EXPERIMENTAL STUDIES OF LIGHT-MICROWAVE FIELD INTERACTION AND NONEQUILIBRIUM CARRIER TRANSPORT IN GaAs

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Abstract

Contactless nonlinear optics and microwave techniques are combined to study nonequilibrium carrier transport and photoelectric properties of GaAs crystals in electric fields. Peculiarities of complex diffusion-drift processes of photoexcited carrier plasma under microwave heating, and fast transients of carrier transport in space-charge internal electric field are analysed by measuring orientational, temporal and field dependences of light diffraction on light-induced transient gratings.

1. Introduction

Temporal or spatial modulation of light-induced free carrier plasma and its heating by microwave (MW) electric field leads to novel effects in transport phenomena, which may by used as nondestructive, contactless techniques for measurements of kinetic coefficients and nonequilibrium carrier dynamics [1]. This research field is also of great interest in the development of high-speed optoelectronic and MW devices based on semiconducting GaAs-type materials [2].

Light diffraction on transient gratings is a powerful technique of active spectroscopy of semiconductors [3,4], especially for the fast carrier transport in bulk semiconducting crystals or heterostructures. By this technique, a number of nonequilibrium carrier transport peculiarities in external MW fields and internal space-charge electric fields have been observed recently: an enhanced photo-refractive (PR) effect [5], oscillations of diffraction efficiency and multiexponential transient grating (TG) decay in picosecond [6,7] and nanosecond time scale [8], unexpected 3-fold enhancement of self-diffraction efficiency on free carrier (FC) grating in external longitudinal MW electric fields [9]. Some physical mechanisms have been proposed by the authors of given above papers to explain the observed effects: hot carrier diffusion [5], nonsinusoidal grating profiles (both for carriers and internal fields) [6,7], nonuniform carrier heating due to non-uniform external field [9]. Computer simulation of diffusion-drift processes in GaAs has explained only the main features of transient grating decay [10], but neither fast oscillations of diffracted beam intensity nor its enhancement in non-homogeneous electric fields.

In this paper the following cases studied by TG technique will be discussed: (i) the anisotropy of light self-diffraction characteristics in external MW field, (ii) oscillating decay of light-created FC concentration and of internal space-charge (SC) electric fields in semi-insulating and heavily doped GaAs bulk crystals. In addition, the temporal modulation of photoelectric properties of GaAs crystals in MW fields via measurements of light-induced higher MW harmonics is given.

2. Experimental Equipment

We have studied nonequilibrium carrier-fields dynamics and carrier transport in strong electric fields by using two experimental techniques: in *external* MW and *internal* light-induced space-charge electric fields.

In the first case, light-microwave interaction was investigated in undoped semi-insulating GaAs samples with thickness of 0.4-0.6 mm and carrier lifetime 10-30 ns. The TG experiments were carried out in a self-diffraction configuration [1], using 15 ns duration pulses of Nd:YAG laser at $\lambda=1.06$ µm wavelength. The beam splitter produces two waves which interference in the sample and builds-up the nonequilibrium carrier grating. The intensities of the incident I_0, transmitted I_T and first-order diffracted I_1 light beam pulses were measured by photodiodes and led to the data processing system. FC were heated by MW pulses with 9.6 GHz frequency applied to the sample through the wave circuit. The measurements were carried out by successive comparison of the diffracted beam intensity in the presence and absence of external MW field. The longitudinal and transverse orientations of the MW field with respect to the grating vector were investigated. All the experiments were performed at minimal intensity of the laser beam, corresponding to FC concentration $N \approx 5 \cdot 10^{16}$ cm^{-3}.

In the second case, time-resolved studies of carrier and internal electric field dynamics have been carried out by using 30 ps duration YAG-laser pulses. The experimental configuration was a degenerate Four-wave mixing scheme [6]. The TG with period of 1.8 μm were recorded in heavily doped n-type GaAs crystals. Probe diffracted beam polarization (s- or p-) were monitored to separate coexisting FC or PR gratings. More detail description of this set-up is given in [6].

3. Experimental Results and Discussion

3.1. Light diffraction in microwave fields. The strong external electric field in GaAs can influence photoelectric parameters by a number of different mechanisms, such as hot carrier generation, transport and recombination. External MW electric fields intensities used in experiments ($E_m < 7$ kV/cm) provided heating and change of kinetic coefficients for FC plasma with the subsequent spatial redistribution. The field dependences of self-diffracted beam efficiency $\eta = I_1/I_0$ at $T_0 = 300$K for grating period $\Lambda = 25$ μm are shown in Fig.1. The insert displays the orientation of MW electric field with respect to the TG vector. A note-worthy peculiarity of the MW field effect on $\eta(E)$ is the existence of a strong anisotropy and significant (3-fold) enhancement of diffraction efficiency in strong longitudinal MW electric field.

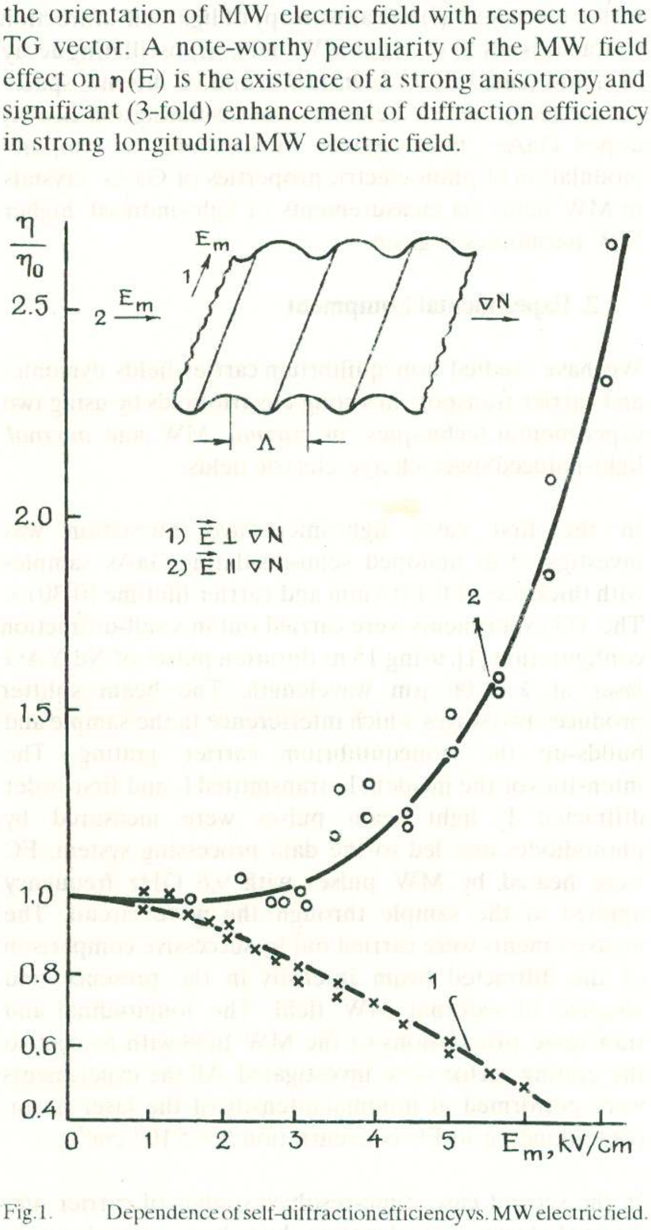

Fig.1. Dependence of self-diffraction efficiency vs. MW electric field.

In the presence of external uniform electric field the dynamics of FC is given by continuity equation:

$$\frac{\delta N}{\delta t} = D_a(E)\frac{\delta^2 N}{\delta x^2} - \mu_a(E)E\frac{\delta N}{\delta x} - \frac{N}{\tau_R} + \alpha(1-R)I_0 f(t)\left(1+\cos\frac{2\pi x}{\Lambda}\right), \tag{1}$$

where D_a, μ_a, τ_R is the ambipolar diffusion coefficient, mobility and lifetime; α, R are absorption and reflection coefficients; f(t) is the temporal shape of the laser pulse. Light self-diffraction efficiency on induced FC phase grating is given by the expression:

$$\eta = \left(\frac{\pi}{\lambda} n_{eh} \int_0^d \Delta N(t,z)dz\right)^2, \tag{2}$$

n_{eh} is the change in the refractive index caused by one e-h pair; $\Delta N = N_{max} - N_{min}$ is the modulating FC concentration which follows from the solution of (1):

$$\Delta N(t) = 2\alpha(1-R)I_0 \int_0^t f(t-\xi)\exp(-\xi/\tau_e)d\xi, \tag{3}$$

where $\tau_e^{-1} = \tau_R^{-1} + D_a\,(2\Pi/\Lambda)^2$.

In the transverse orientation of MW field to grating vector, an uniform electric field is created in the samples, and the field action is only via the dependence $D_a(E)$. Therefore, the decrease of $\eta_T(E)$ in heating MW fields is caused by the increase in the diffusion coefficients of hot carriers. The measured dependences of η_T vs. amplitude of MW electric field were used to determine the field dependences of the transverse ambipolar D_{aT} and electron D_{nT} diffusion coefficients (Fig.2). The solid curves are the

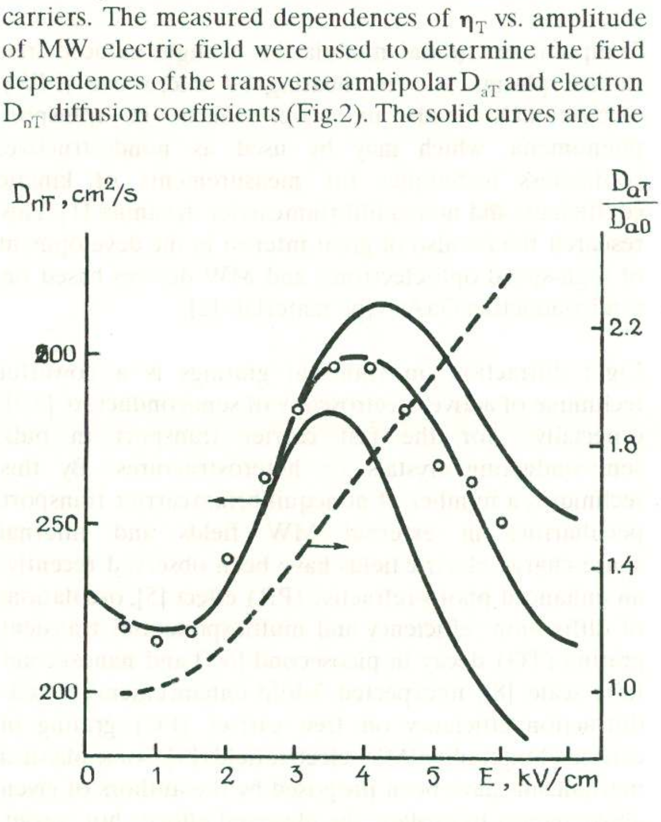

Fig.2. Field dependences of transverse coefficients of hot electrons diffusion (left scale) and ambipolar diffusion (dashed curve, right scale). Curves represent Monte Carlo calculations with different $\Xi_{\Gamma L}$ (in eV/cm): 1- $1.8 \cdot 10^8$, 2- $3 \cdot 10^8$, 3- $5 \cdot 10^8$.

theoretical dependences of D_{nT} on E, obtained by the Monte Carlo method. The calculations performed for the three-valley model, using different intervalley interaction constants $\Xi_{\Gamma L}$, including the scattering by ionized impurities for $N_I=5\cdot10^{15}$ cm^{-3}. The best agreement between the theoretical and experimental results was obtained for $\Xi_{\Gamma L}=3\cdot10^{8}$ eV/cm.

The carrier heating along electric field in bulk GaAs are studied widely both theoretically and experimentally. However, from the analysis (1)-(3), using well-known parameters of GaAs one can estimate, that drift of FC as well as their diffusion will increase the decay velocity of TG. As a result, η decreases while our experiment (Fig.1) have shown quite different dependence. Diffusion or drift transport models do not explain the observed increase of $\eta(E)$ with decreasing grating period. To our opinion, when E||*grad*N, these observations are connected with electrogradient phenomena which arise in non-uniform electric fields due to non-uniform carrier heating and/or due to carrier-field redistribution with subsequent complicated diffusion-drift processes. Such a phenomena, to our knowledge, are not sufficiently studied theoretically. It is a quite complicated problem. Therefore, for deeper understanding of observed effects more detail experimental studies (e.g., by using time-resolved Two- or Four-wave mixing scheme) are desirable.

3.2. Carrier transport in internal space-charge electric field. At short pulse excitation, overlapping of different carrier generation mechanisms leads to varying with excitation carrier transport. Carrier diffusion will create different components of SC electric fields: between ionized donors and mobile charges (E_{sc1}) as well as between electrons and holes (E_{sc2}). In this way, two mechanisms of refractive index modulation - by FC and SC electric fields - may take place simultaneously and create coexisting FC and PR gratings.

Light induced SC electric fields may peak up to $E_{sc1}+E_{sc2}=1150$ V/cm for $\Lambda=1.8$ µm and significantly affect carrier redistribution: electron drift in E_{sc1} will oppose diffusive decay of electron grating; hole redistribution will create hole grating in a new position (half-period shifted); the latter grating will partially screen SC field E_{sc1}. After the equilibrium of diffusion-drift processes is reached, the further decay of coexisting FC and PR gratings is governed by carrier recombination. Modelisation of carrier-field dynamics has shown monotonous two-exponential decay of FC and PR gratings [10].

Nevertheless, in contrary to the theoretical predictions, the fast oscillations of diffracted beam intensity on the exponential shape of grating decay have been observed experimentally [6,7].

FC and PR grating decay have been measured in heavily doped n-type GaAs with electron mobility $\mu_n=2500$ cm^2/V·s. In Fig.3 FC grating decay at two fixed excitation energies is presented. Substraction of slowly decaying component $\tau_{12}=\tau_R=1.45$ ns 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 $\mu_p=(\Lambda/2\pi)^2\cdot(e/kT)\cdot\tau_1^{*-1}=190$ cm^2/V·s. At higher excitations, the initial diffusive decay time $\tau_{21}=240$ ps corresponds to higher carrier effective mobility $\mu_{eff}=270$ cm^2/V·s $>\mu_p$, but below estimated bipolar mobility $\mu_a=350$ cm^2/V·s.

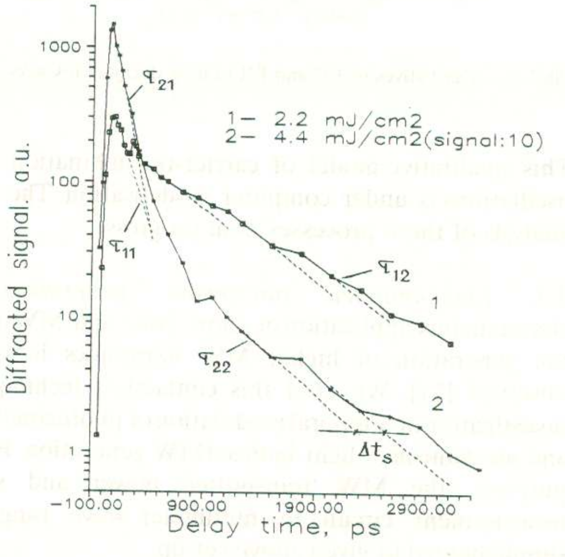

Fig.3. Free carrier grating decay in heavily doped n-GaAs.

The most interesting observation, to our opinion, is found in the tails of FC decay, where exponential decay is superimposed with step-like modulation (or periodic amplification) of diffracted beam intensity (Fig.3). Grating decay here is periodically stopped for a fixed time Δt_s, after which recombination is erasing the grating again. It's interesting to note that the value of Δt_s correlates well with the initial diffusive decay time of FC grating, i.e. $\Delta t_{s1}=170$-180 ps$=\tau_1^*$ for curve 1 and $\Delta t_{s2}=240$-250 ps$=$ $=\tau_{21}$ ps for curve 2. This correlation indicates that the observed delay has diffusive origin. The additional information concerning the mechanism of periodic amplification of diffracted beam was obtained from the comparison of FC and PR grating decay dynamics, where the derivatives of both grating decay were found correlated quite well (Fig.4). The latter behavior points out that the periodic increase of SC electric field E_{sc1} takes place. If this increase would be of diffusive origin, then the correlation of derivatives in the opposite phases is expected. We suppose that E_{sc1} increase is due to different rate of carrier recombination in maxima and minima of interference field. This field will redistribute carriers with the time constants, corresponding to diffusive-drift processes at given N/P ratio. The new carrier redistribution will take time interval Δt_s and compensate grating erasure by recombination.

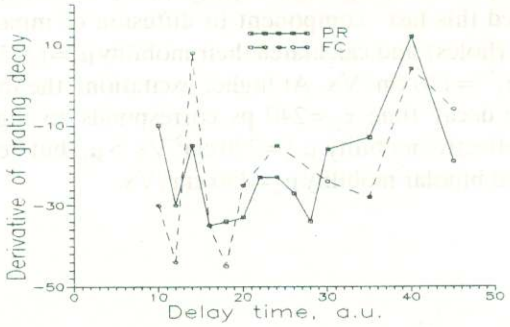

Fig.4. Derivatives of FC and PR grating decay in n-GaAs.

This qualitative model of carrier-recombination driven oscillations is under computer modelisation. The future analysis of these processes is in progress.

3.3. Light-induced microwave generation. At simultaneous application of short laser and MW pulses, the generation of higher MW harmonics have been observed [11]. We used this contactless technique for investigation of temporal modulation of photoconductivity and mechanism of light-induced MW generation. For this purpose, the MW transmitted power and spectra measurement circuit in millimeter wave range was supplemented to given above set-up.

The main part of MW generation output was observed at the triple frequency of the pump MW field. The power of third harmonics varies in nonlinear way (close to cubic law) with increasing external MW electric field amplitude. This behaviour was connected with electron mobility change due to FC heating in MW fields. The higher harmonics then third one have less output, and appears only at very high excitations at the leading edge of laser pulse. We also would like to note, that the effect of MW generation takes place only if external MW and optical pulses overlap temporally.

The additional information about FC dynamics, generation and recombination rates may be obtained from the investigations of temporal characteristics of MW harmonics signals, their dependences on light pulse duration, power, etc. The transient behaviour of light-induced MW power correlated well with the dynamics of time-resolved photocurrent in the crystals studied (GaAs, Ge, Si). Moreover, by using highly absorbed light pulses, this technique allows possibility to investigate nonlinear phenomena in the surface layers. As an example, we observed 3-rd MW harmonics radiation in InGaAs/GaAs superlattice grown on semi-insulating GaAs by MOCVD technique. By illumination of front and back sides of this sample with the second harmonic of the YAG laser ($\lambda=0.53$ μm) we have observed different speed of recombination processes in the bulk crystal surface and in the superlattice.

In conclusion, these given above contactless techniques proved being useful in the studies of hot carrier effects and fast carrier transport in bulk GaAs and related III-V compounds. The similar processes may be studied in low-dimensional structures and superlattices as well. In addition, the transient effects of light-microwave field interactions open novel ways of short microwave pulses generation, modulation and detection.

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