Photon drag of electrons and holes in interband transitions in semiconductors and the resonant-recoil effect

V. L. Al'perovich, V. I. Belinicher, V. N. Novikov, and A. S. Terekhov

Institute of Automation and Electrometry, Siberian Branch, Academy of Sciences of the USSR; Institute of Semiconductor Physics, Siberian Branch, Academy of Sciences of the USSR

(Submitted 27 January 1981)

Pis'ma Zh. Eksp. Teor. Fiz. **33**, No. 11, 573–576 (5 June 1981)

Photon drag has been detected experimentally in interband transitions in gallium arsenide. A theoretical description is offered. Peaks are caused in the photocurrent by a recoil effect as optical phonons are emitted by electrons.

PACS numbers: 72.40. + w, 72.80.Ey

The photon drag or entrainment, which occurs when light is absorbed by free charge carriers, was studied in Refs. 1-3 in semiconductors with substantial doping levels and at rather high temperatures ($T \geqslant 78$ K). The drag was measured with lasers, so that it was difficult to obtain detailed spectra. In the experiments reported by us in this letter, in contrast, the samples were pure semiconductors, and the drag spectra were measured with a monochromator at liquid-helium temperature. These differences in experimental procedure have made it possible to obtain a complex-oscillation spectrum of the effect for interband optical transitions.

The experimental procedure and the samples were the same as those in a previous study[4] of the surface photogalvanic current. In this method, we measure the voltage V which arises across contacts when polarized light is incident obliquely on the sample (the plane of incidence is parallel to the direction along which the voltage is measured). In general, this voltage would consist of several components, corresponding to the drag effect, to the surface photogalvanic effect, to the volume photogalvanic effect, and to inhomogeneities of the sample (V_0). In order to extract V_{dr} from the overall signal we calculate the difference between the voltages measured in experiments with two angles of incidence of opposite sign, $\pm\theta$, with light polarized perpendicular to the plane of incidence. In this geometry there is no surface photogalvanic current,[4] and V_0 is eliminated by subtraction. The volume photogalvanic effect was measured in a special geometry [light was incident normally on the (110) plane] and was found to be much weaker than the drag effect or the surface photogalvanic effect.

The points in Fig. 1 show the spectrum $V_{\mathrm{dr}}(\omega)$ measured at $T=4.2$ K with $|\theta|=45°$ for a sample with a mobility of 150 000 $\mathrm{cm}^2/(\mathrm{V}\cdot\mathrm{s})$ and a free-electron concentration of 2×10^{14} cm^{-3} (at $T=78$ K). This spectrum consists of alternating-sign oscillations, caused by incomplete relaxation of electron momentum in the emission of longitudinal optical (LO) phonons.[5,4] Aside from the positive oscillation, whose sign corresponds to an electron current along the direction of the photon momentum, **q**, there are some narrow negative "recoil" peaks at the thresholds for the

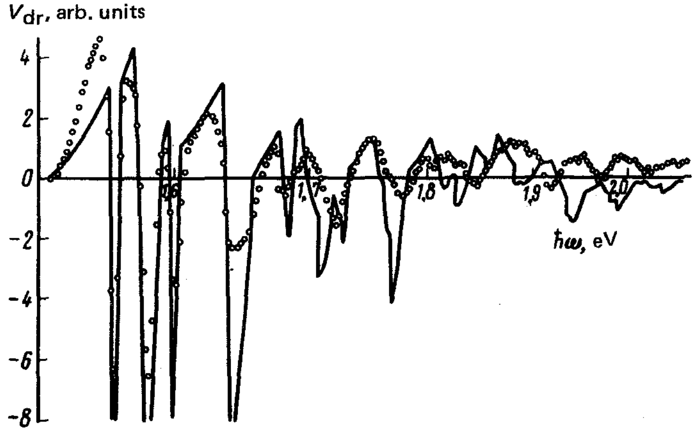

FIG. 1.

emission of LO phonons by electrons.[6,3] The resonant-recoil effect occurs because at the given light frequency ω the energy of photoexcited electrons with momentum $\mathbf{k}\uparrow\uparrow\mathbf{q}$ is higher than that for electrons with $\mathbf{k}\uparrow\downarrow\mathbf{q}$. As ω increases, the electrons with $\mathbf{k}\uparrow\uparrow\mathbf{q}$ are the first to emit LO phonons, so that they do not contribute to the current. The sign and magnitude of the current in the resonance region are determined by electrons with $\mathbf{k}\uparrow\downarrow\mathbf{q}$, which cannot emit an LO phonon.

Grinberg *et al.*[7] have derived a theory for the drag effect for interband transitions in $A^{\rm III}B^{\rm V}$ crystals. Their results do not apply to the present experiments, since they are actually limited along the light-frequency scale by the first threshold for the emission of an LO phonon, and they neglect the Coulomb attraction of the electron and the hole. A theory derived to incorporate these factors yields the following expression for the total photocurrent along the surface:

$$j = \frac{2eI}{5\hbar\omega}\sum_{\nu,\nu'=\pm 1}\frac{q\kappa_\nu}{k_\nu\kappa}\Bigg\{\delta_{\nu\nu'}\Bigg[\Lambda^e(\tilde{\epsilon}_\nu^e)\,U_1^e(\epsilon_\nu^e)\left(\frac{\mu_\nu}{m_\nu}\tilde{a}_\nu+\beta_\nu-\frac{\mu_\nu}{m_e}\frac{d\tilde{a}_\nu}{d\epsilon_\nu^e}\right)$$

$$+\frac{\mu_\nu}{m_\nu}\tilde{a}_\nu\epsilon_\nu^e\, d(U_1^e(\epsilon)\Lambda^e(\tilde{\epsilon}))\Big/ d\epsilon\,\Big|_{\epsilon=\epsilon_\nu^e}\Bigg]-\Lambda_{\nu'}^h(\tilde{\epsilon}_\nu^h)\,U_{1\nu'\nu}^h(\epsilon_\nu^h) \tag{1}$$

$$\times\frac{\mu_\nu}{m_e}\left(\tilde{a}_\nu+\epsilon_\nu^h\frac{da_\nu}{d\epsilon_\nu^h}\right)-\frac{\mu_\nu}{m_e}\tilde{a}_\nu d\left(U_{1\nu'\nu}^h(\epsilon)\,\Lambda_{\nu'}^h(\epsilon)\right)\Big/d\epsilon\,\Big|_{\epsilon=\epsilon_\nu^\mu}\Bigg\};$$

$$\tilde{a}_\nu = 2(a_\nu+1)\,,\ \beta_\nu = 2-3a_\nu,\ a_\nu = (3-\nu+(1+\nu)\cos\psi(k))/4,$$

Here m_e and m_ν are the mass of the electron and of a ν hole; μ_ν is their reduced mass; $\epsilon_\nu^{e(h)} = k^2/2m_{e(\nu)}$; κ_ν is the partial light absorption coefficient ($\kappa = \kappa_+ + \kappa_-$), which is proportional to the Sommerfeld factor [this factor incorporates the Coulomb interaction of the electron and the hole and is independent of **q** in the approximation $(\mu_- - \mu_+)/(\mu_- + \mu_+) \ll 1$]; $\psi(k)$ is the mixing angle of the states with helicity 1/2 in the valence band [at the absorption edge, $\cos\psi(k) = -1/3$]; and I and n_ω are the intensity of the light and the corresponding refractive index. Expression (1) is derived for the case in which the momentum relaxation of the charge carriers occurs in two steps. First, there is a partial momentum loss during the emission of $n = \mathrm{Int}(\epsilon/\Omega_{LO})$ LO phonons; for electrons, this loss is described by the function $U_1^e(\epsilon)$, while for holes it is described by $U_{1\nu'\nu}^h(\epsilon)$, where the conversion of light and heavy holes is taken into account. The final step of the relaxation occurs in a passive zone, where the electrons and holes have respective mean free paths $\Lambda^e(\tilde{\epsilon})$ and $\Lambda^h(\tilde{\epsilon})$ with respect to scattering by impurities and the emission by impurities of acoustic phonons, $\tilde{\epsilon} = \epsilon - n\Omega_{LO}$. The four series of recoil peaks in (1) arise from the energy derivatives of the step functions $\Lambda^e(\tilde{\epsilon})U_1^e(\epsilon)$ and $\Lambda_{\nu'}^h(\tilde{\epsilon})U_{1\nu'\nu}^h(\epsilon)$.

The solid curve in Fig. 1 is a theoretical drag spectrum. The theory predicts the drag current correctly in order of magnitude, and it gives a good description of the position of the oscillatory features up to $\hbar\omega \approx 1.8$–1.9 eV, at which spin-orbit holes begin to form, and electrons begin to be scattered into the side minimum of the conduction band. In terms of the shape of the oscillation, on the other hand, there are some important differences between theory and experiment. The hole part of the photocurrent is smaller than the electron part because of the stronger scattering of holes by acoustic phonons.

Figure 2 shows the first recoil peak according to measurements with a resolution higher than that in Fig. 1. The integral intensity of this peak, normalized to the photocurrent at the maximum (at $\hbar\omega \approx 1.55$ eV) is $\approx 0.5\Omega_{LO}$, in approximate agreement with the theoretical value calculated from Eq. (1), $0.7\Omega_{LO}$. The experimental width of the peak is ≈ 5 meV; the broadening, which results from the finite photon momentum,[6] is 2 meV, and that due to the modulation of the hole dispersion laws[3] is

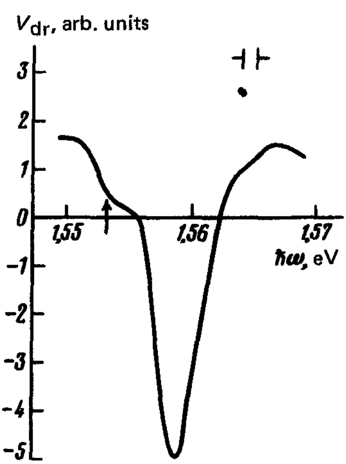

FIG. 2.

1 meV. The remaining 2 meV is apparently caused by inhomogeneous and instrumental broadening. The width of the recoil peaks on the theoretical curve in Fig. 1 is found as the sum of the widths corresponding to all of these mechanisms; the integral intensity corresponds to Eq. (1); and the shape of the peaks is chosen to be parabolic, since the exact shape of the recoil peaks is rather complicated. The dip on the left wing of the recoil peak, shown by the arrow in Fig. 2, lies ≈ 5 meV from the center of the peak and is apparently caused by the capture of an electron by a shallow donor, accompanied by the emission of an LO phonon. The drag effect is actually a "differential" method [terms with $\partial\Lambda/\partial\epsilon$ are retained in (1)]. It has thus been possible to identify a faint spectral feature which is not observed in the photoemf spectrum[8] or the spectrum of the surface photogalvanic current.[4]

1. A. M. Danishevskiĭ, A. A. Kastal'skiĭ, S. M. Ryvkin, and I. D. Yaroshetskiĭ, Zh. Eksp. Teor. Fiz. **58**, 544 (1970) [Sov. Phys. JETP **31**, 292 (1970)].
2. A. A. Grinberg, Zh. Eksp. Teor. FIz. **58**, 989 (1970) [Sov. Phys. JETP **31**, 531 (1970)].
3. A. F. Gibson and S. Montasser, J. Phys. C **8**, 3147 (1975).
4. V. L. Al'perovich, V. I. Belinicher, V. N. Novikov, and A. S. Terekhov, Pis'ma Zh. Eksp. Teor. Fiz. **31**, 581 (1980) [JETP Lett. **31**, 546 (1980)].
5. V. D. Dyminkov, M. I. D'yakonov, and V. I. Perel', Zh. Eksp. Teor. Fiz. **71**, 2373 (1976) [Sov. Phys. JETP **44**, 1252 (1976)].
6. A. A. Grinberg and L. V. Udod, Fiz. Tekh. Poluprovodn. **6**, 1012 (1972).
7. A. A. Grinberg, A. S. Bulyanitsa, and E. Z. Imamov, Fiz. Tekh. Poluprovodn. **7**, 45 (1973) [Sov. Phys. Semicond. **7**, 29 (1973)].
8. V. L. Al'perovich, A. F. Kravchenko, N. A. Pakhanov, and A. S. Terekhov, Fiz. Tekh. Poluprovodn. **14**, 1768 (1980) [Sov. Phys. Semicond. **14**, 1052 (1980)].

Translated by Dave Parsons
Edited by S. J. Amoretty