Light diffraction on Gunn-domain gratings

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(Received 4 February 1997)

We present a different way of creating a sequence of quasilocalized Gunn domains in biased bulk GaAs and InP crystals due to illumination by a pulse of light interference field. Theoretical calculations of hot carrier transport in nonuniform electric fields revealed criteria of bipolar Gunn-domain formation with an electro-optic refractive index modulation exceeding one by free carriers. The numerical data are in good agreement with the experimentally observed enhancement of light self-diffraction efficiency on transient grating by an external microwave field. [S0163-1829(97)01520-8]

Carrier transport based optical nonlinearities are among the most promising to reach an effective response of media at nonresonant light-matter interaction. The recent studies of photorefractive wave mixing in biased multiple-quantum-well structures[1] or bulk crystals[2] pointed out the significance of high-field electronic transport, which may cause a different phase-shift mechanism of the space-charge field or create a moving multiple high-field domain structure, phase locked with the interference fringes.

In this paper, we demonstrate a different way of creating simultaneously a number of quasilocalized high-field Gunn domains, the formation of which is triggered by a short single pulse of the light interference field in biased GaAs and InP bulk crystals. We report a very efficient electro-optic mechanism of refractive index modulation in real time by Gunn-domain grating, in which high-field domains are quasilocalized in the minima of light interference pattern. The domains are created through hot carrier transport in *spatially modulated and nonuniformly heated electron-hole plasma*.[3] Using the Monte Carlo or extended drift-diffusion techniques, redistribution of hot carrier concentration and the dynamics of the internal space-charge field are analyzed in a picosecond and nanosecond time scale. Peculiarities of this transient structure are revealed through parameters of light self-diffraction on it.

We investigate the dynamics of spatially modulated nonequilibrium electron-hole plasma, generated by two interfering short laser pulses and simultaneously heated by external dc or microwave (mw) field. Carrier redistribution is analyzed theoretically in the short (up to 1 ns) and long (up to 50 ns) time scales by Monte Carlo particle (MCP) and extended drift-diffusion (EDD) techniques, respectively. Basic transport equations are completed with the Poisson one for the self-consistent nonhomogeneous electric field. The MCP procedure accounts for a nonparabolic conduction band with Γ-, *L*-, and *X*-valley ordering and a nonparabolic heavy-hole band. A strong-coupling model[4] for intervalley transfer in GaAs and InP is used. Interband carrier photogeneration and linear recombination processes are assumed.

For the EDD approximation the basic continuity equations are written in the form

$$\frac{\partial N}{\partial t}=gI(x,t)-\gamma N-\frac{\partial}{\partial x}\left[N\mu_n(E)E(x,t)-D_n(E)\,\frac{\partial N}{\partial x}-N\tau_v(E)\,\frac{\partial\phi(E)}{\partial x}\right], \tag{1}$$

$$\frac{\partial P}{\partial t}=gI(x,t)-\gamma P-\frac{\partial}{\partial x}\left[P\mu_p(E)E(x,t)-D_p(E)\,\frac{\partial P}{\partial x}\right], \tag{2}$$

where N and P are electron and hole concentrations, g is generation rate of electron-hole pairs, $I(x,t)=I_0f(t)[1+m\cos(2\pi x/\Lambda)]$ is the interference pattern of the incident light, m is the modulation depth of interference field, Λ is the spatial period of grating, $f(t)$ describes the temporal shape of a laser pulse, γ is the linear recombination rate, $\mu_n(E)$, $D_n(E)$, $\tau_v(E)$, $\phi(E)$ are parameters of hot electrons in the EDD model [see Eqs. (37), (38), and (40) of Ref. 5], $\mu_p(E)$, $D_p(E)$ are the hole mobility and diffusion coefficient, and $E(x,t)$ is the spatially varying electric field, obtained from the solution of a Poisson equation.

The calculations of nonequilibrium carrier and internal field dynamics at high ($E=5-10$ kV/cm) dc or mw ($f=10$ GHz) external fields by the MCP technique revealed time-resolved processes of a Gunn-domain grating formation, its spatial profile, and the localization. For example, at an excitation of GaAs crystals by a 30-ps duration laser pulse and a high modulation depth of interference pattern ($m=1$, $\Lambda=5-15$ μm, $\Delta N=10^{16}$ cm^{-3}), Gunn domains are simultaneously created in all grating minima during the action of the laser pulse. The internal electric-field values are essentially higher than the bias field and peaks up to 30–80 kV/cm. In the dc field, the motion of domains is maintained up to 200 ps despite of stochastic character of the scattering events, and their periodical distribution is later destroyed by domain interaction. The decay time of Gunn-domain grating decreases for a lower carrier concentration and smaller grating periods. In mw fields, the created dipole Gunn domains are more stable if compare to dc field, and their amplitude follows the temporal variation of the mw electric field. To extend calculations of carrier-field dynamics in nanosecond

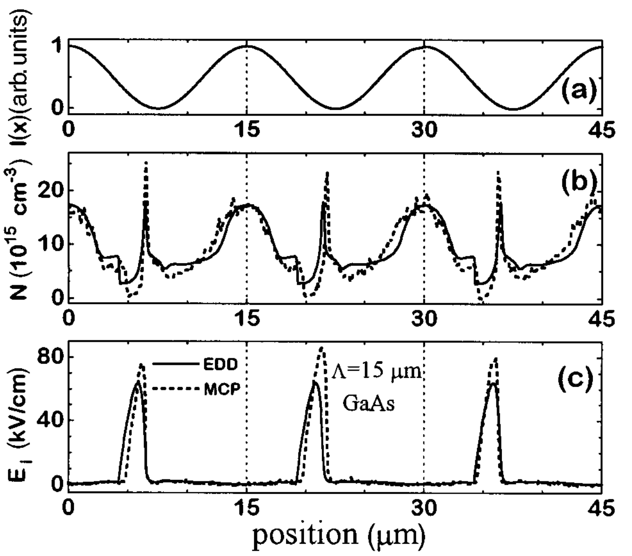

FIG. 1. Spatial distribution of light interference field intensity (a), nonequilibrium electron concentration (b), and internal electric field (c) in GaAs at the peak of an external mw field with an amplitude $E_m = 8$ kV/cm. Carrier-field profiles, calculated by using Monte Carlo (dash) and extended drift-diffusion (solid) techniques, are given at $t = 500$ ps. Laser-pulse duration $\tau_L = 30$ ps, grating period $\Lambda = 15$ μm.

time scale, we applied the EDD model and got an excellent agreement with MCP data (see Fig. 1).

We used the EDD model to evaluate numerically the Kroemer's criterion of the Gunn-domain formation for a bipolar carrier plasma, created in high-resistivity samples by a short laser pulse. This bipolar situation with relatively low electron-hole pair densities has not been considered sufficiently before. It is well known,[6] that a positive differential mobility of holes leads to a rising branch of the current-voltage characteristic while the drift velocity of hot electrons becomes saturated. Accordingly, the holes can influence the critical value $N \times L \cong 10^{12}$ cm^{-2} given by the Kroemer's criterion for monopolar plasma[6] as well as the electric-field region in which the Gunn domains may exist.

At excitation by a laser pulse with a $\tau_L = 30$-ps duration and very weak modulation depth of the light interference field ($m \ll 1$), the Kroemer's criterion for applied dc voltage and a threshold field $E^{\min}$ for the Gunn-domain formation were found: $N \times L \cong 2 \times 10^{11}$ cm^{-2} and $E^{\min} \cong 4.5$ kV/cm for GaAs (for InP, $N \times L \cong 4 \times 10^{11}$ cm^{-2} and $E^{\min} \cong 11$ kV/cm); here L corresponds to the grating period Λ. Thus, the Kroemer's criterion for the bipolar high-field domain is satisfied at lower carrier concentrations than for the monopolar domain. In addition, we found that hole drift in high-field region $E > E^{\max}$ leads to the situation when high-field domains are very unstable or not created at all. Such a situation in GaAs may take place at $E^{\max} \cong 10$ kV/cm for low charge densities, corresponding to the threshold value of $N_1 \cong (2.5 \times 10^{11}/L)$ cm^{-3}. The limiting upper value of $E^{\max}$ increases with a nonequilibrium carrier concentration for the given L value, e.g., if $N = 10 \times N_1$, then $E^{\max} \cong 15$ kV/cm, and for $N = 100 \times N_1$, $E^{\max} \cong 20$ kV/cm. Thus a bipolar Gunn domain may evolve in a field interval $E^{\max} - E^{\min}$, if the carrier concentration satisfies the Kroemer's criterion. In InP, due to lower mobility of holes, the formation of the Gunn domain is found even at 30 kV/cm. We should also note that Gunn domains propagate through the GaAs sample with the velocity $v_t \cong 1.2 \times 10^7$ cm/s and $v_t \cong 1.5 \times 10^7$ cm/s for InP.

In alternating electric field, Gunn domains may be created only at a frequency lower than the inverse formation time of the Gunn domain. The limiting transient frequency f_t (Ref. 6) can be estimated from the given above Kroemer's criterion as approximately $f_t^{-1} \times N = N \times L / v_t \cong 1.7 \times 10^4$ cm^{-3} s for GaAs, and $f_t^{-1} \times N \cong 2.7 \times 10^4$ cm^{-3} s for InP. The latter condition for $f_t = 10$ GHz is satisfied, when $N > (1.7 - 2.7) 10^{14}$ cm^{-3} for GaAs and InP, correspondingly. However, as follows from our simulations for external 10-GHz frequency field $E = E_m \cos(2\pi f t)$, the required minimal electron-hole concentration to create stable high-field domains must be an order of magnitude higher [e.g., to satisfy the condition $f^{-1} \times N \geq (1.5–2.5) 10^5$ cm^{-3} s for GaAS and InP, correspondingly].

For the case of high modulation depth ($m = 1$), carrier and internal field spatial profiles as well as their dynamics are more complicated. Due to spatially modulated light pattern, internal electric fields with local values $E_i > E_{\text{ext}}$ are created in the interference minima within the dielectric relaxation time. The value of E_i may reach the threshold value for the Gunn-domain formation at a relatively low external voltage. However, the initial carrier concentration in the grating minima is rather low for the case $m = 1$, and the high-field domain formation is delayed until the diffusive-drift currents will supply the necessary amount of carriers to the grating minima. Therefore, the threshold conditions for carrier concentration as well as for local-field value must be satisfied simultaneously. The light-triggered Gunn-domain formation may be easily modified by the intensity of illumination, the modulation depth of interference pattern, and especially by the transient grating period.

Due to nonequilibrium carrier plasma and the strong internal field in the vicinity of the Gunn domain, two coexisting mechanisms of refractive index modulation Δn may take place: by electron-hole plasma and by electro-optical nonlinearity. Free-carrier nonlinearity is isotropic and for laser frequencies ω far away from the direct band gap is described by the Drude-Lorentz model.[7] For nonuniformly heated carriers, Δn_{FC} is modified by field-dependent electron effective mass m^* [Eq. (3)]:

$$\Delta n_{\text{FC}}(x) = -(e/2n\varepsilon\varepsilon_0\omega^2)[\Delta N(x)/m^*(x) + \Delta P(x)/m_p]. \tag{3}$$

As concerns linear electro-optic effect, it is anisotropic and forbidden for the used (001)-cut GaAs and InP crystals, when light propagates along the (001) axis.[8] Consequently, we have taken into account a quadratic electro-optic nonlinearity,[9] associated with Kerr effect [Eq. (4)], which may take place in semiconductors with cubic or other class symmetry:

$$\Delta n_{\text{EO}} = -n^3 g_{\text{EO}} (\varepsilon - 1)^2 \varepsilon_0^2 E_i^2 / 2, \tag{4}$$

here n is refractive index, g_{EO} is quadratic electro-optic coefficient, and $\varepsilon, \varepsilon_0$ are the permittivity of material and vacuum.

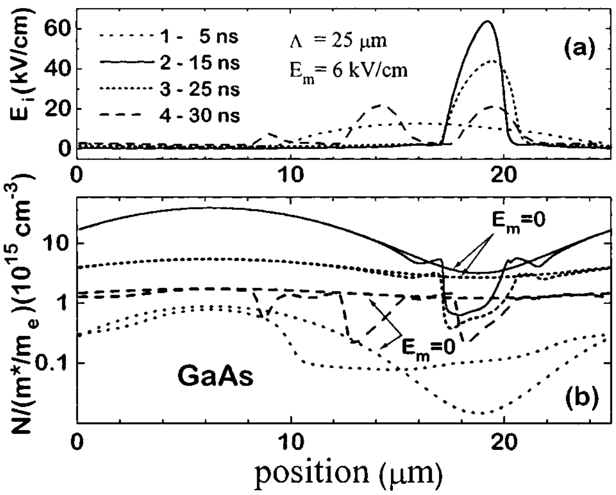

FIG. 2. Spatial profiles of internal electric field (a) and electron concentration normalized to the effective mass (b) in GaAs at $E_m = 6$ kV/cm (a), (b) and $E_m = 0$ (b). Results are given for 5 ns (1), 15 ns (2), 25 ns (3), and 30 ns (4) at excitation by $\tau_L = 10$ ns; $\Lambda = 25$ μm.

The temporal changes of Δn can be measured by using light diffraction on the transient grating technique.[7] The simplest way to observe light-induced diffraction is a configuration of light self-diffraction, when two laser beams create a grating and probe it simultaneously. The grating diffracts a probe beam into the direction of the first diffraction order with an efficiency $\eta_1 = I_1/I_T = (\pi \Delta n d/\lambda)^2$; here I_1, I_T are intensities of the diffracted and transmitted probe beam, d is sample thickness, and λ is laser wavelength.

Experimentally, the essential enhancement of self-diffracted beam intensity was observed in semi-insulating GaAs and InP bulk crystals, using 10-ns duration pulses of Nd:YAG laser ($\lambda = 1.06$ μm) for carrier excitation and their simultaneous heating by the external 10-GHz microwave field.[10] For simulation of carrier and field dynamics in InP and GaAs under the experimentally realized conditions, we used the EDD model, assuming electron-hole plasma generation by two-photon absorption of light and linear carrier recombination with a time of 5 ns. The influence of electron-gas heating and intervalley redistribution is emphasized by comparing electron concentration (normalized to the field-dependent effective mass of hot electrons) without and with the applied external voltage (Fig. 2). At $t = 5$ ns, the initial carrier concentration in the grating minima is not yet sufficient to support the formation of the *high-field* domain, and the trapezoidal-shape domain occupies all the grating minima. At the maxima of laser-pulse intensity ($t = 15$ ns), the Gunn domain is already created in an area of a few micrometers at the grating minima (here E_i peaks to 60 kV/cm), and the shape of carrier profile [see Fig. 2(b)] confirms the hot carrier related origin of this E_i peak. Essentially decreased carrier concentration and its modulation depth at longer times determines the decrease of high-field domain amplitude and its splitting (see Fig. 2).

Temporal behavior of refractive index changes induced by free-carrier and electro-optical nonlinearities shown on Fig. 3. Simulations show that free-carrier nonlinearity is not so sensitive to the field as electro-optic one. The field effect

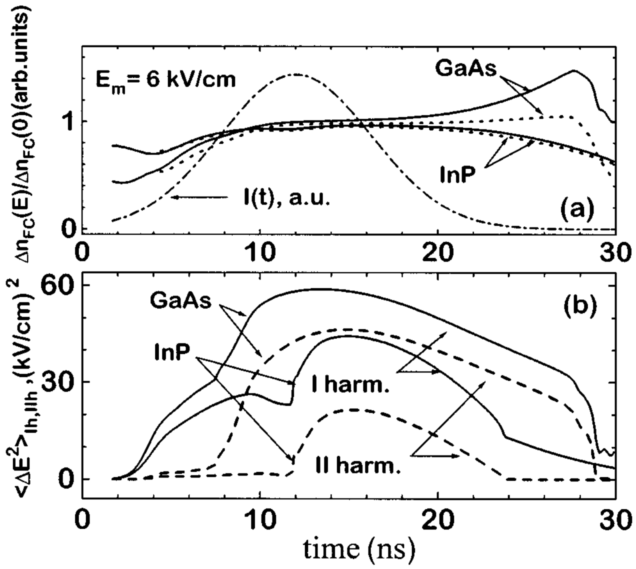

FIG. 3. Temporal evolution of normalized refractive index modulation by free-carrier plasma (a) and by a quadratic electro-optic effect (b). In (b), the first (solid) and the second (dash) spatial Fourier harmonics of E_i, averaged over mw period, are shown. Short dashes in (a) are simulation results assuming $m^*(E) = m_e(0)$, and $I(t)$ is a temporal shape of 10-ns laser-pulse duration.

on the free-carrier grating may be observed at the very beginning of the laser pulse and after the pulse, i.e., when carrier concentration is relatively low. The increased ambipolar diffusion coefficient of hot carriers diminish the Δn_{FC} value, while the increased effective mass of hot electrons in grating minima increases Δn_{FC} [Fig. 3(a)]. However, the latter hot carrier effect is weaker in InP [compare curves at $t > 20$ ns in Fig. 3(a)].

Meanwhile, Gunn-domain induced changes of refractive index dominate during the action of laser pulse both for

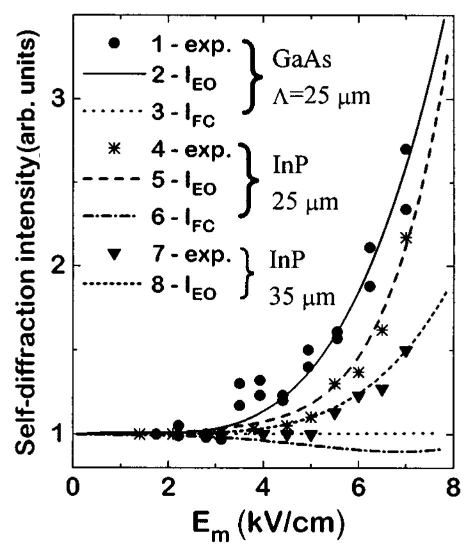

FIG. 4. Comparison of experimental data (points) and calculations (lines) of normalized self-diffraction intensity I_1^* vs external mw field amplitude in GaAs (1–3) and InP (4–8) for transient gratings with $\Lambda = 25$ μm (1–6) and $\Lambda = 35$ μm (7,8). I_{EO} stands for electro-optic Gunn-domain grating, and I_{FC} for free-carrier grating.

GaAs and InP samples. Shrinking of E_i into a spatially narrow domain with a *high-field* magnitude (see Fig. 2) leads to a number of higher spatial field harmonics in addition to a fundamental one. The appearance of the second Fourier harmonics [see Fig. 3(b)] indicates a time when the nonequilibrium carrier concentration as well as the field in grating minima are sufficient to produce a stabile high-field domain.

We calculated field dependencies of the self-diffracted beam intensity I_1^*, averaged over a ns laser pulse-duration, for electro-optic and free-carrier gratings, taking into account the overlapping of diffraction from the first and the second spatial Fourier harmonics. The calculated curves were superimposed with experimental data to reach their fit at $E_m = 7$ kV/cm (Fig. 4). A good agreement between the field dependencies leads to conclusion that hot electron transport in an external mw field creates a Gunn-domain grating and determines the enhancement of light self-diffraction, both in GaAs and InP crystals.

At $E_m = 7$ kV/cm, we found Gunn-domain induced refractive index changes approximately twice as high as those due to free carriers. The latter value, $|\Delta n_{FC}| \approx (\eta_{FC})^{1/2} \lambda/(\pi d) = 5\times 10^{-5}$ was determined from the diffraction efficiency of free-carrier grating without external field, $\eta_{FC} \approx 0.5\%$. The Gunn domain created electro-optic nonlinearity may reach a value of 10^{-4}, which is essentially higher than the diffusive field limited linear electro-optic effect in photorefractive semiconductors.

In summary, we have demonstrated the way to reach a very efficient and fast electro-optic refractive index modulation by transient Gunn-domain grating. The light-triggered Gunn-domain formation in an external microwave field is confirmed experimentally by the enhancement of light self-diffraction efficiency. The transient grating serves as a simple but powerful tool for the studies of nonlinear optical and transport phenomena in nonuniform electric fields.

We would like to acknowledge the support of this work by the Lithuanian Science and Education Foundation (Grant No. 96-213/2F).

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