Mean free path and diffusivity of surface scattering of electrons in GaAs

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A measurement of the surface-photocurrent spectra in a magnetic field has made it possible to determine for the first time the energy dependence of the mean free path and diffusivity of the surface scattering of electrons.

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The surface photocurrent (SPC), which was discovered[1] for band-to-band transitions in GaAs, is caused by the anisotropy of the momentum distribution of photoproduced electrons and their partially diffuse scattering at the surface. The magnitude of the SPC is proportional to the product of the mean free path Λ of electrons with respect to momentum in the semiconductor and the diffusivity coefficient P. The magnetic-field dependences of the SPC obtained in this study made it possible to separate the contributions to the effect from the volume and surface scattering and to determine independently the energy dependences of both the mean free path and the diffusivity of the surface scattering of electrons.

A rotation of the anisotropic part of the electron momentum distribution function occurs in a magnetic field **H** (Refs. 2 and 3); this leads to a change in the SPC. In a geometry in which the normal to the surface has the components (0, 0, 1), the linear polarization vector of the light has the components $(0, e_y, e_z)$, and the magnetic field has the components (0, 0, H) the electron contribution to the passive band is

$$J_y + iJ_x = e_y e_z P \frac{eI}{\hbar\omega\kappa}\left[\kappa_h \Lambda_h f\left(\frac{\kappa_h \Lambda_h}{1 + i\omega_h \tau_h}\right) - \kappa_l \Lambda_l f\left(\frac{\kappa_l \Lambda_l}{1 + i\omega_l \tau_l}\right)\right] \tag{1}$$

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

Here e is the electron charge, I, ω, and c are the light intensity, frequency, and velocity, $\Lambda_{l,h}$, $\omega_{l,h} = eH/m_{l,h}c$, $m_{l,h}$, $\tau_{l,h} = \Lambda_{l,h}/v_{l,h}$, and $v_{l,h}$ are the mean free path, cyclotron frequency, mass, collision time, and the velocity of the electrons produced together with a light and heavy hole by light with a frequency ω; correspondingly, $\kappa_{l,h}$ are the partial light-absorption coefficients, and $\kappa = \kappa_l + \kappa_h$. Equation (1) is obtained in the τ approximation and at $H = 0$ it is identical to the electron contribution to the SPC, which was obtained in Ref. 1. The contribution of holes to the SPC is small at a concentration $N < 10^{15}$ of charged impurities, because of the efficient loss of momentum by the holes in the emission of phonons, and we ignore it here. For $\kappa\Lambda \gg 1$ the application of the magnetic field results in a decrease of the

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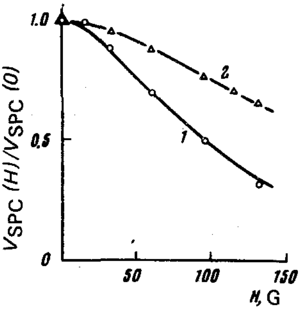

FIG. 1. Dependence of the SPC on H for ħω = 1.535 eV (1) and 1.547 eV (2), which corresponds to the kinetic energy of 16 and 28 meV, respectively, for the electrons produced in the band of heavy holes.

SPC along the y axis by a factor

$$J_y/J_y^\circ = \left(\frac{\kappa_h\Lambda_h}{1+\omega_h^2\tau_h^2} - \frac{\kappa_l\Lambda_l}{1+\omega_l^2\tau_l^2}\right) \Big/ (\kappa_h\Lambda_h - \kappa_l\Lambda_l). \qquad (2)$$

The SPC was measured at $T = 4.2$ K in a 190-μm-thick epitaxial GaAs layer that was grown on a semi-insulating substrate with a (111) orientation. The electron mobility in the layer was $\sim 10^5$ cm^2/V sec, and their density was 1.5×10^{14} cm^{-3}. The SPC was isolated from the total signal by making use of the polarization dependence.[1] The magnetic field was applied perpendicularly to the surface.

Figure 1 shows the dependence of the emf, which is caused by the SPC (V_{SPC}), on the magnetic field for two different photon energies ħω, which correspond to the energy $\epsilon < \hbar\Omega_{LO}$ of the photoproduced electrons, where $\hbar\Omega_{LO} = 36.7$ meV is the energy of the longitudinal optical phonon (the passive band). It can be seen that the SPC decreases in the magnetic field. The dependence of the field $H_{1/2}$, in which the SPC is reduced by a factor of 2, on the energy ħω is shown in Fig. 2. Curve 1 is the theoretical $H_{1/2}(\omega)$ dependence calculated from Eq. (2) with allowance for electron scattering by charged impurities with a density $N = 3 \times 10^{14}$ cm^{-3} and scattering by the deformation potential of the acoustic phonons with a constant $\sigma = 7$ eV. The values of the constants from Ref. 1 were used to calculate the scattering proba-

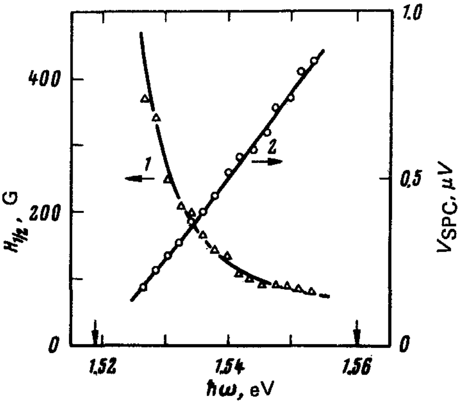

FIG. 2. Spectral dependence of the field $H_{1/2}$ (1) and the SPC (2). Solid lines correspond to the theory (see text). The forbidden-band gap $\hbar\omega_g = 1.519$ eV and the threshold for the emission of optical phonons by electrons from the heavy channel $\hbar\omega_{thr} = 1.560$ eV are shown by the arrows on the abscissa axis.

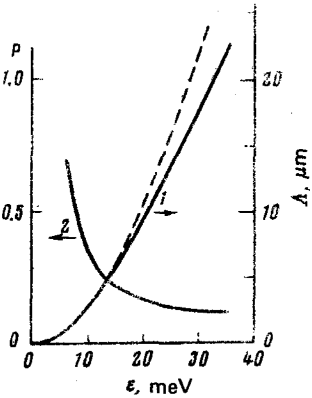

FIG. 3. The $\Lambda(\epsilon)$ (curve 1) and $P(\epsilon)$ (curve 2) dependences determined from comparison of experiment and theory. The dashed line represents $\Lambda(\epsilon)$, ignoring the scattering by acoustic phonons.

bilities. The value of N was chosen from the condition of best agreement between theory and experiment. The contribution to the SPC of electrons produced from the heavy- and light-hole bands was taken into account in the calculation. The energy dependence of the mean free path, which was calculated from the impurity concentration defined in this manner, is shown in Fig. 3. $\Lambda \approx 20$ μm near the top of the passive band; this exceeds the mean free path of thermalized electrons at helium temperature by three or four orders of magnitude. In this sample the dominant relaxation mechanism of the electron momentum for $\epsilon < \hbar\Omega_{LO}$ is the scattering by charged impurities, since the emission of acoustic phonons reduces Λ by no more than 30%.

A theoretical estimate of the mean free path $\Lambda = 1/N_D\sigma_D$ for the scattering of electrons by shallow neutral donors with a density $N_D \approx 10^{14}$ cm^{-3} (σ_D is the total scattering cross section of an electron by the donors) shows that this process should contribute significantly to the momentum relaxation of electrons. The use of this mechanism resulted in a much poorer agreement with the experiment. The discrepancy is probably attributable to the fact that the inelastic scattering of electrons with an energy $\epsilon \gg \epsilon_D$ (ϵ_D is the ionization energy of the donor) slightly isotropizes the electron momentum distribution.

The experimental SPC spectrum in the passive band is represented by the circles in Fig. 2. The energy-dependent diffusivity coefficient P was used in Ref. 1 in the theoretical description of $V_{\mathrm{SPC}}(\omega)$. The determination of the $\Lambda(\epsilon)$ function from the magnetic-field experiment made it possible to determine the $P(\epsilon)$ dependence from a comparison of the SPC spectrum with theory. Curve 2 in Fig. 2 was calculated for a $P(\epsilon)$ of the form

$$P(\epsilon) = P_o + P_1/\epsilon^2, \tag{3}$$

where $P_0 = 0.1$ and $P_1 = 25$ meV^2 were determined by the least-squares method. The term P_1/ϵ^2 corresponds to scattering by charged surface centers with a density $N_s = 1.7 \times 10^{10}$ cm^{-2}. The introduction of this term reduced the rms deviation by two orders of magnitude compared to $P = \mathrm{const}$. The microscopic nature of the ϵ-independent term P_0 is not clear. Its occurrence is possibly attributable to electron scattering by geometrical irregularities of the surface and by neutral surface defects.

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