Bistable Photogenerated Effects in Low Resistivity GaAs

W. V. Machado, A. F. S. Landim and M. A. Amato
Departamento de Física, Universidade de Brasília
70910-900, Brasília, DF, Brazil

Received July 21, 1995

The photo quenching effect (PQ) followed by an anomalous quenching of the dark current after illumination with strong broad and/or monochromatic light in the range 0.1eV to 1.5eV in low resistivity GaAs was observed. The presence of a 0.2eV level below the conduction band which controls the dark conductivity was noticed. After the illumination the control is taken over by a deeper level, which was estimated to be around 0.3eV below the conduction band. The following time constants were studied: (i) the transient decay for the photocurrent while the light was still on, (ii) the decay time after light removal which decayed well below the dark level, (iii) the recovery time to reach the dark level again. All of the three time constants exhibited the same activation energy dependence on the temperature, around 0.33 eV, but ranging about three orders of magnitude between them in a given temperature. Below 80K the relaxation time from the depleted state back to the normal one, can be as large as 10^{10} seconds, therefore the material behaved like a bistable switch. The main property involving the quenching of the dark current, does not seem to be fully reversible via illumination in the studied range of energy. The type of conduction also remained n-type during the quenched state.

I. Introduction

Although it is possible to show that an impurity introduced into a semiconductor gives rise to one or more levels into the bandgap, it is often difficult to identify the defect responsible for the observed states. For instance, the case of the dominant electron trap at 0.8eV below the conduction band in GaAs (which has been associated with the PQ phenomena) is very confusing. For a long time it has been associated with oxygen, though contested by Huber *et al.*[1]. These mid-gap levels, also believed to be associated to native defects, have been named EL2 family after Martin *et al.*[2]. Tanigushi and Ikoma[3], Lagowsky *et al.*[4], however, have identified a level, in GaAs which is also capable of exhibiting photopersistent effects, and called it EL20 and ELO respectively.

II. Experimental details

We have used boat grown low resistivity GaAs nominally doped with oxygen (2Ωcm) with room-temperature mobilities about 6000cm^2/Vsec, etchpit density of 10^3cm^{-2} and impurity concentration of about 10^{16}cm^{-3}. The material was obtained from Monsanto Co. All samples present the same behavior as far as the PQDC effect is concerned. The dark conductivity is n-type in all the temperature ranges studied, and does not change its nature unless the material is exposed to illumination with energies above 1.1eV, especially the band gap energy at low temperature. Four types of measurement are carried out: i) Small signal AC spectral photoconductivity between 40K and 300K; ii) DC Photoconductivity in the same temperature range; iii) Photo- Hall and spectral Hall-photoconductivity; iv) Thermally Stimulated Conductivity (TSC). The AC photoconductivity measurements were carried out using standard lock-in techniques in a system with a rock salt prism monochromator operating in the visible-IR range, together with a 100Watt secondary tungsten light source filtered to produce the spectral region 1-3μm. The Photo-Hall measurements were carried out using a 500 lines/inch diffraction grat-

ing monochromator blazed at 2μm and a superconducting magnet. The TSC measurements were carried out with standard techniques, but in our case with a low warming rate to avoid thermal shocks in the samples.

III. Results

Low resistivity samples containing oxygen and/or EL2 level impurities normally exhibit a photoquenching of the dark current (PQDC) when exposed to strong extrinsic exciting light in the range of 1.0eV - 1.4eV, at low temperatures (around 130K)[5]. When the exciting light is removed the conductivity falls to values well below the stable dark level characteristic of samples unexposed to light. Below 80K this quenched state can remain almost indefinitely, provided the temperature is kept constant. The ratio between the conductivity in the states prior to and after illumination depends very much on the temperature, the intensity, and the sample time exposure to light. It has also shown to be dependent on the energy of the exciting light. In order to take the sample from the stable state with no previous exposure to light at low temperature to the metastable one, it has been cooled down (about 1 00K) in the dark, and allowing for the thermodynamic equilibrium. Next the sample is submitted to illumination with light in the range of 1.0eV to 1.4eV. After a time Δt_1, of exposure to light the sample will be in a time varying photoconducting state due to illumination. Removing the light, we observe that the photocurrent falls to values well below to the values prior to illumination reaching its lowest value after a time Δt_2, which can be associated to the photoquenching of the dark current.

Letting the system undisturbed for a length of time Δt_3, the dark current will return to values similar to those prior to illumination. This cycle is completely reproducible at any temperature, provided one waits for the right Δt_3 that allows the system relax to its normal state. At low temperature, Δt_3 is too long to measure. The normal state can also be recovered from the metastable state by a temperature annealing above 130K. In Fig. 1 we have indicated Δt_1, Δt_2 and, Δt_3.

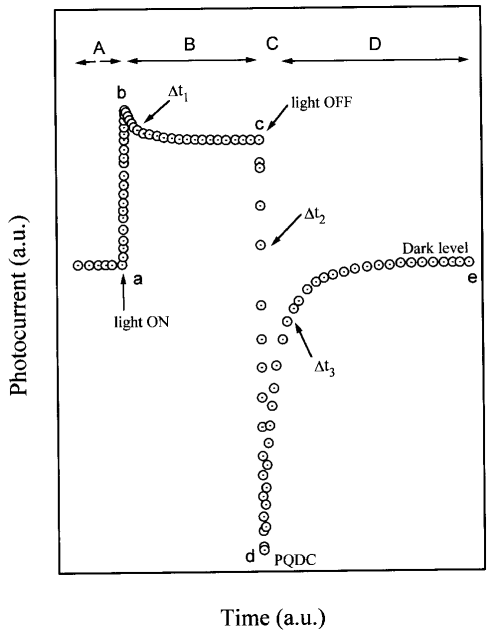

Figure 1. PQDC effect sketch (capital letters mean regions, otherwise points). (A) Sample in darkness before illumination. (a) - Light ON (Intense 100W Si filtered tungsten light). (B) Sample under intense illumination. (b) - Peak value of the photocurrent which decays to steady value after Δt_1. (c) - Light is turned OFF. (C) Photocurrent decays during Δt_2. (d) - The lowest value the photocurrent can reach named here PQDC state. (D) Recovery from the PQDC state (see text) during Δt_3. (e) - Recovery of dark level. The whole cycle is done always keeping the temperature constant. Time scale in regions (B) and (D) are about six and sixty times higher than in region (C), respectively.

In Fig. 2 we show the temperature dependence of the three time constants Δt_1, Δt_2 and, Δt_3 and can be noticed that they have the same activation energy of 0.33eV. From the temperature dependence of the carrier concentration (Fig. 3), one has an activation energy of 0.2eV below the conduction band prior to illumination, but after exposure to light it changes to 0.3eV.

The thermally stimulated conductivity measurements(TSC) shown in Fig. 4. were carried out using a slow warming rate in order to avoid the possibility of thermal shocks in the sample causing, for instance, a broadening on the response due to acoustic phonons. From the picture one can see that after illumination, the E_c-0.2eV level is absent or gives place to another level, claimed here to be E_c-0.3eV, which is not present before the illumination. As the temperature is raised, with a slow but constant warming rate, a large step-like response appears from a level somewhere about 0.3eV below the conduction band (open circles). The carrier type has been checked and found to be of n-type. A similar procedure carried out in thermal equilibrium with

no prior illumination presented no anomalous response, reproducing the normal thermally activated behavior characterized by an activation energy of 0.2eV. Fig. 5 shows the spectral photoresponse for four different situations. Using a 1.24eV light with chopping frequency of 62.5Hz, one can notice a large decrease in the photoresponse at 40K which we believe to be due to the large relaxation time associated with the PQDC effect. One can also notice in this picture, an extra photoresponse in the energy range 0.4eV to 0.7eV which tends to disappear for subsequent scans unless the material is reilluminated with the characteristic light. This extra photoresponse, we believe, can be associated to a population of holes at a set of levels above the valence band, but still under investigation. Finally, the spectral efficiency shown in Fig. 6 for creating the PQDC states agrees fairly well with those in the literature[6,7].

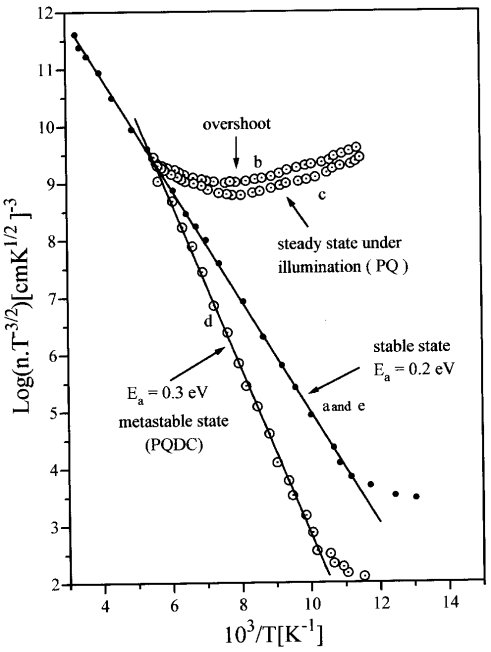

Figure 3. Arrhenius plot of the carrier density for the situation indicated in Fig. 1 by the points a, b, c and d. Curve (a) is related to the stable state without pre-illumination (heavy dots). Curve (b) is related to the highest photocurrent obtained when light is turned on. Curve (c) is related to the steady state photocurrent under illumination (i.e with light still on). Curve (d) is related to the lowest value for the current after illumination removal (open circles).

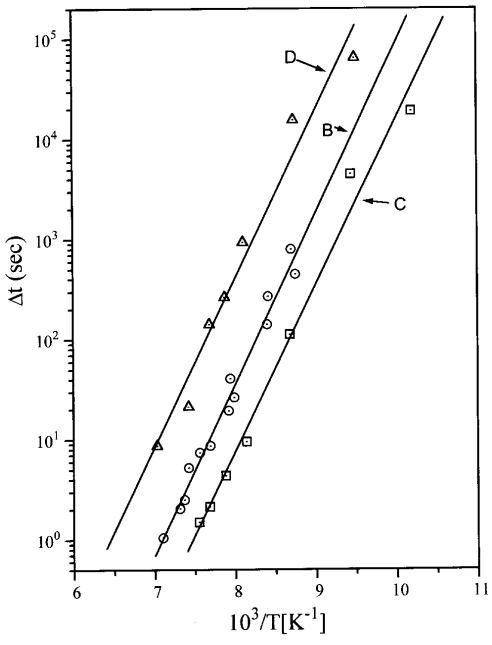

Figure 2. Temperature dependence for the transient processes Δt_1, Δt_2 and Δt_3 associated with the PQDC effect (labels on curves are related to Fig. 1). Δt_1 is the time interval associated with the photocurrent decay after light ON. Δt_2 is associated with the current decay after the light removal and Δt_3 is the current recovery time from the PQDC state. All these PQDC transient processes are thermally activated with a characteristic 0.33eV activation energy. Time constants are extracted from the exponential component of the transient currents.

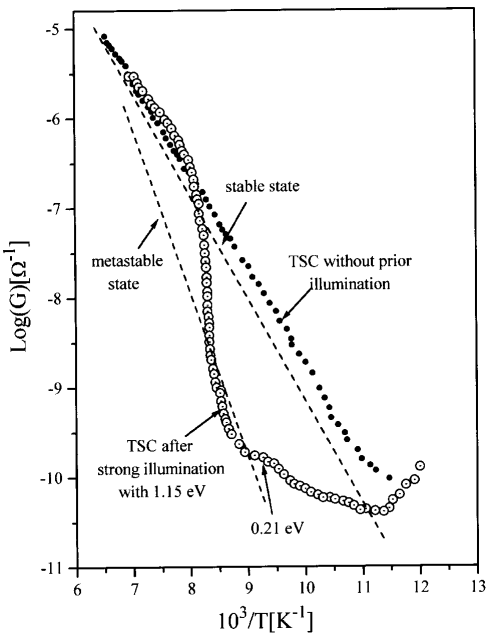

Figure 4. Thermally Stimulated Current (TSC). The quenched region is attributed to the absence of the level 0.2eV below the conduction band. The large step-like recovery is due to a flow of electrons coming from a level 0.3eV below the conduction band photogenerated during the illumination (region B of Fig. 1).

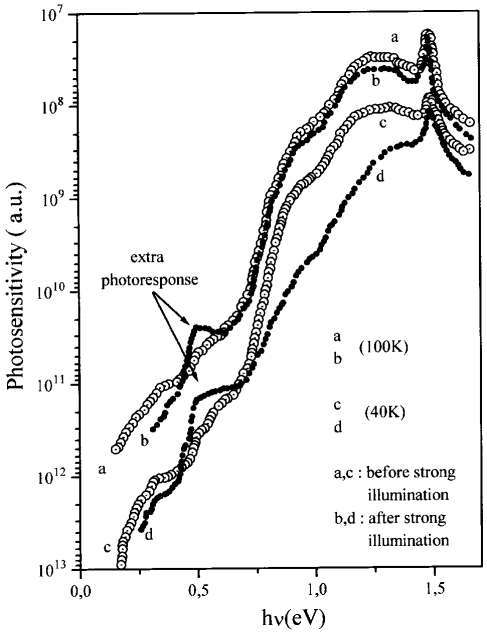

Figure 5. Photo-response as a function of photon-energy at 40K and 100K. (a) and (c) taken with no prior exposuse to light. (b) taken after intense exposure to illumination of 1.24eV during 5 minutes. (d) was taken after illumination for 60 minutes. Scans were carried out with a steady current even after illumination except for curve (d) because transient processes are too slow at 40K. Extra photo-responses on curves (b) and (d) are found to be related mainly to holes trapped into levels in the lower part of the band gap.

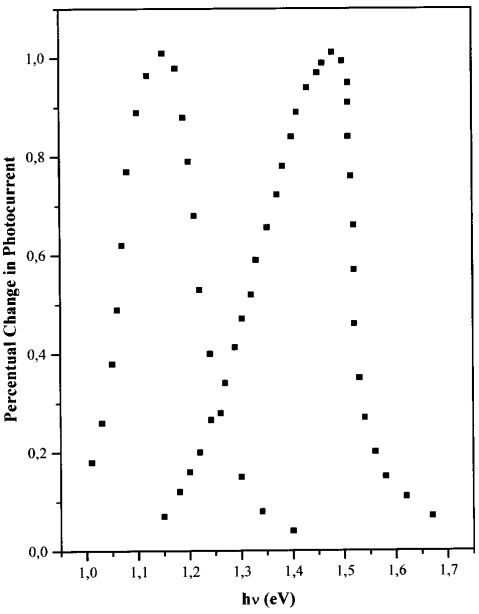

Figure 6. Percentual change of Photocurrent versus incident photon energy (eV). (l) Spectral dependence for the PQDC effect which peaks at 1.15eV. Data are collected in a DC current mode. (r) Spectral dependence for the extra photo-response (see Fig. 5). It peaks at 1.49eV. This time the measurements are obtained in a AC current mode by chopping the probing light to keep it in the small signal regime. Both processes can be excited simultaneously if broad illumination is applyed in the interval 1.1 eV to 1.5eV.

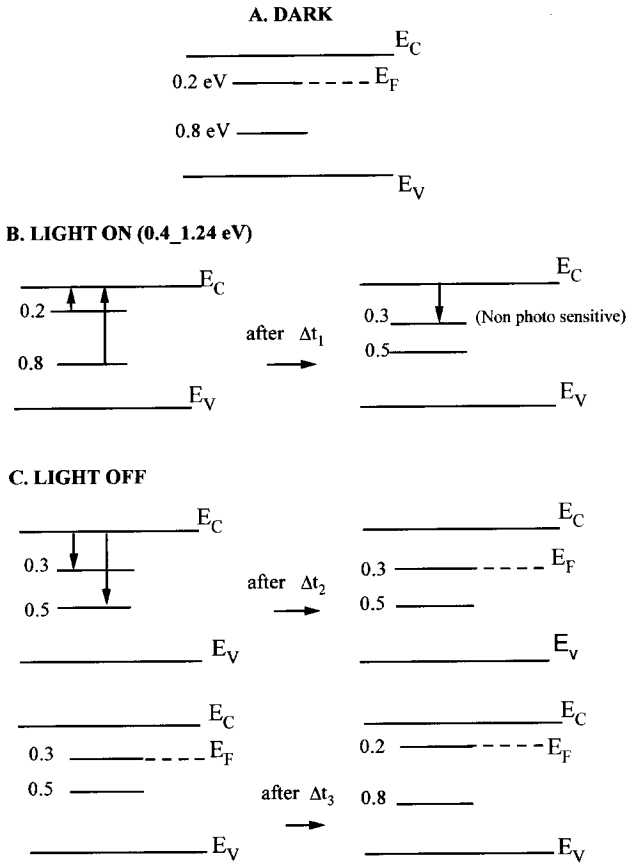

Figure 7. Model for the PQDC effect. (A) The system is in thermal equilibrium at low temperature (below 130K). Two levels characterize this stage: 0.2eV and 0.8eV. (B) Intense light (best around 1.15eV) empties levels 0.2eV and 0.8eV and transforms them into 0.3eV and probably 0.5eV respectively after Δt_1. The 0.3eV level is believed to be non-photosensitive because it is not seen easily in photoconduction scans, but controls the dark conductivity after illumination. (C) When the light is removed, levels are filled during Δt_2 accounting for the PQDC effect (see Fig. 1). After Δt_3 the system relaxes back to its stable configuration.

IV. Discussions

Our observations may be summarized as follows: (a) Activation energies of the dark conductivity "prior and after" illumination are 0.2eV and 0.3eV respectively; (b) All transient processes (Δt_1, Δt_2 and Δt_3) sketched in Fig. 1 are characterized by an activation energy of 0.33eV; (c) No "overshoot" is observed if the sample is reilluminated after Δt_1; (d) TSC measurements show the 0.2eV level absent after illumination and the 0.3eV level largely populated, but presenting a low optical cross-section; (e) A level populated by electrons about 0.5eV below the conduction band, is present in

the photo-Hall measurements. We therefore, propose a simple model which is suitable to explain most aspects of the photoquenching effect (Fig. 7). The model assumes the 0.8eV and the 0.2eV levels belonging to the same defect complex. Before the exposure to light, the 0.8eV level is completely full while the 0.2eV controls the dark conductivity. Light in the range 1.0eV to 1.4eV not only depletes the 0.2eV level, but also transforms it, via configurational rearrangements, into 0.3eV, which will dominate the dark conductivity. We suspect that somehow part of the 0.8eV levels are also transformed into probably 0.5eV, since this level appears mostly after strong exposure to illumination. One of the charge states turns out to be more occupied than the other during the illumination, while the second becomes fully occupied only when the exciting light is removed. These centers return to the stable state after the time interval Δt_3. The evidence for the 0.2eV to 0.3eV transformation while the sample is being illuminated is the overshoot ((region (B) of Fig. 1) which has a 0.33eV thermal activation energy. This affirmation is supported by TSC results (Fig. 4) which show the 0.2eV level absent and the 0.3eV appearing as a consequence of illumination. It can be concluded that one of the charge states becomes occupied during the illumination. Furthermore, when the system is at point (c) (Fig. 1) no more overshoot (region (B)) can be observed by further light exposure i.e., if the light is turned OFF and ON the system goes directly to point (c) without passing through (b). These arguments taken together suggest that the 0.3eV level has a small optical cross-section. In other words it is nonphotosensitive.

The relaxation from the metastable state back to the normal state can be processed after the time interval Δt_3 by either the thermal excitation of the 0.3eV electron followed by a configurational relaxation of the center or by a configurational relaxation while still doubly charged followed by the normal thermal emission of the electrons trapped at 0.2eV level. The first possibility, however, is more plausible since the later implies that the charge state transformation is equally probable at any temperature even in the absence of light, which does not agree with our observations. The state transformation possibly happens through a Coulombic action where the two main charged parts of the center become separated when both levels are empty and become close together when the 0.3eV level is occupied and the other is not. The separation or joining of the two center parts must then occur through a potential barrier, which is more difficult to overcome as the temperature is lowered. The light action will merely pump the system into the metastable state. When both states become occupied, after light removal, the metastable state will be held for much longer since it is doubly charged and hence has a repulsive nature. Fig. 2 shows that Δt_3 is more than an order of magnitude longer than Δt_1 and this is about an order of magnitude longer than Δt_2. This is shown in Fig. 2.

We are, naturally, assuming that the levels transformation is via configurational rearrangements inside complexes. To the authors' knowledge, the ones responsible for the PQDC effect, however, does not seem to fit all the properties expected for the EL2 centre as claimed for the majority of models published to date[8−10]. The present phenomena can only be understood if the center involved manages to accommodate two or more electrons without disrupting the metastabe configuration.

Whatever the centres responsible for the PQDC effect are, they seem to be different from the ones proposed for the EL2 centre and are probably more complex than those proposed so far. The results in the present research are more likely to support the model proposed by Wager and Van Vecheten[11−13] for oxygen or alike. The model proposed here does not aim to quantitative assesment of specific levels. It mainly aims to provide a conceptual framework for understanding and interpreting the experimental data.

References

1. A. M. Huber, N. T. Linh, M. Valladon, T. L. Debrun, G. M. Martin, A. Mitonneau and A. Mircea, J. Appl. Phys. **50**, 4022 (1979).
2. G. M. Martin, A. Mitoneau and A. Mircea, Electron. Lett. **13**, 191 (1977).
3. M. Taniguchi and T. Ikoma, Appl. Phys. Lett. **45**, 69 (1984).
4. a) J. Lagowski, D. G. Lin, T. Aoyama and H. C. Gatos, Appl. Phys. Lett. **4**, 336 (1984). b) Skovronski, J. Lagowski and H. C. Gatos, J. Appl. Phys. **59,** 2451 (1986).
5. R. A. Malinauskas, L. Ya Pervova and V. I. Fistul', Sov. Phys. Semic. **16**, 296 (1982).

6. V. Yu. Vorob'eV, I. Yu. Karkhanin, O. V. Tretyak, Phys. Stat. Sol. **36**, 499 (1969).
7. a) S. Nojima, J. Appl. Phys. **57**, 620 (1985). b) S. Nojima and H. Asaki, J. Appl. Phys. **61**, 1073 (1987). c) S. Nojima, J. Appl. Phys. **58**, 3485 (1985).
8. G. Vincent, D. Bois and A. Chantre, J. Appl. Phys. **53**, 3643 (1982).
9. M. Levinson, Phys. Rev. **B28**, 3660 (1983).
10. C. Delurue and M. Lannoo, Phys Rev. **B38**, 3966 (1988).
11. J. F. Wager, J. A. van Vechten, J. Appl. Phys. **62**, 4192 (1987).
12. J. F. Wager, J. A. van Vechten, Phys. Rev. **B35**, 2330 (1987).
13. J. F. Wager, J. A. van Vechten, Phys. Rev. **B38**, 10956 (1988).