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BEHAVIOUR OF SEMI-INSULATING GaAs ENERGY LEVELS

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Abstract. The behaviour of *EL2* intrinsic defect in the Semi-Insulated (SI) undoped and Cr-doped GaAs is studied by measuring the Dember effect short circuit current. Appropriate illumination with peak in the 1100 nm region results in the transition of the *EL2* state to its metastable one (*EL2*M). Of major importance is the Cr concentration, which is influencing the photoconductivity spectra, as in high concentrations its contribution in the photoconductivity overlaps the *EL2* contribution.

1. INTRODUCTION

The mid-gap electronic levels in GaAs have interesting and complex physical properties. The dominant native defect, known as *EL*2 center is directly linked with compensation mechanisms that lead to semi-insulating (SI) GaAs [1]. This center is known to undergo a photoinduced transition into a metastable state under suitable conditions [2,3]. The characteristic feature of the metastable state is the quenching of a number of physical properties such as the optical absorption [3], photoconductivity [4], photocapacitance [5,6], electron paramagnetic resonance (EPR) [7] and photoacoustic signals [8]. At low temperatures (<100K), the lifetime of the metastable state is quite long. The *EL*2 is usually present in samples grown by the liquid-encapsulated-czochralski (LEC) method at a concentration of about $N = 1–2 \times 10^{16}$ cm^{-3}. This center is known to contain at least an Arsenic antisite (As_{Ga}), and doubts still persist whether or not it is associated with other centers such as an Arsenic interstitial (As_{Ga}–As_i) or vacancies and the most recent structure proposed consists of a three-center-complex made by association of an Arsenic vacancy (V_{As}), an Arsenic antisite and a Gallium antisite (Ga_{As}) [1, 9]. The stable $EL2^{0/+}$ defect energy level is localized at around 0.75 eV below the conduction band [10] and photons with energy ≥0.7 eV are able to induce optical transitions to the bands. Besides these transitions, there are two subbandgap absorption bands superimposed, related to an intracenter absorption. Photons with energy between ~1.0 and ~1.3 eV induce transitions from the normal to the metastable state (quenching) and photons with energy between ~0.75 and ~1.0 eV induce the reverse transition, i.e., from the metastable to the normal state (recovery) [3]. The lifetime of the metastable state is affected by several factors, such as temperature [10], light [3,11] and electric field [12,13]. Dreszer and Baj [14] later demonstrated that the thermal recovery process is controlled by an acceptor state of the metastable *EL*2 which is resonant with the conduction band.

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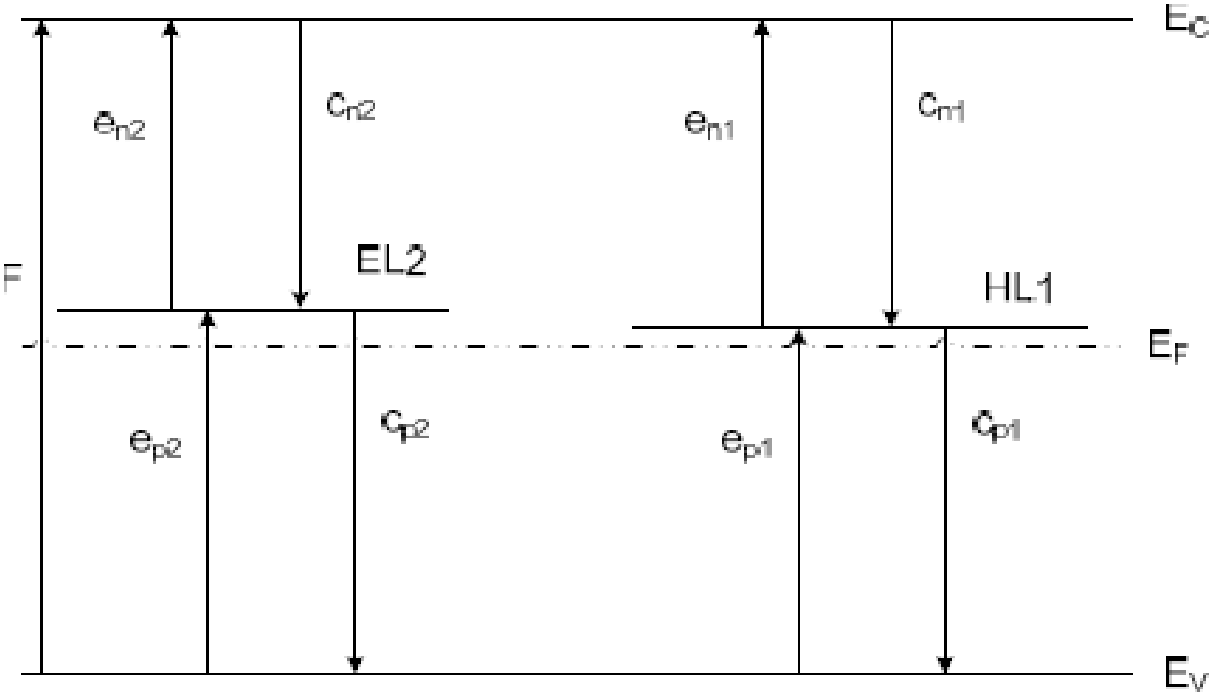

Fig. 1. Position of EL2 and HL1 in the GaAs band gap.

This acceptor state has also been found to participate in the very efficient recovery observed under visible illumination [11].

Finally, the stable level *EL*2 compensates the well known Cr doping level (*HL1*) [1,15], the latter has been used for several years to compensate native donors and produce semi-insulating (SI) material. The presence of the stable *EL2* and *HL1* levels in SI-GaAs was found to directly affect the room and low temperature extrinsic photoconductivity spectrum [16] and control the intrinsic photoconductivity through the SRH recombination process [17] (e_{ni}, e_{pi} the thermal emission coefficients and c_{ni}, c_{pi} the capture for electrons and holes respectively) (Fig.1).

The aim of the present work is to investigate the effect of the presence of the two levels *EL2* and *HL1* (Cr acceptor) on the extrinsic photoconductivity of SI-GaAs. Moreover, the aim is to study the effect of the concentration of *HL1* on the transition of *EL2* to its metastable state and the resulting photoconductivity spectrum.

In order to minimize the effect of increased photoconductivity and to determine the sign of the dominant photoexcited carriers the resulting photoeffects are studied through the Dember effect short circuit current. The experimental results reveal that the presence of Cr deep acceptor compensates the macroscopic photosensitivity of the material when illuminated with extrinsic illumination. Moreover, the increase of Cr concentration suppresses the presence of *EL2*, which transition to its metastable state is practically not detected.

2. EXPERIMENTAL TECHNIQUE

The effect of the intrinsic defect *EL2* in the presence of *HL1* has been investigated by measuring the short circuit Dember effect photocurrent generated under extrinsic illumination ($h\nu<E_g$) in the photons range of 0.82 - 1.37 eV (1500-900 nm). The monochromatic light was obtained by an ORIEL Optics 77250 monochromator from a 250 W halogen incandescent lamp. Semi-insulating GaAs, undoped and Cr doped were employed. Cr-doped samples with different concentrations (Cr5: 1-3x10^{16} cm^{-3} and Cr6: 0.5-1x10^{17} cm^{-3}) were grown with the LEC method. All samples were chemically treated in order to remove the surface native oxide and ohmic contacts were applied using high purity indium. The samples' temperature was controlled by the Compressor CS-202 Displex of the Air Products, in a closed cycle He cryostat and the measurements were performed in the temperature

range of 90 - 130K. The dependence of the transition rate of *EL2* from the fundamental to the metastable state was studied measuring the diffusion photocurrent with a Keithley 617 programmable Electrometer.

Before each spectrum measurement the sample was illuminated for 20 min with monochromatic light with increasing, every time, wavelength values in the region 900 - 1400 nm. The criterion of the chosen duration of illumination (5 min or 20 min) was to achieve transition of *EL2* to its metastable state. Finally, according to the experimental setup the measured current was positive when the diffusion of electrons was predominated and negative when the diffusion of holes was predominated.

3. THEORETICAL CONSIDERATIONS

When a semiconductor is illuminated with photons of energy lower than band gap the deep-level occupancy can be changed by the optically induced emission of carriers. If the deep levels are located close to mid-gap (Fig. 1), so that the probability of thermal release of trapped carriers can be neglected, the evolution of the occupancy of the level under illumination is given by the classical differential equation [18]

$$\frac{\mathrm{d}n_t}{\mathrm{d}t} = -\sigma_n^0 \Phi n_t - \sigma_p^0 \Phi (N_t - n_t), \tag{1}$$

where n_t is the concentration of trapped electrons in N_t traps, σ_n^0 and σ_p^0 the capture cross sections for optical transitions for electrons and holes respectively and Φ the photon flux. Under steady state conditions ($t \to \infty$) Eq. (1) leads to

$$n_t = N_t \frac{\sigma_p^0}{\sigma_n^0 + \sigma_p^0}. \tag{2}$$

In the case of a semi-insulating material like GaAs, with and without Cr doping, the change of carriers' population in the conduction and valence bands due to extrinsic illumination will be given by:

$$\Delta n = N_t \frac{\sigma_p^0 \sigma_n^0}{\sigma_n^0 + \sigma_p^0} \Phi \tau_n \quad \text{and}$$
$$\Delta p = N_t \frac{\sigma_p^0 \sigma_n^0}{\sigma_n^0 + \sigma_p^0} \Phi \tau_p. \tag{3}$$

Regarding the Dember effect, it arises from the photocarriers' diffusion due to non uniform generation and before their recombination. Because of the different mobilities of electrons and holes, the pair diffusion yields an electric field, called Dember field, and between the illuminated and dark surfaces of the semiconductor the Dember voltage appears. The Dember voltage can be short circuit externally and the algebraic sum of the electrons and holes diffusion currents can be measured in the external circuit [19]. This current can be derived by taking into account previous publications [19-23]. Adopting the procedure proposed in paragraph 3 of [19] and taking into account that the absorption coefficient is low for extrinsic illumination (αd<<1), which leads to a low contribution from surface recombination, as well as that the density of photo-generated electrons and holes is low compared to N_t, as shown in [17] even for intrinsic illumination ($h\nu > E_g$) we can derive an approximate equation for the Dember effect short circuit current arising from the contribution of the two levels (i.e. *EL2* and *HL1*) and measured in the external circuit:

$$J \cong \frac{qd\left(L_n^2 - L_p^2\right)\Phi e^{-ad}}{1 - e^{-ad}} \cdot \left(N_{t,EL2} \frac{\sigma_{p,EL2}^0 \sigma_{n,EL2}^0}{\sigma_{n,EL2}^0 + \sigma_{p,EL2}^0} + N_{t,HL1} \frac{\sigma_{p,HL1}^0 \sigma_{n,HL1}^0}{\sigma_{n,HL1}^0 + \sigma_{p,HL1}^0} \right). \tag{4}$$

Here, it must be pointed out that the two cross sections are mixed, so that it is impossible to deduce $\sigma_n^0(h\nu)$ and $\sigma_p^0(h\nu)$. So, the Dember effect short circuit current spectrum, obtained by continuous recording the current as a function of photon energy/wavelength, is a complex function of both cross sections and the trap concentrations.

3. RESULTS AND DISCUSSION

The Dember effect short circuit current, for the undoped material, as a function of the wavelength of the illuminating light for temperatures from 90 up to 130K is shown in Fig. 2a. The optical cross section of EL2 is shown in Fig. 2b.

In the undoped material the measured current was always positive. The spectra revealed three peaks corresponding to energies of 0.90 eV (1378 nm), 1.09 eV (1137 nm), and 1.22 eV (1016 nm). A comparison of the present work data with the ones reported in [18] (Fig. 2b) indicate the peaks correspond to the transitions from the *EL*2 level to Γ, *L*, and *X* minima (Fig. 2b). Comparing the data it seems that the transition *EL*2 $\to \Gamma$ is somehow overestimated while the transitions to *L* and *X* are in good agreement. The low illumination intensity

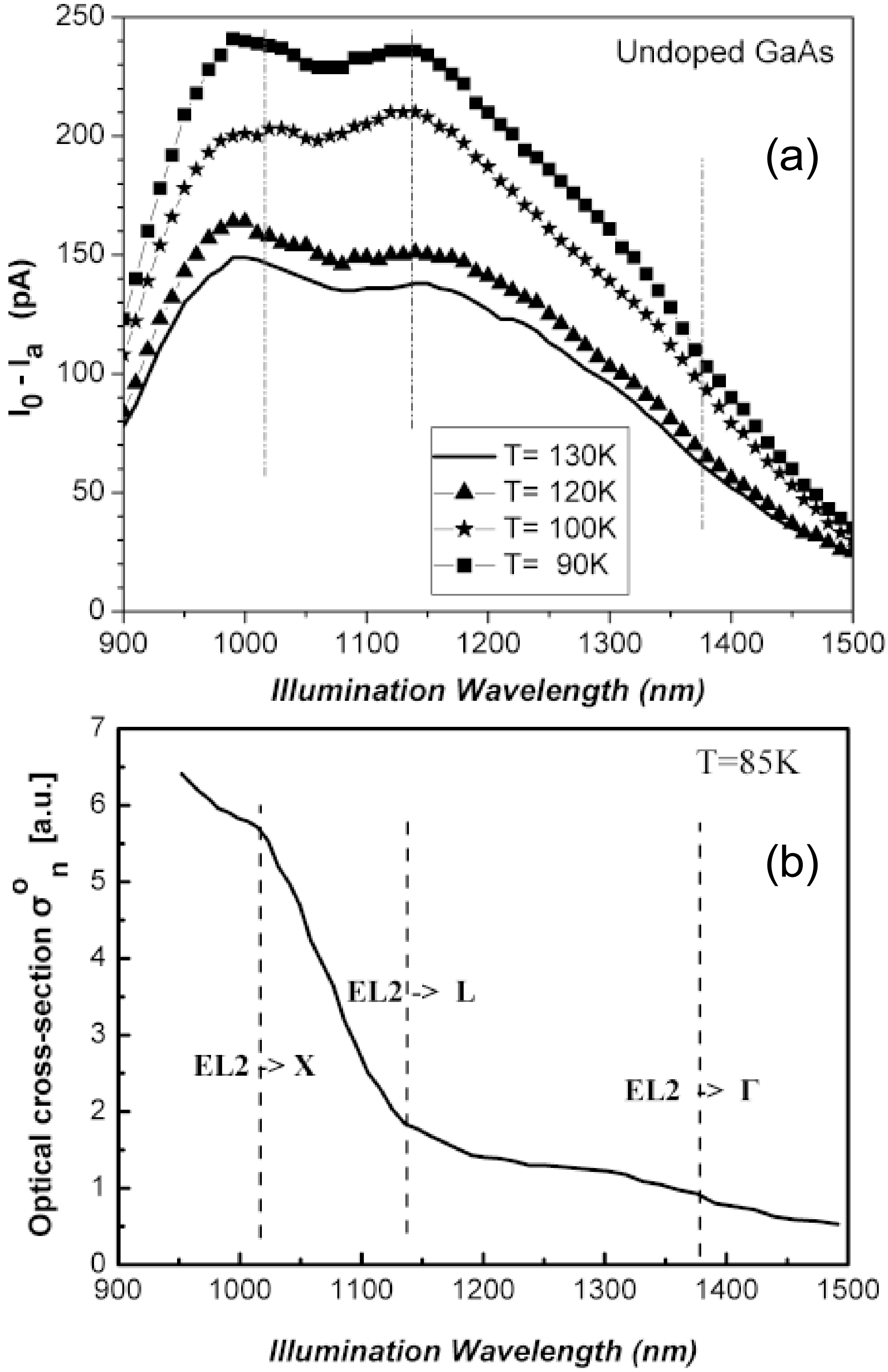

Fig. 2. (a) Diffusion photocurrent for the undoped GaAs (1.22eV, 1.09eV, and 0.90eV); (b) optical cross section for EL2, replotted from [18].

did not affect the spectra and there was no transition from *EL*2 to its metastable state at temperatures below 120K (Fig. 2a).

The introduction of Cr acceptors (Cr5 material) changes the current spectra dramatically. Fig. 3 shows that in the low photon wavelengths regime

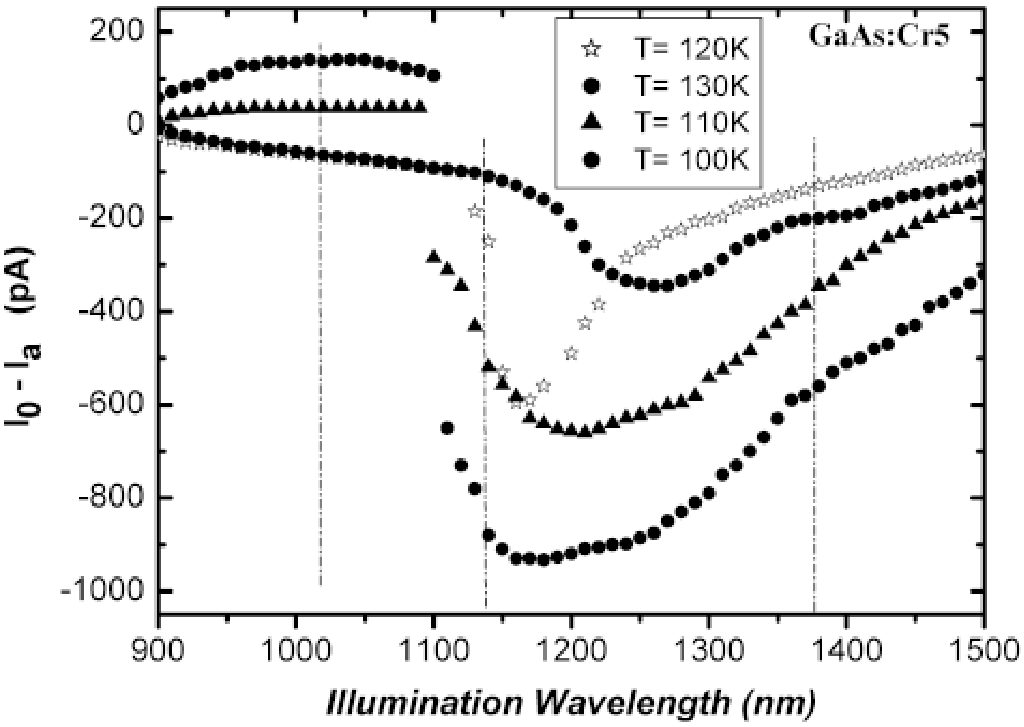

Fig. 3. Diffusion Photocurrent for GaAs:Cr (Cr5 material).

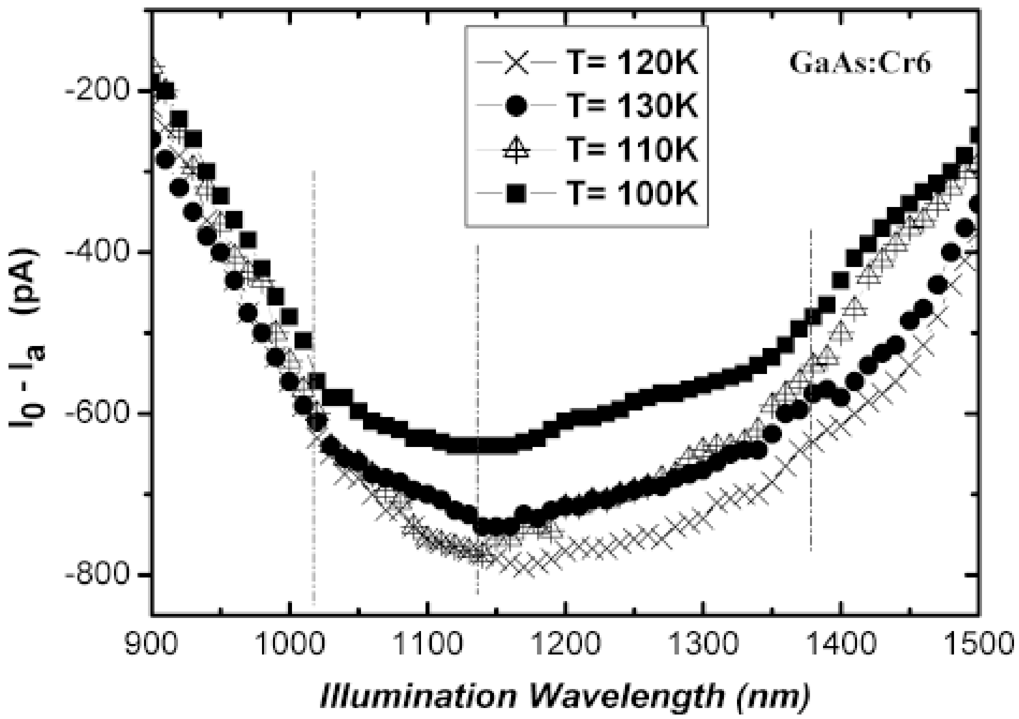

Fig. 4. Diffusion Photocurrent for GaAs:Cr (Cr6 material).

the current arises from holes diffusion. The Dember current is negative in the long wavelength region and changes polarity at about 1100 nm. Below this wavelength the current is positive. This behaviour arises from the differences between the capture cross sections for holes transition from valence band into *EL*2 and *HL*1 (Cr) levels and electrons transition from *EL*2 and *HL*1 levels to the Γ, *L* and conductions bands [24]. More specifically the structure with the negative photocurrent value is attrib-

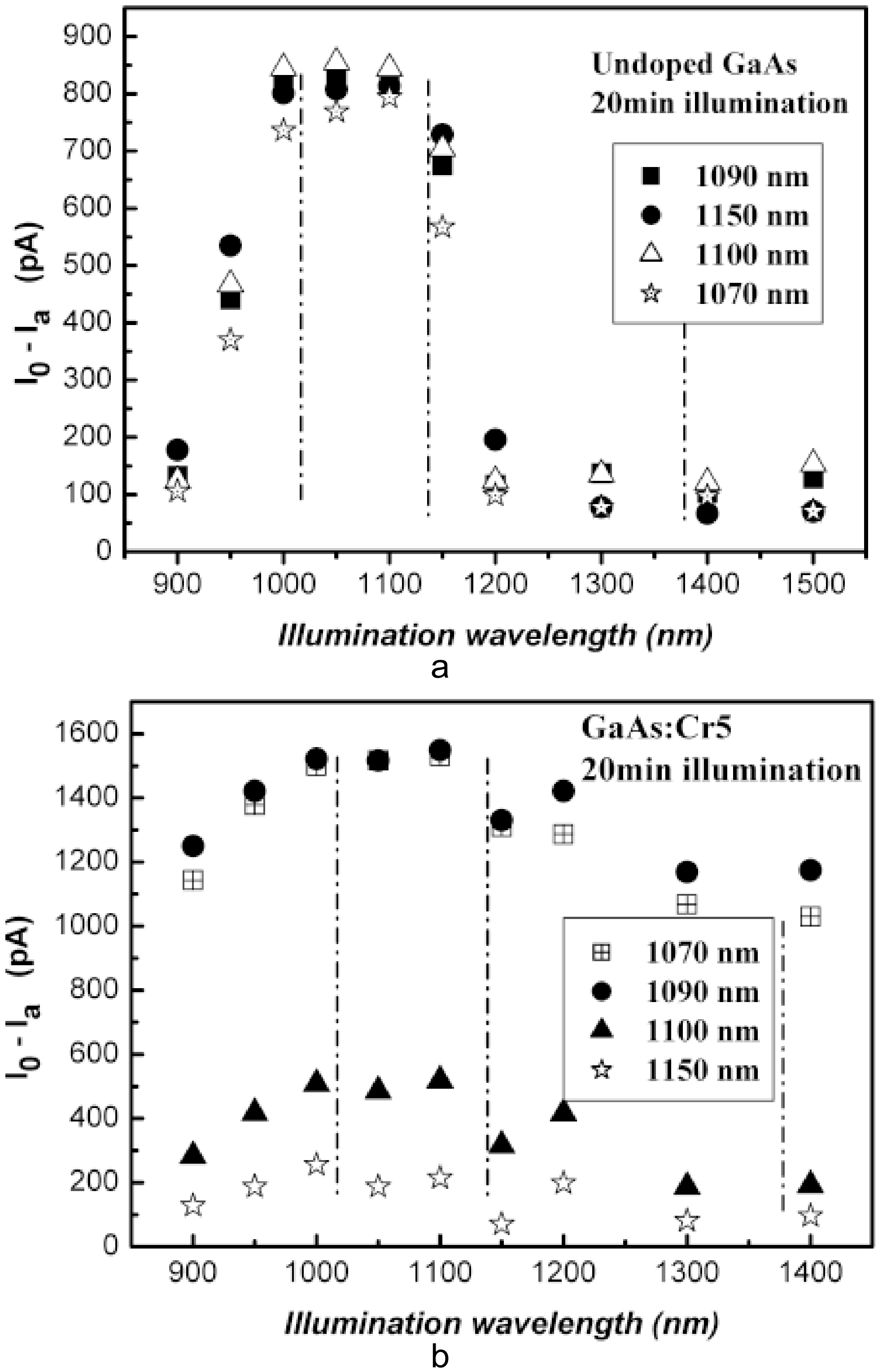

Fig. 5. (a) $\Delta I(\lambda)$ for the undoped GaAs;(b) $\Delta I(\lambda)$ for GaAs:Cr (Cr5 material).

uted to holes transportation from Cr^{3+} to the valence band (0.96 eV) [25]. Another feature, shown in Fig. 3, is the sensitivity of the Dember effect current to small changes in *EL*2 concentration. The negative peak in the range of 1200 nm changes magnitude and position when the sample temperature is increased from 100K to 130K. This has to be attributed to the fact that at low temperatures part of *EL*2 are transferred to the metastable state and the ratio of *HL*1 to *EL*2 levels increases, thus holes transitions are advantaged. When the temperature is increased *EL*2 recovers from its metastable state and the holes transitions are compensated from those of electrons from the *EL*2 states. The peak shift has to be attributed to the different spectral response of optical cross sections.

Finally, in the Cr6 material (Fig. 4), due to large concentration of Cr the contribution of the *EL*2 level according to Eq. (4) is fully suppressed. So, Cr appears to practically determine the electric properties of the material.

The effect of the presence of Cr acceptor (*HL*1) on the sensitivity of semi-insulating GaAs to the *EL*2 transitions to its metastable state has been investigated by measuring the difference $\Delta I(\lambda) = I_0(\lambda) - I_a(\lambda)$ as a function of wavelength, where $I_0(\lambda)$ and $I_a(\lambda)$ are the diffusion photocurrents before and after continuous illumination with wavelengths from 900 nm up to 1400 nm with steps of 50 nm and 20min illumination. The difference $\Delta I(\lambda)$ is plotted in Figs. 5a and 5b for the undoped and Cr5 materials. The data from Cr6 material are not presented since as shown in Fig. 4 there is no contribution from the *EL*2 level and the differences are within the level of noise.

Fig. 5 shows that in both materials $\Delta I(\lambda)$, is positive. This is due to the fact that with the transition of *EL*2 to its metastable state, its contribution in electrons to the conducting band stops, while the contribution by any other level is not influenced perceptibly. Consequently Figs. 5a and 5b represent in fact the "clear" electron contribution of the *EL*2. The greatest change appears in the 1100 nm region [2,26,27]. Finally it must be mentioned that similar results have been obtained after 5 min illumination.

4. CONCLUSIONS

The effect of the presence of the two levels *EL*2 and *HL*1 (Cr acceptor) on the extrinsic photoconductivity of SI-GaAs has been investigated. The investigation has been performed by measuring the Dember effect short circuit current spectrum versus to extrinsic illumination. The effect of the concentration of *HL*1 on the transition of *EL*2 to its metastable state and the resulting photoconductivity spectrum revealed that the increase of Cr acceptor concentration masks the presence of *EL*2 and the resulting effects from the transition to its metastable state after prolonged illumination at 1100 nm at low temperatures. In materials with intermediate Cr concentration the photosensitivity is determined by both the *HL*1 and *EL*2. The Dember effect short circuit current changes polarity when the illumination wavelength changes from long to shorter wavelengths. In contrast for high Cr concentration the contribution from the *EL*2 donor is fully suppressed and the photosensitivity is directly affected by the deep acceptor. Finally, in all cases the current spectrum becomes more positive when the *EL*2 is transferred to its metastable state.

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