Surface photovoltaic effect in gallium arsenide

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The previously predicted, polarization-dependent photocurrent along the surface of a solid was observed experimentally in GaAs. The theory for this effect, which describes the experimental data quantitatively, is developed.

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Volume photocurrents associated with the absence of the center of symmetry in a medium have been reported in the literature.[1] It was shown[2] that a current similar in nature can be generated in samples whose thickness is comparable with the length of the mean free path of photoproduced electrons. As shown in Ref. 3, a photocurrent can also be generated near the surface of bulk solids, not just in films. A surface photocurrent (*SPC*) is attributable to the anisotropy of momentum distribution of electrons produced in the conduction band as a result of optical transitions in solids. If the scattering of electrons from a surface is taken into account, then the loss of momentum of anisotorpically produced electrons occurs asymmetrically—the cause of *SPC*.

The *SPC* **J** is quadratic with respect to the field of a light wave $\tilde{\mathbf{E}}$:

$$J_i = \theta_{ij}\, \gamma_{iklm} \tilde{E}_k \tilde{E}_l n_m ; \quad \theta_{ij} = \delta_{ij} - n_i n_j . \tag{1}$$

Here n is the vector of the normal to the surface. In isotropic solids the *SPC* is determined by one constant $\mathbf{J} = \gamma \mathbf{Y} |\tilde{\mathbf{E}}|^2$, $\mathbf{Y} = [\mathbf{e} - \mathbf{n}(\mathbf{ne})](\mathbf{ne})$, where **e** is the polarization vector of light.

To calculate *SPC*, we can use kinetic theory. Thus, the nonisotropic correction for the electron distribution function, which satisfies the ordinary kinetic equation and the boundary conditions at the surface, has the form

$$\begin{gathered} f(z, \mathbf{k}) = \frac{W_{\mathbf{k}}}{\Gamma} [T_- e^{-\kappa z} - \theta(k_z)(T_- + \delta T_+) e^{-z/\Lambda_z}] \\ T_{\pm} = (1 \pm \kappa \Lambda_z)^{-1} . \end{gathered} \tag{2}$$

Here **k** is the electron momentum, z is a coordinate in the normal direction to the surface, Γ is the collision frequency, $W_{\mathbf{k}}$ is the density of photoproduced electrons, κ is the absorption coefficient of light Λ_z is the length of the mean free path in the **n** direction, $\theta(k_z)$ is a step function, and δ is the coefficient of reflecting surface ($\delta = 1$ for a reflecting surface and $\delta = 0$ for a surface that diffusely scatters the electrons). The first term in Eq. (2) is due to the diffusion process and the second term is due to the scattering from a surface. This distribution function for holes has an analogous form. GaAs $W_{\mathbf{k}}^{\nu}$ has the following form near the absorption edge[4] [1)]:

$$W_{\mathbf{k}}^{\nu} = \frac{\kappa_\nu l}{8\pi\hbar\omega} \frac{1}{k^3 \mu_\nu} [(2-\nu)k^2 + 3\nu |\mathbf{ke}|^2] \delta(\epsilon_{\mathbf{k}}^{\nu} + E_g - \hbar\omega) . \tag{3}$$

Here $\nu = \pm 1$ for the light and heavy holes, respectively, $\epsilon_{\mathbf{k}}^{\nu} = k^2/2\mu_\nu$, μ_ν is the reduced mass of the electron and hole, and κ_ν is the partial coefficient of light absorption $\kappa = \kappa_+ + \kappa_-$. If the energy of an electron (hole) E exceeds that of an optical phonon $\hbar\Omega_{LO}$, then a partial momentum isotropization of electrons (holes) will occur as a result of phonon emission. Isotropization terminates in the passive zone ($E < \hbar\Omega_{LO}$) with the scattering by charged impurities. Taking this fact into account, we have after substituting Eqs. (2) and (3) in the expressions for the current:

$$\begin{gathered} \mathbf{J} = \mathbf{Y} \frac{el}{\hbar\omega} \sum_{\nu, \nu' = \pm 1} \nu \frac{\kappa_\nu}{\kappa} [(1-\delta_e)\delta_{\nu\nu'} \Lambda_e^{\nu} f(\kappa \Lambda_e^{\nu}) U_e(\nu, \omega, m) \\ (1 - \delta_h^{\nu'}) \Lambda_h^{\nu'} f(\kappa \Lambda_h^{\nu}) U_h(\nu', \nu, \omega, m)], \end{gathered} \tag{4}$$

$$f(x) = [12x^2(1-x^2)\ln\left(\frac{1+x}{x}\right) + 3 - 8x - 6x^2 + 12x^3]/16;$$

$$x = (\kappa\Lambda)^{-1}.$$

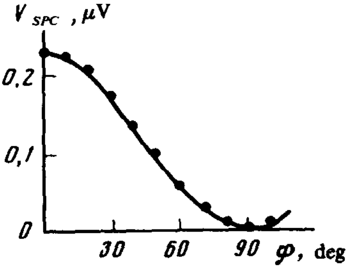

FIG. 1.

Here A_e^ν and A_h^ν are the lengths of the mean free path of electrons and holes in the channel ν, δ_e and δ_h^ν are reflecting surfaces of electrons and holes, and U_e (ν,ω,m) and U_h (ν',ν,ω,m) are functions taking into account the relaxation of the anisotropic particle W_k^ν (3) as a result of emission m of optical phonons and also the conversion of the light and heavy holes. The explicit form of U is not given because of their complexity.

The measurements were performed at temperatures of 1.6 and 4.2 K in the epitaxial layers of n-GaAs (with a mobility $\mu \sim 10^5$ cm^2/V sec and a concentration $n \sim 2\times 10^{14}$ cm^{-3} at $T = 77$K), which were grown on semi-insulating substrates. Two contacts were established by brazing indium onto the surface of the sample (for measurement of photoconductivity). A DFS-24 monochromator served as a source of light. An oblique incidence of light (the incident plane was perpendicular to the contacts) indeed an emf in the contacts, which was measured by using an amplifier with a synchronous detector. One part of this emf V_{SPC} was due to the SPC and the other V_0 was due to a possible doping inhomogeneity. V_{SPC} was identified from the polarization dependence.[2,3] The variation of the intensity of polarized light absorbed by the sample was determined by normalizing the emf to the value of photoconductivity. The ratio V_{SPC}/V_0 at $\hbar\omega = 1.55$ eV varied from sample to sample in the range of 0.15 to 5.

The dependence of V_{SPC} on the angle ϕ between the incident plane and the polar-

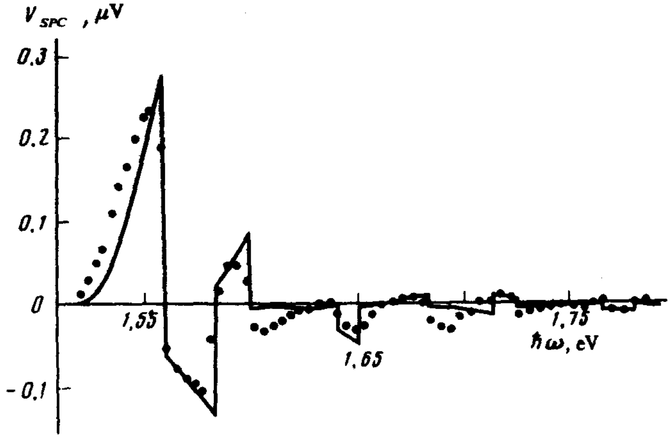

FIG. 2.

ization vector at $\hbar\omega = 1.55$ eV is shown in Fig. 1. It can be seen that the experiment (points) is described well by the dependence $V_{SPC} = v(\omega)\cos^2\phi$ (solid line) obtained from Eq. (1). In all the samples the sign of the effect at $\hbar\omega = 1.55$ eV corresponds to the theory (4) and is reversed as a result of changing the sign of the angle of incidence.

The points in Fig. 2 represent the *SPC* spectrum $V_{SPC}\ (\omega,\phi = 0)\equiv v(\omega)$, which was measured at $T = 4.2$ K in a 80-μm-thick epitaxial film with a (111) orientation and a charged-impurity concentration $N_i \approx 5\times10^{14}$ cm^{-3}. The solid line represent the theoretical *SPC* spectrum calculated on a computer using Eq. (4). The reflection parameters δ were determined from the best agreement between the theory and experiment. The scattering from the surface turned out to be almost specular: for electrons $(1-\delta_e)\approx 5\times10^{-2}$ and for holes $(1-\delta_h^{\nu})\lesssim 2\times10^{-3}$. It can be seen that the theory describes the reversal of the sign of the effect at the emission thresholds of the optical phonons and also the relation between the oscillation amplitudes. Analogous *SPC* spectra were obtained in all the investigated samples. The most significant difference between the spectra of different samples was the change in the magnitude and sign of the *SPC* at large ($\hbar\omega \gtrsim 1.65$ eV) phonon energies, where the magnitude of the effect, as follows from the theory, is determined by the contribution from the heavy holes. These variations and the difference between the oscillations and those predicted theoretically are due to the appreciable effect of the surface electric field on the *SPC*.[3] Note that at low temperatures a partial or total band rectification,[5] whose extent depends on the properties of surface states and on the intensity and duration of exposure to light, is possible in GaAs. Further investigation is necessary to determine the role of surface field in the *SPC*.

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[1)] The distribution ansotropy of photoelecrons in solids (optical alignment) was observed experimentally for the first time by Zakharchenya *et al.*[6] in the study of the polarization of hot luminescence in GaAs.

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[1] V. I. Belinicher and B. I. Strumay, Usp. Fiz. Nauk **130**, 415 (1980) [Sov. Phys. Usp. **23**, No. 3, (1980) (in press)].
[2] L. I. Magarill and M. V. Entin, Fiz. Tverd. Tela **21**, 1280 (1979) [Sov. Phys. Solid State **21**, 743 (1979)].
[3] V. I. Belinicher and V. N. Novikov, Preprint No. 127, IaIe SO ANSSSR, 1980).
[4] V. D. Dymnikov, M. I. D'yakonov, and V. I. Perel', Zh. Eksp. Teor. Fiz. **71**, 2373 (1976) [Sov. Phys. JETP **44**, 1252 (1976)].
[5] N. L. Dmitruk, V. I. Lyashenko, and A. K. Tereshchenko, Ukr. Fiz. Zh. **17**, 1349 (1972).
[6] B. P. Zakharchenya, V. I. Zemskii, and D. N. Mirlin, Pis'ma Zh. Eksp. Teor. Fiz. **24**, 96 (1976) [JETP Lett. **24**, 82 (1976)].