DEFECT-RELATED CARRIER TRANSPORT PECULIARITIES IN LEC-GROWN SEMI-INSULATING AND HEAVILY-DOPED GaAs CRYSTALS

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Abstract

Nonlinear optical techniques based on light diffraction on transient free carrier and photorefractive gratings are used to study growth-defect governed carrier generation and transport properties. The sensitivity of those nondestrutive techniques for monitoring dislocation/EL2 distribution in SI GaAs and direct determination of carrier mobilities/lifetimes in heavily doped GaAs is demonstrated.

1. Introduction.

Fabrication of semiconducting materials and structures with special parameters for micro- and optoelectronics requires development of fast, sensitive, nondestructive measurement techniques, in addition to well-known but expensive and destructive analytic instruments. Many innovations in this novel field are based on achievements in nonlinear optical spectroscopy of semiconductors, when light induced modulation of refractive or absorptive index of semiconductor via photothermal or photorefractive mechanisms, resonant exitonic or free carrier based effects are used. The basic ideas concerning bulk semiconductors and structures and state-of-art in this novel field of spectroscopy are reviewed in number of recent publications [1-3].

Control of quality of the wafer in its initial stage (so called "input control") and after different technological processing (e.g. ion-implantation, irradiation by fast particles, photonic-, laser- or thermal-annealing, gettering of defects) is becoming a normal procedure because it may predict the performance of fabricated devices. In addition, spatially resolved measurements in plane of a wafer (x-y coordinates) will show defectness or electrical homogeneity of a crystal (i.e. distribution of dopants, radiation or growth-defects) while those measurements across the thickness of structure (z-coordinate) will provide information concerning surface quality, defect or impurity profiles, carrier transport across barriers, etc).

Thus, measurement and analysis of the amplitude and dynamics of optical response may give directly the information concerning electrical parameters of semiconductor, as free carrier concentration, mobilities, lifetimes, properties of defects, their spatial distribution and modification by a technological treatment.

In this paper we will review some applications of nondestructive transient grating (TG) techniques for characterization of bulk semiconductors. This technique is based on light induced modulation of refractive index by free carrier concentration (Drude model) or by light induced space charge field (via electro-optic effect). Correspondingly, the gratings are called free carrier (FC) grating or photorefractive (PR) one. The case of coexisting FC and PR gratings and its application for the sensitive control of growth-defects in GaAs wafers will be shown.

2. Transient Grating Technique and Samples

In a case of spatially modulated excitation field (e.g. interference field of two laser beams), the properties of medium are spatially modulated as well. This light induced nonstationary periodic structure of excited states is called dynamic (transient) grating, and its modulation depth and decay rate are reflected in diffraction characteristics [1]. The main characteristics revealing optical and photoelectrical properties of a semiconductor are the following [4]: (i) the exposure characteristic, i.e. the dependence of diffracted beam intensity I_1 on excitation energy I_0, where the ratio of diffracted and transmitted probe beam $\eta = I_1/I_T$ is called diffraction efficiency of the grating; (ii) the kinetics of grating decay $\eta(t)$ which gives directly grating erasure time τ_e at fixed grating period Λ, which is easily changed by monitoring angle θ between interfering beams or their wavelength λ, thus $\Lambda = \lambda/\sin\theta$.

The simplified relations between diffraction efficiency of FC grating $\eta = [(\pi/\lambda)(\Delta N d)]^2$ (here d - sample thickness)and light induced carrier concentration modulation depth $\Delta N = N_{max} - N_{min}$ allows one directly measure light induced carrier concentrations. In a similar way light induced internal electric fields E_{sc} may be obtained from PR grating diffraction efficiency [1]. From $\eta(t)$ decay at known grating period carrier diffusion and recombination parameters are estimated. Variation of grating period will change the role of carrier diffusion in grating decay, while change of excitation power will lead to different carrier generation mechanisms: from deep traps, two-step and two-photon absorption.

Different configurations of TG technique and wavelengths may be chosen to reach the goal. In the given work for investigation the bulk properties of GaAs crystals, the samples were excited by weakly absorbed beams with quantum energy below band gap. As a light source, we used Q-switched or mode-locked pulses of YAG-laser with pulse duration of 10 ns or 30 ps correspondingly. Output energy was up to 2-5 mJ in the single pulse. Using ns pulses, we realized so called self-diffraction regime, when two beams were recording FC grating and synchronously diffracted by it. In this case the diffracted beam is spatially separated from probe beam and gives very high signal-to-noise ratio. Using ps pulses, carrier lifetime and diffusion coefficients have been measured from time-resolved measurements of TG decay, using the delayed probe beam. In both cases, the energies of incident I_0, transmitted I_T and diffracted I_1 beams are measured by silicon photodiodes and recorded in data processing system with programmable microcomputer. The averaged values of 20-40 measurements at each point allowed us to measure linear signals (incident and transmitted beams) within error bar of 0.2% and diffracted beam - within 1% error bar.

The samples used were LEC-grown GaAs wafers (001-cut, both side polished) with different density of dislocations (N_D) and free carrier concentration (N_{FC}):(i) semi-insulating In-alloyed wafers with $N_D= 5 \cdot 10^4$ cm^{-2} in the central part and (ii) heavily doped n-type wafer with $N_{FC}=1 \cdot 10^{18}$ cm^{-3} and $N_D=2 \cdot 10^3$ cm^{-2}.

3. Semi-insulating GaAs wafers

Light self-diffraction on transient FC grating technique revealed the regions with different dislocation densities via variation of diffracted beam intensity across the semi-insulating wafers. The EPD distribution in KOH-etched samples correlated well with the diffracted signal (Fig. 1) and confirmed the applicability of TG technique for nondestructive mapping of growth-defects. The correlation coefficient between the data obtained by two differnt techniques varied from 0.65 to 0.82 in th different samples. The full correlation is not expected because EPD data correspond to area of 0.3 mm^2 at the surface, while light integrates defects in the laser beam cros-section ($\propto$ 1 mm^2) and across the sample thickness.

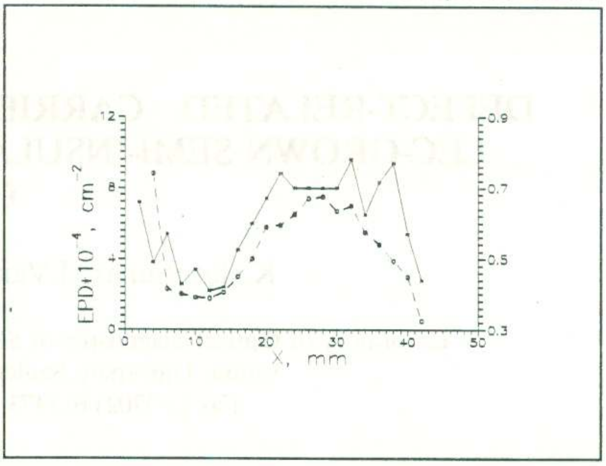

Fig.1. Dislocation density distribution in SI GaAs, revealed by selective etching technique (solid line) and by light diffraction on TG (dashed line).

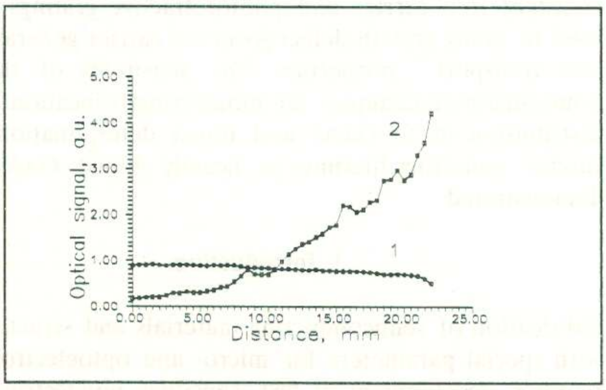

Fig.2. Variation of sample transitivity I_T (curve 1) and diffraction efficiency η (curve 2) in In-alloyed GaAs sample.

The scanning of the sample by interference field of two crossed beams, we measured the distribution of transmittivity and difffraction efficiency in In-alloyed GaAs. The comparison of variations of those data (fig.2) has shown quite small changes of sample transitivity I_T (within 5-10 % across the sample) but the essential variation of diffraction efficiency η (by order of magnitude). This correlation pointed out that light absorption at 1.06 µm is photoactive and reveals deep EL2 trap assisted carrier generation [5]. The effective carrier modulation is amplified via light diffraction in nonlinear way and leads to very high sensitivity of TG technique for monitoring of growth-defects. Thus, the homogeneity of GaAs wafers can be easily controlled in nondestructive way by using the simplest arrangement of photo-diffractive techniques, i.e. light self-diffraction configuration [5].

Time-resolved studies of carrier dynamics have been carried out in two distinct areas of the given GaAs sample with the different dislocation densities. Bragg-gratings with spacing $\Lambda = 1.8\ \mu m$ have been recorded by 30 ps-duration pulses. Four-wave mixing configuration with polarization sensitive read-out optical scheme was used to separate contributions of co-existing FC and PR gratings [6]. We have found that decay times of FC grating are efficiently affected by light-created SC electric fields (Fig.3).

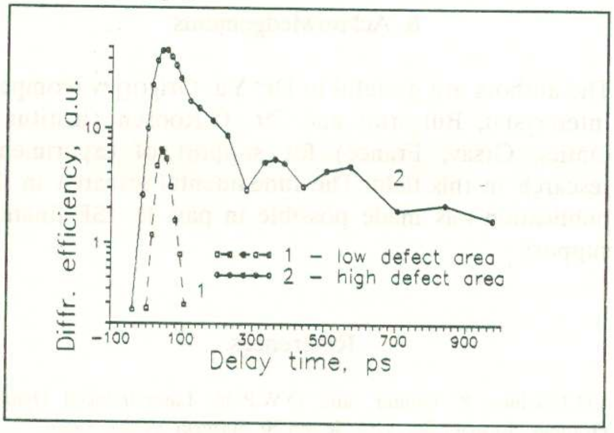

Fig.3. FC grating decay in two areas with high and low growth-defect density of SI GaAs.Excitation level- 1 mJ/cm^2.

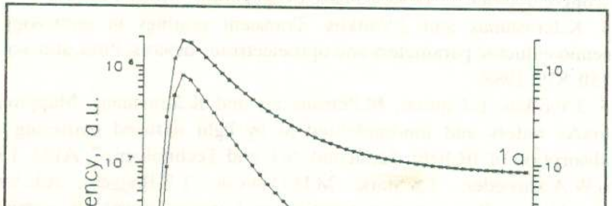

Fig.4. Computer modelization of electron and SC field dynamics in GaAs with deep trap EL2 density $N_T = 1{\cdot}10^{16}$ cm^{-3} (a) and $N_T = 5{\cdot}10^{15}$cm^{-3} (b); 1-diffraction on electron grating, 2-light-induced SC electric field. Excitation power - 2 mJ/cm^2. Ratio of ionized donors N^+ to total density N_T is 0.2 in high defect area and 0.5 in low defect area [10].

In the area with high defect density, electron generation from donor traps dominates, and SC electric field via electron diffusion is created at low excitations. This field opposes the initial diffusive decay of FC grating, until drift current compensates diffusive one. Finally, free carrier modulation and SC fields decay by carrier recombination (see Fig. 3, curve 1) with $\tau_R = 1.5$ ns. If defect density is low, the bipolar carrier generation dominates; then SC electric field is weak, and FC grating decays by ambipolar diffusion. For given experimental arrangement the latter time $\tau_a = 43$ ps leads to bipolar diffusion coefficient $D_a = 18.8$ cm^2. At high excitation levels, two-photon absorption of light dominates over deep trap related one, and the initial parts of decay curve are independent on defect density: in both areas gratings decay by ambipolar diffusion.The SC internal field between ionized donors and electrons determine the slow decay and do not differ significantly.

Thus, the role of the internal electric fields may be very effective and depends on defect density and excitation level. This observation opens novel possibilities to optimize TG technique for even more sensitive control of defect distribution in GaAs wafers or related compounds. Numerical calculations of carrier and field dynamics using a set of material equations [7] have confirmed the observed peculiarities (see Fig.4 and ref.[8]).

We would like to note, that by varying power of grating recording beams it was possible to observe carrier transport at different N/P ratio, i.e. from quasi-monopolar carrier generation (N>>P) up to pure ambipolar case at N=P. At low excitations hole mobility was estimated from time-resolved FC or PR decay [9]. In this way, using experimental data of μ_a and μ_p, electron mobility $\mu_n = 5200$ cm^2/V·s was calculated in SI GaAs [9].

4.Heavily doped GaAs

Using short ps pulses and four-wave mixing set-up, time-resolved decay of FC and PR gratings have been measured in heavily doped GaAs wafer with given electron mobility $\mu_n = 2500$ cm^2/V·s. The decay of FC gratings at some fixed excitation levels (Fig.5) reveals varying with excitation grating decay. At low excitations, FC grating decay is due to carrier recombination with $\tau_R = 1.5$ ns, and fast initial component arises with increasing the excitation. Subtraction of slowly decaying component τ_R from the fast one $\tau_{11} = 300$ ps leads to the real time of the first decay component $\tau_{1*} = 170$ ps. Assuming high doping level (N>>P), we attributed this fast ,component to diffusion of minority carriers (holes) and calculated their mobility $\mu_p = (\Lambda/2\pi)^2(e/kT\tau_{1*}) = 190$ cm^2/V·s. At higher excitations (curves 2,3), the initial diffusive decay time τ_{21}= 240 ps and τ_{31}=105 ps correspond to higher carrier effective mobilities (μ_{eff}=270 cm^2/V.s an μ_{eff}=310 cm^2/V.s). The latter values indicate that the observed mobilities are still below of estimated bipolar one μ_a=350 cm^2/V.s for case N=P. The other explanation might be that the electron mobility in fact is lower than the given one in the sample certificate. In the latter case, the descrepancy between the measured and expected values of μ_a may be caused by effective value of homogeneous area in the crystal.

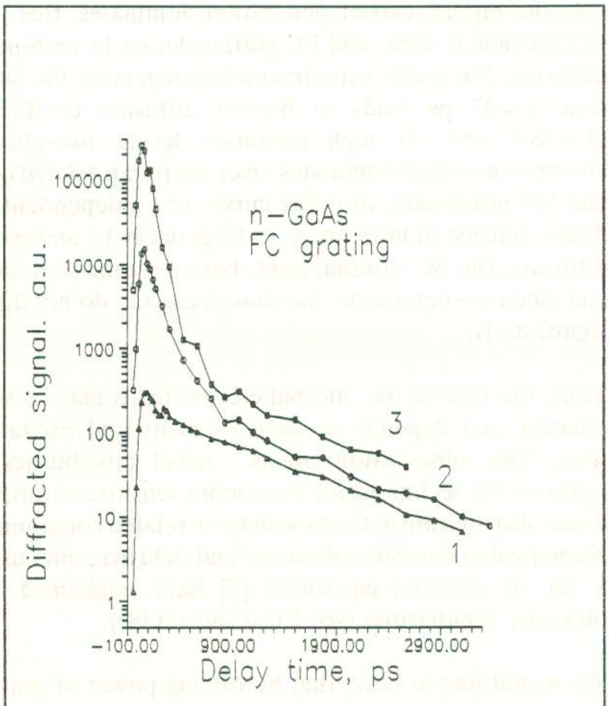

Fig.5. FC grating decay in heavily doped n-GaAs crystals at three fixed excitation levels: 2.2 mJ/cm^2 (1), 4.8 mJ/cm^2 (2) and 8.5 mJ/cm^2 (3).

The procedure of measurements of FC grating decay at various excitation levels allows one to find the limit of the fast diffusive component and to calculate the hole, ambipolar, and electron mobility for various dopants and their concentrations. To our opinion, this technique might be useful in direct determination of minority and majority carrier mobilities in doped GaAs to test predictions of theoretical modelization of dominant carrier scattering mechanisms [11]. The accurate data of carrier mobilities are important for GaAs device modeling.

5.Conclusions

The measurements and analysis of carrier generation mechanisms related to deep traps and carrier diffusive transport have opened novel possibilities for optimizing non-destructive TG technique for sensitive control of defect distribution in GaAs wafers. The application of this technique to measure carrier diffusion and recombination parameters in heavily-doped GaAs crystals has been demonstrated. This method is well-suitable for studies of other III-V semi-insulating or low-resistivity compounds.

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