has not been corroborated. The analysis of the OITS spectra at temperatures where the thermal recuperation is larger than the quenching efficiency does not show any time constant in the quenching efficiency range with enough amplitude to justify the quenching reduction.

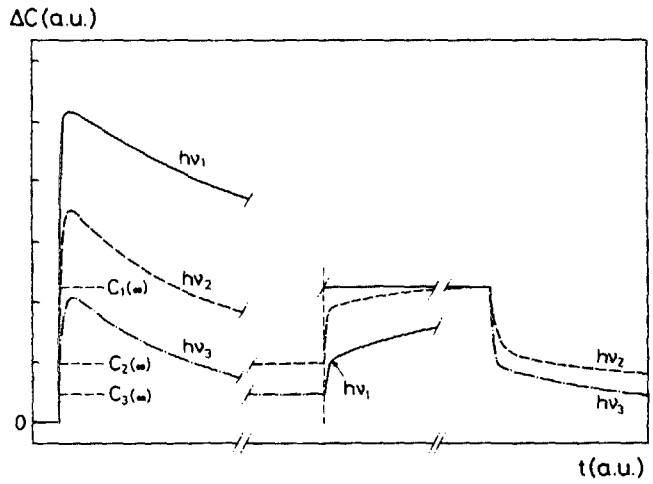

FIG. 14. Theoretical simulation of the experimental measurements shown in Fig. 10.

This can be seen in Fig. 15, which shows the OITS spectra of a photocapacitance transient at 140K. It does not appear any level of amplitude comparable to that of the EL2 level. The theoretical fitting has been realized using three time constants of 10.7, 165.4, and 708.9 s with amplitudes, respectively, of 0.16, 4.2, and 0.9 a.u. We have assumed a smooth dependence on the temperature of the optical cross sections of every level. Moreover, neither the illumination with photon energy of about 0.67 eV, nor the annealing at temperatures greater than 700 °C, where the EL2 concentration becomes negligible, have led to the identification of residual levels with concentration and optical parameters suitable to explain the experimental data. The residual levels show a concentration smaller than 10^{15} cm^{-3}.

Besides the photocapacitance behavior at low temperatures, there is another interesting feature which indicates the contribution of the second level associated with the EL2 center. It appears at room temperature, when all the EL2 centers have been thermally emptied and the sample is illuminated with a photon energy greater than about 1 eV. The photocapacitance initially increases; afterwards it decreases towards its steady value which agrees with that obtained from the initial condition with all the EL2 centers filled, Fig. 16. The thermal recuperation of the steady value in darkness shows also a special evolution. First, the capacitance rapidly diminishes. Then, it increases with a slower relaxation. This situation can also be simulated by means of the above model, dashed line in Fig. 16.

Moreover, in the case of all the EL2 centers being full, the model gives an only exponential transient. The amplitudes associated with the other time constants are negligible. Thus, in spite of the three time constants involved according to the model, the experimental EL2 emptied phototransients are found to be exponential. On the contrary, in the case of the existence of other levels, the emptied phototransient should be clearly nonexponential. The good accordance confirms the existence of the second level associated with the EL2 center. Similar behavior has been found in the samples

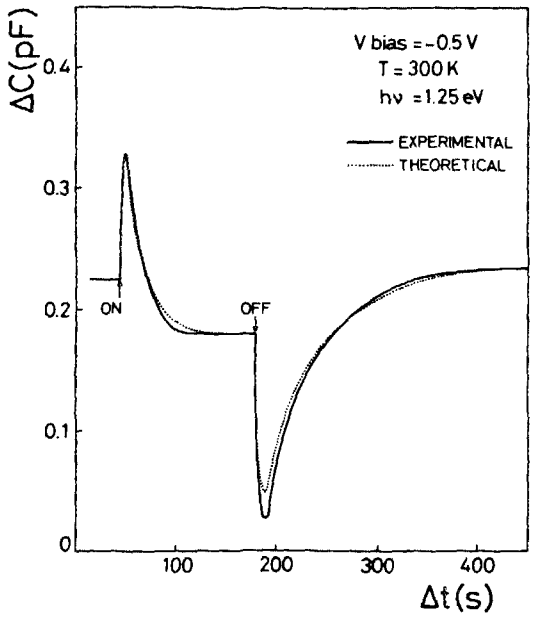

FIG. 16. Photocapacitance transient at room temperature with a photon energy $h\nu = 1.25$ eV. The dots are the theoretical fitting according to the developed model.

obtained on the nonimplanted material and whose DLTS spectra show only the EL2 peak. We think that the small difference between the experimental and theoretical curves is due to the ionization of other hole traps. The developed analysis corroborates that this behavior is an intrinsic characteristic of the EL2 center and does not depend on other levels with optical response, as the P level.

CONCLUSION

In conclusion, from the OITS analysis of the near-band and extrinsic photocapacitance of the boron implanted GaAs Schottky barriers, annealed at several temperatures, we have shown that in the samples annealed at 600 °C, where there is no contribution of the EL6 level, besides the EL2 center, there are other two levels with optical response: (i) the P level, (ii) the second level associated with the EL2 center.

The P labeled level shows an optical electron cross section greater than that of the EL2 center, which has exactly been deduced, solving the apparent incompatibility between its theoretical model and the DLOS data previously reported for values greater than 1.39 eV. The concentration of this P level has been found to increase with the annealing temperature. We think that it may be due to the B_{As} or Ga_{As} according to the data reported by Dansas,[17] Bishop *et al.*,[18] and Elliot *et al.*[19]

The other level, located about $E_c - 1.05$ eV, has been assumed in order to explain the inequality between the EL2 and quenching peak amplitude, on the basis of our experimental results and those of Wosinsky[4] and Lagowski *et al.*[5] The developed model has allowed us to explain the evolution of the photocapacitance transients as well as its behavior even at room temperature. The most significant feature of the developed model is the verification, using capacitance technique, of the optical recuperation previously reported by Najima,[12] from photocurrent measurements. The distinction between the effects originated by the presence of a level as the X level or the second level associated with the EL2 center is not straightforward. However, the confirmation of the double donor character of the EL2 center would necessitate a revision of the measurements previously carried out about the EL2 level.

On the other hand, we have not found any dependence on the annealing temperature of the EL2 optical parameters which have been measured using the OITS technique. The quenching efficiency increase found from 1.35 eV, has been explained taking into account the variation of the σ_n^0 and σ_p^0 values corresponding to the EL2 level and the developed model. Also, the disagreement between the previous data reported by other authors and the theoretical model of the σ_n^0 has been eliminated by introducing the separation of the contributions of each level obtained using the OITS instead of standard photocapacitance or DLOS.

However, in spite of the agreement between the model developed and the experimental results, more experimental details are necessary, especially the use of different starting GaAs materials and processes, in order to obtain an exact assessment of the electrical and optical properties of the EL2 center. Nevertheless, the results reported are in agreement with those recently reported by J. Lagowski *et al.*[5] using p-type bulk GaAs.

ACKNOWLEDGMENTS

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