Polarization-dependent ballistic photovoltaic effect in a metal-semiconductor structure

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The ballistic photo-emf in gallium arsenide which results from the interaction of photoelectrons with a metal-semiconductor interface has a polarization-dependent component because of the corrugation of the valence band.

At liquid-helium temperatures the photovoltaic effect in (gallium arsenide)-metal structures is caused primarily by the flow of ballistic photoelectrons into the interior of the semiconductor (a ballistic Dember voltage) and into the metal (a surface photovoltaic effect).[1] In this letter we show experimentally and theoretically that when light is incident normally on a cubic crystal, these ballistic photovoltaic effects contain polarization-dependent components that result from the anisotropy of the wave functions and of the dispersion laws in the valence band.

The spectra of the photo-emf are measured on Al-(n-GaAs)-(n^+-GaAs) structures by the procedure described in Ref. 1. An electrooptic device modulates the polarization (**e**) of the light in the measurements of the polarization-dependent component of the photo-emf. The parasitic intensity modulation during the modulation of the polarization is less than 3×10^{-4}.

Figure 1 shows the spectra of the photo-emf and of the polarization-dependent photo-emf measured for a sample in the (110) orientation. The oscillations in the spectra at $\hbar\omega > \epsilon_g$ (the right side of this inequality is the gap width) are caused by a stepped thermalization of electrons accompanied by the emission of optical (LO) phonons at $\hbar\omega \approx 1.56$ and 1.60 eV. The apparent reason for the structure at $\hbar\omega \lesssim \epsilon_g$ is a

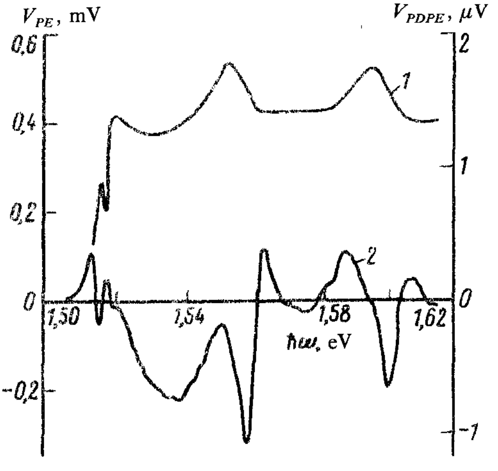

FIG. 1. Spectra of the photo-emf (1) and of the polarization-dependent photo-emf (2) at $T = 4.2$ K. The thickness of the epitaxial n-GaAs layer is $d = 22$ μm; the density is $n_{77} \sim 10^{14}$ cm^{-3}; and the mobility is $\mu_{77} \sim 10^5$ cm^2/(V · s).

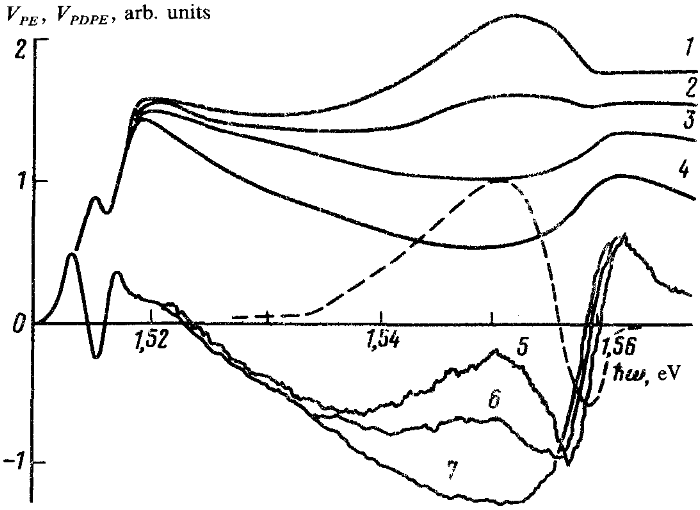

FIG. 2. Spectra of the photo-emf (1–4) and of the polarization-dependent photo-emf (5–7) in the region of the first phonon oscillation in various magnetic fields H, Oe: 1—0; 2—95; 3—175; 4—700, 5—0; 6—40; 7—100.

spatial dispersion due to excitons.[2] Figure 2 shows spectra of the photo-emf and of the polarization-dependent photo-emf corresponding to the passive region[1)] and to the first threshold for the emission of LO phonons, from measurements in various magnetic fields H. As H is raised from 0 to $\sim$200 Oe, the changes in the photo-emf spectrum result from a decrease in the ballistic Dember voltage. In fields $H > 200$ Oe, the photo-emf depends only slightly on H and is instead governed by the barrier-layer photo-emf. This behavior of the photo-emf spectra in a magnetic field corresponds to the results of Ref. 1. We see from Fig. 2 that the spectrum of the polarization-dependent photo-emf also has a component that varies by a factor of two in a weak field $H \approx 50$ Oe. At $H > 100$ Oe, the changes in the spectrum of the polarization-dependent photo-emf are relatively small. We believe that the component of the polarization-dependent photo-emf which depends strongly on the magnetic field (the component found by subtracting the spectra of the polarization-dependent photo-emf at $H = 0$ and $H = 100$ Oe, as shown by the dashed line in Fig. 2) is caused by the ballistic Dember voltage,[3] while the component that depends only weakly on H is due to the ballistic surface photo-emf.

When light is incident normally on the (110) plane, the polarization dependence of the ballistic Dember voltage and of the surface photo-emf arises from a corrugation of the valence band in the photoproduction probability W_{ph}. In this geometry, there is no normal component of the bulk photovoltaic current,[4] which arises because GaAs lacks an inversion center. Consequently, the normal component of the photocurrent, including both types of photo-emf, can be described by the phenomenological expression

$$j_{\mathbf{n}} = (\mathbf{j}\mathbf{n}) = T_{klmn} n_k n_l e_m e_n , \tag{1}$$

where the tensor T_{klmn} has three independent components in a cubic crystal, and $\mathbf{n}$ is the unit normal. Solving the kinetic equation with W_{ph}, which incorporates the corrugation effects, we find the following expression for the ballistic Dember voltage:

$$V=\frac{eI}{4\sigma\omega}\sum_{\nu}\frac{\kappa_{\nu}}{\kappa}\Lambda_{p}(\epsilon_{\nu})\Big\{(1{,}7+0{,}1\nu)-1{,}5\times10^{-2}\beta\Big[\nu+0{,}1N\mu_{\nu}\Big(1{,}5+\frac{\epsilon_{\nu}}{\Lambda_{p}}\frac{\partial\Lambda_{p}}{\partial\epsilon_{\nu}}\Big)\Big]\cos 2\varphi\Big\}, \qquad (2)$$

where I is the light intensity, σ is the conductivity, φ is the angle between **e** and the [001] direction, $\epsilon_{\nu}=(\omega-\epsilon_{g})\mu_{\nu}/m_{e}$ is the kinetic energy of an electron produced in pathway $\nu(\nu=-1$ corresponds to production from the light-hole band, and $\nu=1$ corresponds to the heavy-hole band), μ_{ν} is the reduced mass of the electron and hole, $\Lambda_{p}(\epsilon_{\nu})$ is the momentum mean free path of an electron, κ_{ν} is the partial absorption coefficient in pathway $\nu,\kappa=\kappa_{+}+\kappa_{-}$, and $\beta=3[N^{2}-(L-M)^{2}]/2(L-M)^{2}$ is the corrugation parameter, expressed in terms of the standard parameters of the valence band (M, L, and N). Expression (2) was derived in a model with an elastic, isotropic volume scattering, with interfaces between the n-GaAs and the metal and with the n^{+} substrate which are ideally penetrable by electrons, and with a thickness $d\gg\Lambda_{p}$ of the n:GaAs layer. In this model, as can be seen from (2), the Dember voltage is proportional to Λ_{p}, reflecting its ballistic nature. The reason for the polarization dependence of the Dember voltage is that as the polarization direction **e** is changed, there is a change in the ratio of the numbers of electrons produced with momenta directed along the surface and perpendicular to it. Consequently, **e** determines the ratio of the numbers of electrons which are emitted into the metal and which go into the interior of the n-type layer and therefore the ratio of the ballistic Dember voltage and the surface photo-emf. This model can explain the following results. The measured polarization dependence of the polarization-dependent photo-emf is $V\sim\cos2\varphi$. For a sample in the (100) orientation, there is no polarization-dependent photo-emf, in accordance with (1). The ratio of the polarization-dependent photo-emf to the photo-emf is $\sim3\times10^{-3}$, in agreement with the theoretical estimate. This theory predicts the sign and order of magnitude of the narrow negative peak in the spectrum of the polarization-dependent Dember voltage (the dashed line in Fig. 2). This peak is due to a decrease in Λ_{p} at the threshold for the emission of an LO phonon and to the derivative $\partial\Lambda_{p}/\partial\epsilon_{\nu}$ in (2). Why the measured spectrum of the polarization-dependent photo-emf has no contribution from electrons from the light-hole pathway is not clear. It should be noted that the observed polarization-dependent photo-emf may consist of components due to (in addition to the ballistic Dember voltage) ballistic effects of a different microscopic nature, in particular, effects of a photon drag of electrons.[5] In our geometry, the polarization properties of the Dember voltage and the drag effect are identical, but the latter effect is smaller than the former by a factor $q/k\sim0.1$, where k is the momentum of a electron at the vertex of the passive region, and q is the momentum of the photon.

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[1)] The passive region corresponds to an electron energy $0 < \epsilon < \hbar\Omega_{LO}$ above the bottom of the conduction band.

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