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Non-uniform Distribution of Deep Donor EL2-centres in Semiinsulating GaAs Plates*

The influence of inhomogeneities on photoelectric and optical properties of semiinsulating GaAs plates has been investigated by the comparison of light transmittivity, induced diffraction efficiency and photosensivity data. The variations of transmitted light intensity and diffraction efficiency over a plate area have been observed. This has been explained by non-uniform planar distribution of deep donor EL2 density, which causes more effective non-equilibrium charge carrier generation in EL2-enriched regions. PACS numbers: 78.50G, 81.70.

INTRODUCTION

For the production of high speed high frequency integrated circuits semiinsulating GaAs as a substrate material is to be used. However, as compared with silicon, very large scale of integration can hardly be achieved. One of limitations is relatively large local variations of electrophysical parameters over a GaAs substrate area. These substrates are usually cut and polished from single-crystal boules, which have considerable inhomogeneity, both radial and longitudinal. The inhomogeneity arises due to thermoinduced stresses when the boule is cooled after its crystallization and its external and internal temperatures are being different. Thus, macroscopic crystal imperfections emerge, which act as gettering agents for the point defects. Macrodefects in light emitting devices give non-radiative transitions and so significantly decrease light output and device reliability. According to [1], linear macrodefects (dislocations) do not affect significantly the parameters or general performance ability of integrated circuit. However, in most cases the

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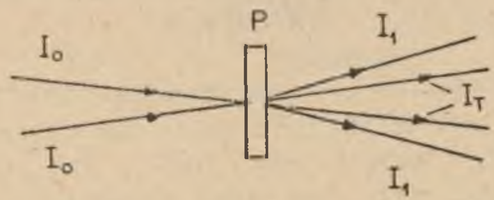

Fig. 1. Laser beam propagation in self-diffraction configuration: I_0 — two coherent beams, forming the grating within the volume of the sample P; I_T, I_1 — transmitted and diffracted beams, correspondingly

macrodefects are surrounded by the regions of higher density of point defects, latter ones being electrically and optically active [2–4]. It is known, that local electric properties of undoped semiinsulating GaAs samples are controlled by deep donors, which are commonly named as EL2-centres [5–7]. Their origin still is not clear, despite of numerous data concerning their properties. The EL2-centres also play significant role in determining GaAs optical properties in the near infrared range (photoquenching of luminescence and photoconductivity, absorption of IR radiation etc. [8, 9]). This fact is often used in modern methods of nondestructive, contactless testing of local electric properties of semiinsulating GaAs wafers, when the application of electric methods is limited by high resistivity of the material.

In this paper the electrically and optically active microdefects have been investigated from the viewpoint of their interaction with laser radiation. Laser light transmission and self diffraction have been studied in various regions of GaAs plates. Similar investigations were made earlier in other semiconductor materials [10–12], where the mechanisms of optical properties modulation were studied and nonequilibrium charge carrier parameters were determined. Therefore such experiments must be of interest in the case of GaAs. Here the results of these optical investigations have been compared with photoconductivity data in order to elucidate the mechanism of laser light interaction with different GaAs substrate regions.

EXPERIMENTAL METHOD AND RESULTS

Optical measurements were carried out using equipment, which has been made in Vilnius university and was described elsewhere [13]. As a light source a single mode Q-switched YAG laser was used (wave length $\lambda = 1.06$ μm, pulse duration $\tau_L = 14$ ns, pulse energy E up to 20 mJ). The measurement of light-induced diffraction efficiency η was performed using self-diffraction regime, where two coherent laser beams both create the grating and diffract on it (Fig. 1). By the measured intensities of incident light, transmitted and diffracted beams (I_0, I_T, I_1, correspondingly) the diffraction efficiency $\eta = I_1/I_T$ and sample transmittivity $T = I_T/I_0$ were determined. Local values of these parameters and their dependence on coordinate were obtained by the scanning of laser beams over the surface of GaAs plate. The grating period in our case was 30–40 μm, the area of excited spot <2 mm^2. The commercially available substrates of undoped or isovalent impurity doped GaAs, grown by Czochralski method, were investigated. Their

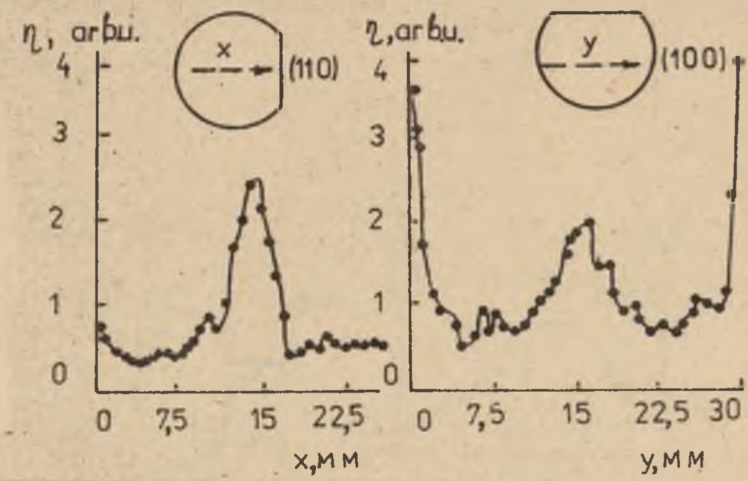

Fig. 2. Diffraction efficiency dependences on coordinate. Scanning directions on GaAs plate are shown above

Tab. 1. Parameters of GaAs samples from different plate regions

Parameter	Sample No, according to Fig. 3		
	1	2	3
Dark conductivity σ_0, 10^{-7} $(\Omega\cdot cm)^{-1}$	1.9	23	35
Maximum photoconductivity σ_{ph}, $(\Omega\cdot cm)^{-1}$			
at excitation $6\cdot10^{24}$ $cm^{-2}s^{-1}$	1.3	1.8	2.5
Photo-Hall mobility μ_H, $cm^2/V\cdot s$	3200	3070	2370

thicknesses were 0.3–0.6 mm, diameters 30–80 mm, dark resistivities $\rho = 10^6$–10^8 $\Omega\cdot$cm at 293 K, n-type conductivity (indicated by Hall effect).

Typical experimental diffraction efficiency dependencies on coordinate are presented in Fig. 2. Here plate area was scanned along two perpendicular diameters. Such curves, „W"-shaped as a rule, were obtained for all samples and all directions of plate diameters. In order to obtain more of information about the origin of such η distribution, some photoelectric parameters of three different plate regions were measured. For this purpose three rectangular samples were cut from a plate. Diffraction efficiencies in these samples were in a ratio approximately as 1:2:4,5 (Fig. 3). The photoelectric parameters of these samples at 293 K are presented below in Table 1.

The measured diffraction efficiency was compared with the light transmittivity of the same scanned region of the plate. Typical curves are presented in Fig. 4. Lux-diffraction characteristics at different temperatures $T_1 = 293$ K and $T_2 = 100$ K were measured for the regions of maximum and minimum of $\eta(x)$ values (see Fig. 4) and are presented in Fig. 5.

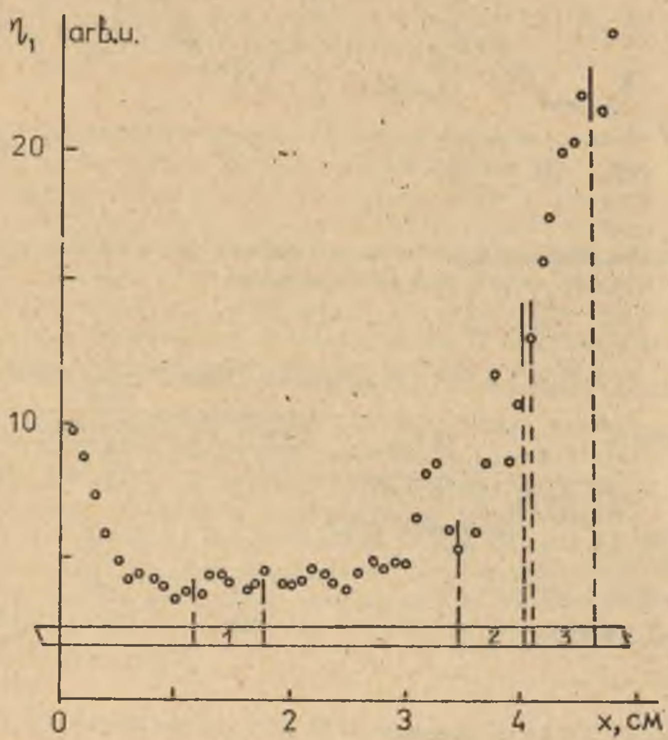

Fig. 3. Three GaAs samples 1, 2, 3 cut from a plate and corresponding regions of $\eta(x)$ dependence

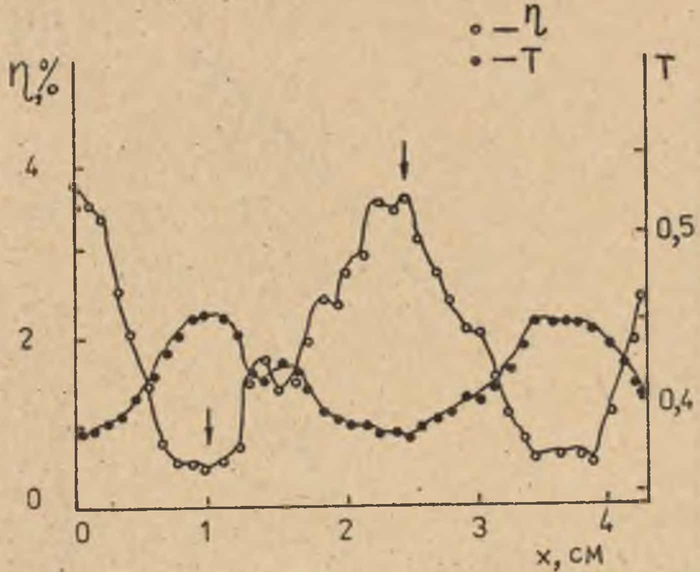

Fig. 4. Comparison of $\eta(x)$ and $T(x)$ curves. The points of $\eta(x)$ extrema for lux-diffraction measurements are shown by vertical arrows (see also Fig. 5)

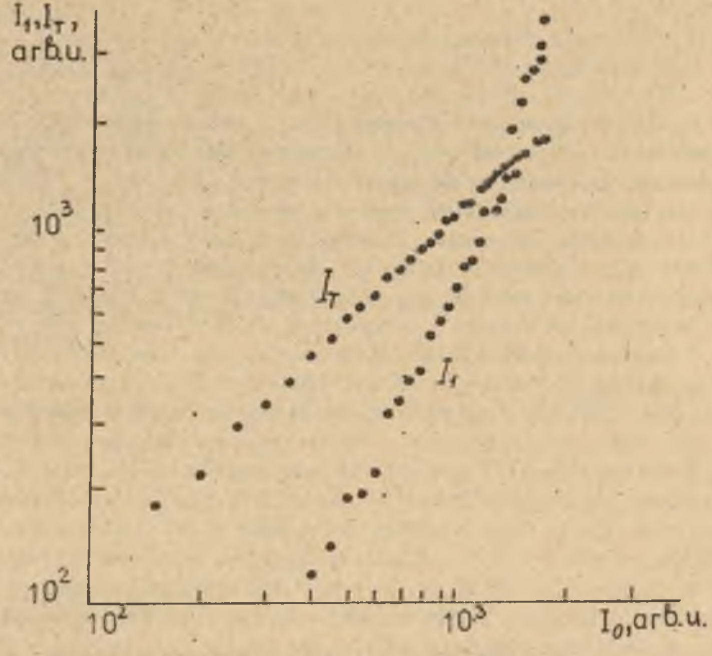

Fig. 5a. Lux-diffraction characteristics in $\eta(x)$ maximum region at 293 K

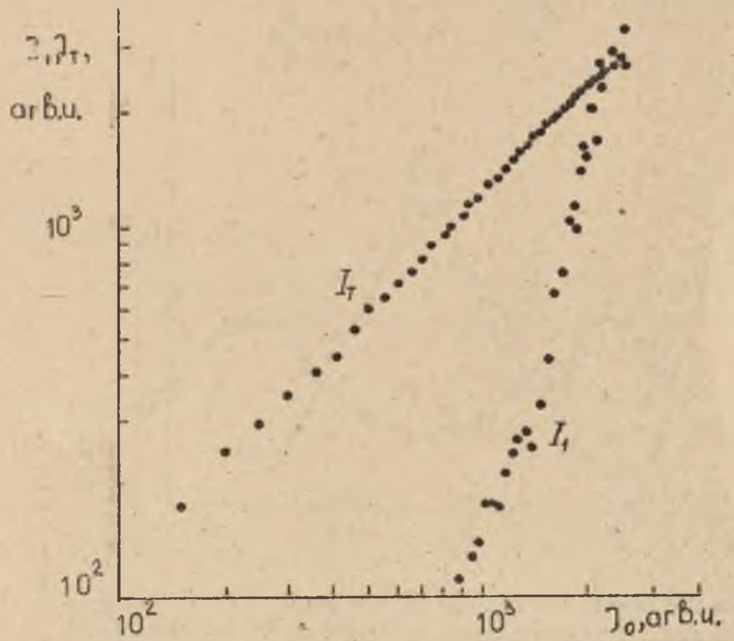

Fig. 5b. Lux-diffraction characteristics in $\eta(x)$ maximum region at 100 K

DISCUSSION

The results of Figs. 2–4 suggest, that inhomogeneities of semiinsulating GaAs substrate may be characterized by the local values of diffraction efficiency η, which may be considered as a relatively new parameter for the nondestructive GaAs testing. Similarly to earlier used parameters (photosensitivity, resistivity, dislocation density etc.) $\eta(x)$ dependencies have characteristic „W" shape. The mechanism which determines the observed local η values is to be elucidated and thus $\eta(x)$ dependencies are to be related to the distribution of some kind of crystal defects. Considering diffraction efficiency curve, one may see, that its extrema are situated in opposition to those of transmittivity curve $T(x)$ (see Fig. 4). Consequently, the larger the light absorption, the more effective is free electron-hole pair generation, and so is light-induced diffraction efficiency at corresponding points of GaAs plate. This is also in a good agreement with larger photoconductivity values of the samples, which are cut from the substrate regions with larger diffraction efficiency (see Fig. 3 and the Table 1). At low exciting light intensities I_0 the slope of lux-diffraction characteristic $\gamma_1 \approx 3$, but at high ones it becomes $\gamma_2 \approx 5$ (Fig. 5). However, upper points of the curve Fig. 5c seem to give again the slope $\gamma_1 \approx 3$, but it is not the case of Fig. 5a. At low temperature $T_2 = 100$ K the $\eta(I_0)$ values are several times lower than those at 293 K. Moreover, at 100 K the slope $\gamma_2 \approx 5$ is dominant and there is no $\gamma_1 \approx 3$ slope even at the highest light intensities. As the energy of incident light quanta 1.17 eV is less than the forbidden energy gap of GaAs, the generation of non-equilibrium charge carriers may occur due to either impurity, two-photon or two-step transitions [13]. Impurity-related absorption coefficient α_0, which has been determined experimentally in

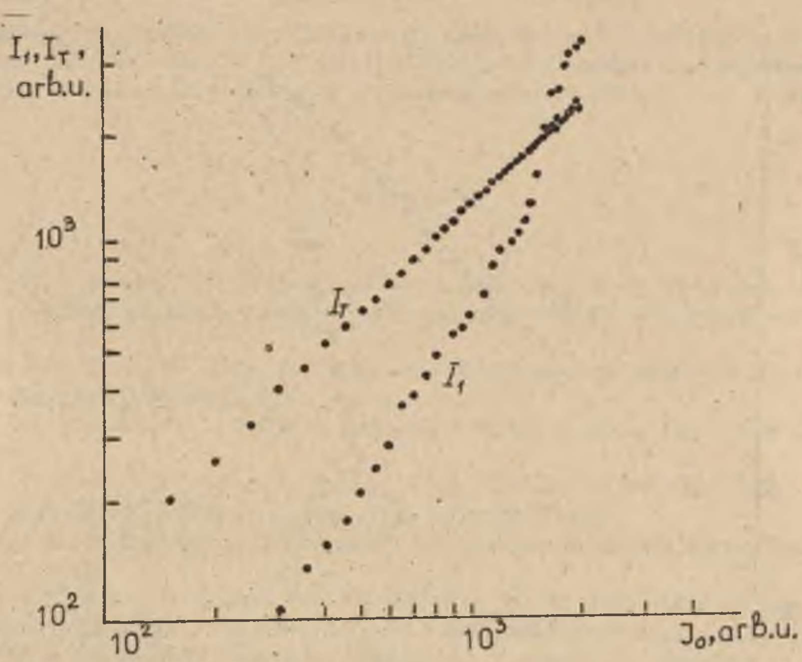

Fig. 5c. Lux-diffraction characteristics in $\eta(x)$ minimum region at 293 K

our case equals $\approx$ 6 cm^{-1}. The influence of two-photon processes on total absorption coefficient $\alpha = \alpha_0 + \beta I_0$ [14] for $\beta = 0.35$ cm/MW is significant only at incident light power >15 MW/cm, which was not achieved in our experiments. Thus, the square law of free carrier density dependence on I_0 and the corresponding slope $\gamma_2 = 5$ in the lux-diffraction characteristic can not be explained by the dominant two-photon absorption. The reason, which results the slope $\gamma_2 = 5$, may be understood if one assumes the possible two-step transitions between EL2-levels and both valence and conductivity bands. When neglecting recombination of charge carriers as well as their secondary trapping processes, the non-equilibrium electron density $\Delta\eta$ and EL2-level filling Δm may be expressed by exciting light intensity I_0, initial EL2-level density M and their equilibrium filling m_0 in the following way:

$$\Delta n = \frac{\sigma_p\sigma_n}{\sigma_p + \sigma_n}\int I_0 dt - \left(\frac{\sigma_p M}{\sigma_p + \sigma_n} - m_0\right)\frac{\sigma_n}{\sigma_p + \sigma_n}\{1 - exp[-(\sigma_p + \sigma_n)\int I_0 dt]\} \quad (1)$$

and

$$\Delta m = \left(\frac{\sigma_p M}{\sigma_p + \sigma_n} - m_0\right)\{1 - exp[-(\sigma_p + \sigma_n)\int I_0 dt]\} \quad (2)$$

where $\sigma n, \sigma p$ — photon trapping cross sections of the centres for free electron or hole generation, correspondingly [15].

At low I_0 values, $(\sigma_p + \sigma_n)\int I_0 dt \ll 1$ and (1), (2) give:

$$\Delta n = m_0\sigma_n\left(1 + \frac{M\sigma_p\int I_0 dt}{o^{2m}}\right)\int I_0 dt, \quad (3)$$

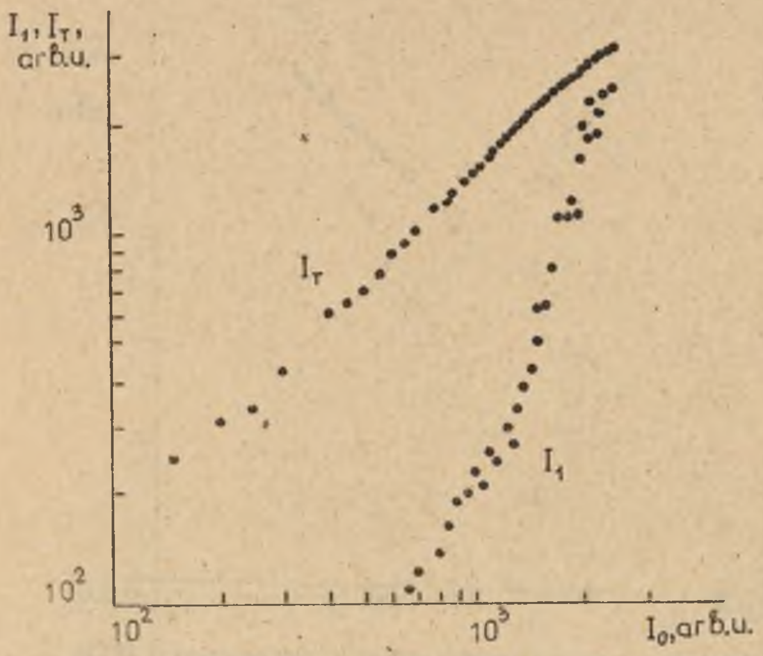

Fig. 5d. Lux-diffraction characteristics in $\eta(x)$ minimum region at 100 K

$$\Delta m = m_0 \left[\left(\frac{M}{m_0} - 1 \right) \sigma_p - \sigma_n \right] \int I_0 dt. \tag{4}$$

At high I_0 values, $(\sigma_p + \sigma_n) \int I_0 dt \gg 1$, therefore

$$\Delta n = M \frac{\sigma_p \sigma_n}{\sigma_p + \sigma_n} \int I_0 dt \tag{5}$$

$$\Delta m = m_0 \frac{(M/m_0 - 1)\,\sigma_p - \sigma_n}{\sigma_p + \sigma_n}. \tag{6}$$

It is seen, nonequilibrium charge carrier densities tend to the saturation values at increasing I_0 if two-step transitions are not taken into account. Conversely, two-step excitation ($\sigma_p \approx \sigma_n$) excludes the saturation — instead of latter one, a superlinear (square) region occurs in lux-diffraction characteristic, which further transforms into linear one at higher excitation level. When two-step processes take place by initially exhausted levels, then electron generation is proportional I^2_0 at first, and becomes $\sim I_0$ at higher I_0 values, where the filling of levels increases up to its saturation. The greater the initial level filling, the less is the region of I_0, corresponding to square charge carrier density dependence on exciting level. This is in agreement with the experimental data, when temperature drops from 293 to 100 K (curves Fig. 5a with 5b, and 5c with 5d are to be compared). The transition from the slope $\gamma_2 = 5$ to $\gamma_1 = 3$ in Fig. 5c at the highest I_0 values allows us to conclude, that the filling of EL2-levels becomes saturated, because their density is small. This is not the case of Fig. 5a — there EL2 density is maximum. Thus, experimentally observed $\eta(x)$ dependencies (Figs. 2–4) may be explained by non-uniform distribution of EL2-type levels over the plate area. This distribution depends upon a plate production technology. As the defects of EL2-family are most important in determining of semiinsulting GaAs properties [15], the method of light-induced gratings may be useful for the nondestructive contactless testing of this semiconductor material.

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