Dragging of electrons by light in semimetals

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(Submitted September 27, 1976; resubmitted December 17, 1976)
Pis'ma Zh. Eksp. Teor. Fiz. **25**, No. 2, 113–116 (20 January 1977)

Dragging of carriers by CO_2-laser light has been observed. The effect is anisotropic and the longitudinal dragging emf reverses sign in the interval $T = 300$–77.3°K.

PACS numbers: 73.60.Fw, 79.60.Eq, 79.20.Ds

The photoelectric effect due to a light pulse following absorption of the light by the free carriers was observed and investigated in semiconductors.[1–5] It can be shown that in metals and semimetals owing to the large light-absorption coefficient a, the dragging emf in a direction longitudinal relative to the photon momentum $\hbar\kappa$ should be very small. This leads to considerable difficulties in the experimental observation of the effect. Askar'yan *et al.*[6] have observed a signal in a coil placed near the surface of a metal when the surface was irradiated by a ruby-laser pulse. They propose that the signal is the result of the current caused by the light pressure on the electrons in the metal.

We present here the results of the experimental observation and investigation of the dragging effect is semimetal films, with the dragging emf measured directly. The registration of the dragging emf in films of thickness comparable with the depth of penetration of the light is facilitated in the following situations: application of a magnetic field perpendicular to κ,[3] observation of the transverse dragging emf in materials with anisotropic dragging effect,[4,5] and oblique incidence of the light.[6,7] By way of example, taking into account the results of[5], we present the value of the dragging emf for a uniformly illuminated film in the direction of the normal (V_z) and of the separation boundary (V_x) in the case of inclined incidence of the light (Fig. 1):

$$V_x = V_z \frac{l}{d} \operatorname{tg} \beta; \quad V_z = \frac{(1-R) e \hbar \kappa I_0 < \tau >}{m^* \sigma} \left[1 - \exp\left(- \frac{ad}{\cos\beta} \right) \right] \cos\gamma \cos^2\beta, \tag{1}$$

where e, m^*, and σ are respectively the electron charge, the effective mass of the carriers, and the conductivity of the bismuth film; I_0 is the intensity of the

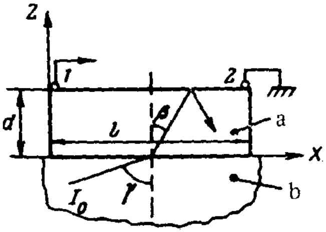

FIG. 1. Oblique incidence of light on bismuth: d and l are the thickness and length of the film; a) bismuth film, b) silicon substrate; 1, 2) electric contacts.

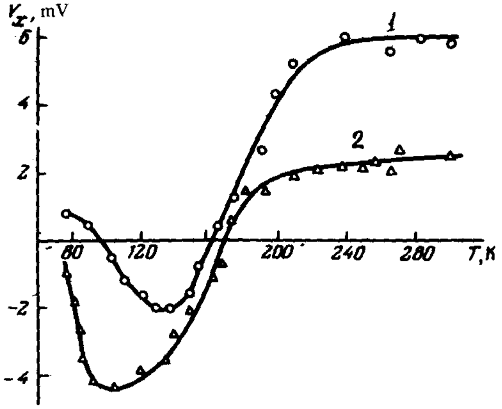

FIG. 2. Dependence of the dragging emf in bismuth on the temperature for oblique incidence of light: 1) $\lambda = 10.6\ \mu$, laser power 10 kW; 2) $\lambda = 9.54\ \mu$, laser power 5 kW.

light at the interface, R is the reflection coefficient, and $\langle\tau\rangle$ is the averaged relaxation time of the directed momentum of the carriers.

As seen from (1), V_x is $\sim (l/d)\tan\beta$ times larger than V_z.

We used in the experiments a pulsed CO_2 laser with a frequency tunable in the range $\lambda \approx 9.2$—$10.8\ \mu$. The intensity of the light on the sample was low enough to exclude the appearance of parasitic photo-emf.[1)]

Bismuth was chosen for the investigation because of its large light-absorption cross section, its large refractive index, and the appreciable penetration depth of the light ($\sim 1\ \mu$). The dragging current in oriented bismuth films should be anisotropic[4] because the equal-energy surfaces in the conduction and valence bands are not spherical. From the symmetry of the crystal it follows that the transverse dragging emf should be equal to zero if the direction of κ coincides with the threefold axis and should be different from zero at other directions of κ. The bismuth was sputtered on a single-crystal-silicon or mica substrate by the technology described in[8]. The bismuth films had a predominant orientation along the twofold axis in a direction normal to the film plane on silicon substrates, and were strictly oriented along the threefold axis in a direction normal to the film on mica substrates. The films had an area $\sim 3.5 \times 6$ mm and a thickness $d \leq 0.3\ \mu$. The electric contacts were deposited in the x direction (Fig. 1). In the experiments with the bismuth films on silicon, we used both oblique (Fig. 1) and normal incidence of the light. The angle γ was set equal to 75° or $-75°$ for each sample. At these angles, the laser light experienced total internal reflection at the bismuth-vacuum interface (Fig. 1). In the case of bismuth on mica, we investigated the dragging only with normal incidence of the light. The measurements were performed in the temperature interval from 300—77.3 °K.

Oblique incidence of light on the bismuth-silicon sample generated across the contacts a fast emf that duplicated exactly the waveform of the laser pulse. A change over from the TM to the TE mode decreased the emf V_x by the ratio of the reflection coefficients for these modes. The emf V_x varied linearly with the light intensity. When the angle γ was changed from 75 to $-75°$, only the sign of V_x was reversed. With decreasing temperature (Fig. 2) from 300 to 77.3 °K, the emf V_x reversed sign twice at $\lambda \approx 10.6\ \mu$ and once at $\lambda \approx 9.54\ \mu$. The strongest spectral dependence of V_x occurred near the inversion temperature, in the vicinity of which V_x had opposite signs for adjacent laser-emission lines. In the case of normal incidence of the light on the bismuth films at $T \sim 300$ °K, an emf perpendicular to κ appeared and varied like $\cos 2\phi$ with the rotation angle ϕ between the light-polarization vector and the direction of the line joining the contacts. The amplitude of the transverse emf was smaller by one order of magnitude than the value of V_x for oblique incidence at the same temperature. In the samples of bismuth on mica, the transverse emf V_x was equal to zero. The observed form of the angular[4] and the temperature[1] dependences of the emf V_x, as well as other results, show definitely that the rapid emf V_x is a result of the transfer of the momentum of the light to the system of the carriers in the bismuth during the course of the absorption of the light. The CO_2 laser emission is absorbed independently by the electrons and holes in intraband transitions and in direct interband transitions in bismuth, and it can be shown[1] that each of these interactions results in two oppositely directed fluxes of carriers that differ in energies by one light quantum. The fluxes have different temperature dependences; the temperature dependences of the dragging emf is therefore complicated and dependence on the quantum energy. It follows from the sign of V_x (Fig. 2) that the electrons in bismuth are dragged in the κ directly at $T \sim 300$ °K.

The observed dragging effect in semimetals can be of interest in connection with the possibility of its practical utilization in the near infrared and visible regions of the spectrum, and also the expected possibility of registering the resonant increase of the dragging current[7,9,10] in the region of the plasma minimum of reflection in metals.

[1)] At light intensities $I_0 \gtrsim 0.5$ MW/cm^2, parasitic photo-emfs were observed in bismuth, but could be easily distinguished from dragging emfs in our experiments. The parasitic photo-emfs lagged the laser pulse by a time $t \sim (20-100)\times 10^{-9}$ sec and their magnitude at $I_0 \gtrsim 0.5$ MW/cm^2 varied with the light intensity like $V \sim I_0^{2.0-2.5}$. The mechanism that produces these photo-emfs is not clear at present. The experimental results described above were obtained at $I_0 < 0.5$ MW/cm^2.

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