Ballistic electron transport through epitaxial GaAs films in a magnetically induced surface photocurrent

V. L. Al'perovich, A. O. Minaev, and A. S. Terekhov
Institute of Semiconductor Physics, Siberian Branch of the Academy of Sciences of the USSR

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A nonmonotonic dependence of the magnetically induced surface photocurrent on the magnetic field has been observed. This behavior is evidence of a transport of ballistic photoelectrons through a thick ($d \sim 10\,\mu$m) epitaxial film of n-type GaAs and of a scattering of these electrons at the interface with the substrate. The diffuseness coefficient of the scattering of 30-meV electrons by the free surface of the epitaxial film is $P_1 \approx 0.2$, and that of the scattering by the film-substrate interface is $P_2 \approx 0.7$.

The ballistic photocurrent which arises in the stage of the free motion of photoelectrons between the time at which they are produced by the light and the time at which they undergo a momentum scattering makes it possible to study the ballistic transport not only in structures of submicron size by also in ordinary macroscopic structures. Of particular interest is the use of ballistic photocurrents to study the scattering of interfaces in layered semiconductors structures. In this letter we are reporting the observation of a new mechanism for a ballistic photocurrent. This mechanism involves an optical alignment[1] and a diffuse scattering of the photoelectrons at the boundaries of an epitaxial film.[2–4] It has been shown experimentally that when the momentum mean free path satisfies $\Lambda_p \gtrsim d$, the photoelectrons cross the film in a ballistic regime and lose momentum at the inteface with the substrate. A comparison with calculations has yielded an estimate of the "diffuseness coefficient" of the scattering at an interface between n-type GaAs and a semi-insulating substrate.

The ballistic photocurrent along the surface is measured during normal incidence of the light in a tangential magnetic field **B**, which rotates the paths of the optically aligned electrons. The diffuse scattering at the boundaries of the film leads to an asymmetry in the distribution function and to a corresponding photocurrent. The direction of the optical alignment is determined by the light polarization vector **e**, so the photocurrent is polarization-dependent[4]:

$$\mathbf{j} \sim \mathbf{e}(\mathbf{e}[\mathbf{B} \times \mathbf{n}]), \tag{1}$$

where **n** is the normal to the surface. A ballistic photocurrent similar in nature was studied in Refs. 2 and 3, but in the absence of a magnetic field and with obliquely incident light. Note that a diffuse scattering of momentum, without an energy loss at the boundaries (or at one of the boundaries) of the film, is sufficient for the onset of the photocurrent observed here, while the magnetically induced photocurrent across a film[5] requires a randomization of the photoelectrons at a boundary.

The experiments were carried out at 4.2 K on epitaxial films of n-type GaAs with thicknesses 7–100 μm, mobilities $\mu \approx 3 \times 10^4$–$1.3 \times 10^5$ cm^2/(V·s), and densities

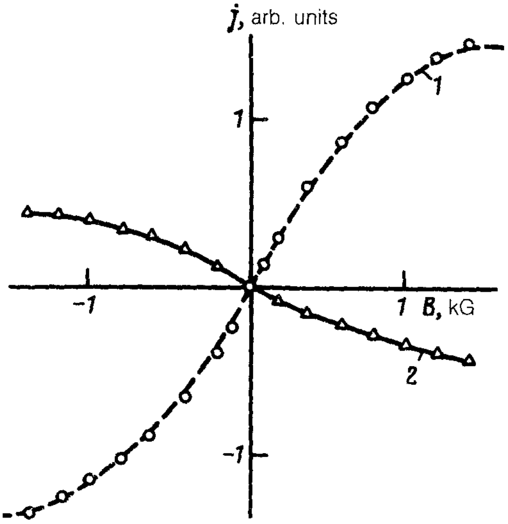

FIG. 1.The $j(B)$ dependence in sample 1. 1—$\hbar\omega = 1.552$ eV; 2—1.571 eV. Solid line) drawings for the experimental points; dashed line) theoretical ($\Lambda_p = 7\ \mu$m).

$n \approx 1\times10^{14}$–2×10^{15} cm^{-3} at 77 K, grown on semi-insulting substrates. The polarization of the light incident on a sample with ohmic contacts was modulated between two orthogonal states. The construction of the apparatus is described in Ref. 6. We measure the photocurrent j at the frequency of the polarization modulation when this current arises upon the imposition of a magnetic field parallel to the surface. To eliminate the effect of the Kikoin-Noskov photomagnetic effect, we use the $\mathbf{j}\|\mathbf{B}$ geometry. The measured dependence of the photocurrent on the angle between the vectors **e** and **B** is described well by expression (1) in all of the samples studied.

Figure 1 shows the photocurrent versus the magnetic field measured in sample 1 [with a thickness $d = 36\ \mu$m and $\mu = 3\times10^4$ cm^2/(V·s)] for photon energies $\hbar\omega = 1.552$ and 1.571 eV, which correspond to initial energies $\epsilon = 30$ and 47 meV of the electrons which are produced with a heavy hole. At $\epsilon = 47$ meV$> \hbar\Omega_{LO} = 37$ meV, an *LO* optical phonon is emitted, so the current is dominated by electrons produced with light holes. The reason for the change in the sign of the effect is that the directions of the predominant emission of electrons from the heavy and light channels are mutually orthogonal.[1]

Figure 2 shows $j(B)$ in the case of greatest interest, $\Lambda_p > d$ [sample 2; $d = 12\ \mu$m, $\mu = 8\times10^4$ cm^2/(V·s), $\Lambda_p = 18\ \mu$m at $\epsilon = 30$ meV]. In weak fields, the photocurrent changes sign. We believe that this is a consequence of a scattering of ballistic electrons by the film-substrate interface; this scattering gives rise to a current component of the opposite sign. This component is predominant in weak fields if $\Lambda_p \gtrsim d$ and $P_2 > P_1$. At large values of B, with a *a* cyclotron radius $r_c < d/2$, the real boundary of the sample becomes inaccessible to the ballistic photoelectrons. In this case we are left with only the component stemming from the scattering by the front boundary, which increases

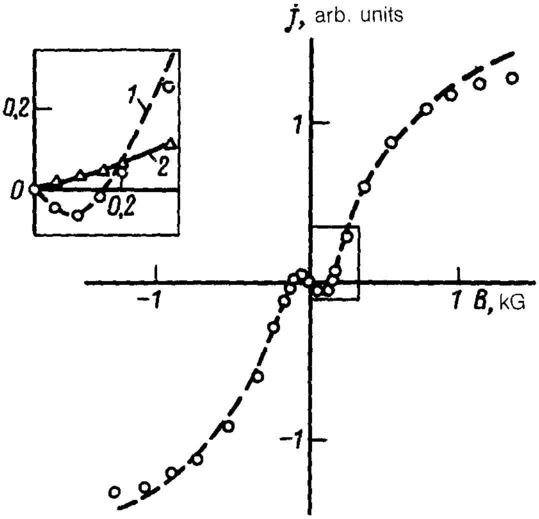

FIG. 2. The $j(B)$ dependence in sample 2 at $\hbar\omega = 1.552$ eV. Dashed line—Theoretical. The inset shows $j(B)$ at small B for (1) $\hbar\omega = 1.552$ eV and (2) 1.540 eV.

as the field is raised to fairly high values, corresponding to $r_c \sim \alpha^{-1}$, where $\alpha^{-1} \approx 1$ μm is the optical absorption depth. In the case of the excitation of photoelectrons with a lower energy, $\epsilon = 19$ eV ($\hbar\omega = 1.540$ eV), the corresponding decrease in the mean free path[2] ($\Lambda_p = 9$ μm) again results in a suppression of the component due to the scattering by the rear boundary (see the inset in Fig. 2).

These qualitative arguments have been confirmed by a numerical calculation of the photocurrent in the Fuchs model for the scattering at both boundaries. The diffuseness coefficients P_1 and P_2 were used as adjustable parameters. The $\Lambda_p(\epsilon)$ calculations incorporated the scattering of electrons by charged impurities and by the strain energy of the acoustic phonons.[2] The impurity concentration was found from the mobility μ. The results are shown in Figs. 1 and 2. The best agreement with experiment is found with $P_1 \approx 0.2$ and $P_2 \approx 0.7$ at $\epsilon = 30$ meV. A qualitative correspondence between the experiments and the calculations (a nonmonotonic B dependence at $\Lambda_p \gtrsim d$ and a saturation at large B) was found in all of the samples studied. In some of the samples, however, the $j(B)$ dependence could not be described qualitatively by the calculations. Possible reasons for this discrepancy are effects of an electric field due to a surface charge and of the film-substrate interface.

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