Transverse ambipolar diffusion of hot charge carriers in gallium arsenide

Yu. Yu. Vaĭtkus, L. E. Subachyus, and K. Yu. Yarashyunas
V. Kapsukas State University, Vil'nyus Institute of Semiconductor Physics, Academy of Sciences of the Lithuanian SSR

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The transverse diffusion of hot charge carriers in GaAs has been measured experimentally for the first time. A new contactless method is used to study the diffusion on the basis of an analysis of light-induced diffraction of light in strong microwave fields.

The diffusion of hot charge carriers in GaAs has recently been discussed in the literature[1] and the diffusion coefficients have been calculated numerically. There is, however, a considerable discrepancy in the results of calculations based on various models and intervalley scattering constants. The field dependence of the diffusion is difficult to study experimentally. Until now, only the field dependence of the longitudinal diffusion of electrons,[1,2] $D_{\parallel}$, has been determined. In the present letter we report the results of an experiment on the measurement of the field dependence of the trans-

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verse diffusion, using an optical method, and we discuss the characteristic features of the transverse and longitudinal diffusion of electrons in strong electric fields.

The diffusion of charge carriers was measured from the rate of the diffusive erasing of the distribution of nonequilibrium charge carriers (NCC) which were excited by the interference field of the crossing light beams. The modulation depth of the nonequilibrium charge carrier distribution, ΔN, was measured from the diffusion of light (by the method of the dynamic holographic gratings, which is based on the light-induced variation of the refractive index of the semiconductor according to the Drude model[3,4]). The light-induced periodic NCC distribution is erased in a time typically $\tau_e^{-1} = \tau_R^{-1} + \tau_D^{-1}$, where $\tau_D = \Lambda^2/4\pi D_a$ is the diffusive component of the erasure of the grating with a period Λ, D_a is the ambipolar diffusion coefficient, and τ_R is the lifetime of the nonequilibrium charge carriers. The nonequilibrium charge carriers are heated by microwave pulses from an electric field (the angular frequency is $\omega \simeq 6\times 10^{10}$ Hz), which is oriented perpendicular to the NCC gradient in the grating.

In the experiments we chose samples of a partially insulating GaAs of thickness $d = 0.4$–0.6 mm, in which the lifetime of the charge carriers $\tau_R = 20$–40 ns and $D_{a0} = 15.5$ cm^2/s, determined from the dynamics of the decomposition of the grating, did not affect the diffusive erasure of the grating with $\Lambda = 25$–$40\ \mu$m during the action of a 16-ns laser pulse. The interference field which excited the nonequilibrium charge carriers was produced by placing the sample at the point of intersection of two beams from neodymium lasers (the wavelength was $\lambda = 1.06\ \mu$m). The time required to erase the grating was determined by scanning it with light pulses from another laser, which were delayed relative to those of the exciting laser. The measurements were carried out at $T_0 = 300$ K.

The efficiency of the light-induced diffraction, $\eta = I_l/I_T$, is related to the modulation of the refractive index by a simple relation[3] $\eta = (\pi\Delta n d/\lambda)^2$, where I_l and I_T are the intensities of the diffracted and transmitted beams. The output energy of the incident beam I_0, the transmitted beam and the diffracted beam was measured by photodiodes, and the data, stored in a computer, were presented in the form of $I_t, I_1 = f(I_0)$ plots shown in Fig. 1. In the microwave heating fields the diffraction intensity decreases, indicating a decrease in τ_e.

Figure 2 is a plot of the variation of the diffraction efficiency, η/η_0, found experimentally, versus the amplitude of the microwave electric field, E_m. Also shown in this figure is the transverse ambipolar diffusion of the hot NCC, $\langle D_{a\perp}\rangle$, which corresponds to this plot and which was calculated in accordance with the relationship between D_a and τ_e, using the relation

$$\eta = \left[\frac{\pi}{\lambda}\int_0^t \Delta n f(t-\zeta)\exp\left(-\frac{\zeta}{\tau_e}\right)d\zeta\right]^2, \tag{1}$$

where $f(t)$ is the time-dependent envelope of the exciting pulse. As the period of the grating is reduced, the detectable variation in the efficiency of self-diffraction increases because of the increase in the role of the diffusive erasing of the grating. The values of $\langle D_{a\perp}\rangle$ presented here, which are the average values over the time the microwave

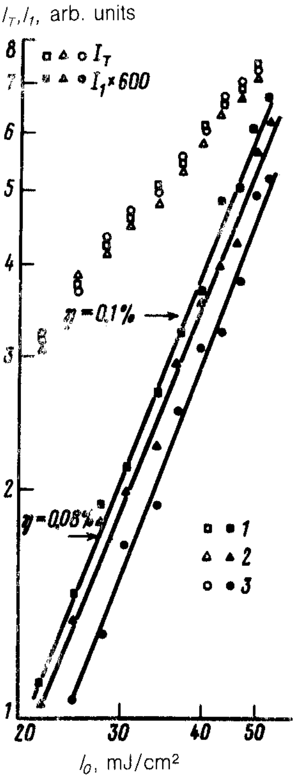
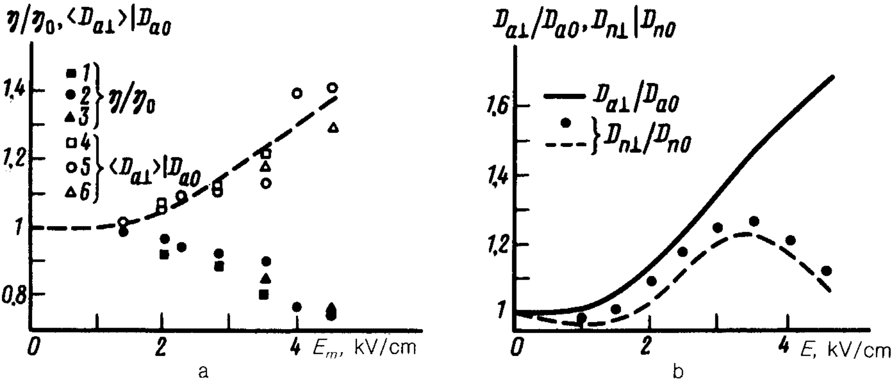


FIG. 1. The intensities of the transmitted beam I_T and the diffracted beam I_1 in GaAs versus the energy density of the laser beam I_0, measured for various amplitudes of the microwave electric field E_m. 1—0; 2—2.8 kV/cm; 3—4.5 kV/cm.



a

b

FIG. 2. (a) Efficiency of self-diffraction η and of the average $\langle D_{a\perp}\rangle$ versus the amplitude of the microwave field E_m, obtained for Λ. 1,3—26 μm; 2—31 μm. Points 1, 2, 4, 5, 3, and 6 correspond to two different samples. (b) $D_{a\perp}$ and $D_{n\perp}$ versus the electric field strength E; dashed curve—calculation of $D_{n\perp}$ by the Monte Carlo method.[1]

heating field is active, are related to the instantaneous values of $D_{a\perp}$ by the integral equation

$$\langle D_{a\perp}(E_M)\rangle = \frac{1}{2\pi}\int_0^{2\pi} D_{a\perp}(E)d(\omega t). \tag{2}$$

Under the assumption that at $T_0 = 300$ K the heating of NCC in GaAs in transverse fields follows very closely the variation of the microwave field,[1] we found the instantaneous values of $D_{a\perp}$ as functions of the electric field E (the solid curve in Fig. 2b) from the field dependence $\langle D_{a\perp}(E_m)\rangle$ (dashed curve in Fig. 2a) by solving Eq. (2) numerically.

The hole mobility μ_p (and apparently the hole diffusion D_p) is known to be independent of the field up to fields[5] $E \gtrsim 60$ kV/cm, and the field dependences of the mobility of hot electrons have been studied extensively.[1] Additionally, the electron-hole interaction in the diffusion flux of the carriers with $N \simeq P$ can be ignored.[6] Consequently, the transverse diffusion of hot electrons, $D_{n\perp}$, can be determined from the field dependence of the transverse ambipolar diffusion. Like $D_{a\perp}$, the transverse diffusion of hot electrons is of considerable interest. The field dependence of $D_{n\perp}$, represented by the points in Fig. 2b, was calculated from the equation

$$D_{a\perp} = \frac{\mu_p D_{n\perp} + \mu_n D_p}{\mu_n + \mu_p}. \tag{3}$$

The calculation was carried out for $\mu_p = 320$ cm^2/(V·s), and the $\mu_n(E)$ curve was found from the data of Ref. 7. The results for $D_{n\perp}$ obtained experimentally are in good agreement with the $D_{n\perp}(E)$ curve calculated by the Monte Carlo method.[1]

The function of the intervalley diffusion in GaAs, which is still disputed, can be determined from the $D_{n\perp}$ vs E curve obtained by us and from the maximum value of $D_{n\perp}$, $D_{n\perp} \simeq 1.3\,D_{n0}$, which is approximately one-third that of the corresponding value of the longitudinal diffusion of electrons.[1] Since the intervalley component of the diffusion in the direction perpendicular to the field is zero,[1] $D_{n\perp}$ is governed by the intravalley diffusion of electrons. Consequently, the strong dependence $D_{n\parallel}(E)$ in n-GaAs reported previously[1] is due primarily to the intervalley diffusion caused by the transfer of hot electrons between the nonequivalent valleys.

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