Energy dependence of the relaxation time of electrons and holes in germanium. Anisotropy effects.

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The energy dependence of the relaxation time of electrons and holes for three directions in the Brillouin zone in germanium and the interaction constants of light and heavy holes interacting with optical phonons for these directions are determined for the first time from the damping of oscillations in multioscillatory electroreflection spectra using the theory of Aronov and Ioselevich [Zh. Eksp. Teor. Fiz. **81**, 336 (1981)] [Sov. Phys. JETP **54**, 181 (1981)].

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Oscillations in electroreflection (ER) spectra resulting from interference of the wave functions of an electron and hole appearing in interband optical transitions are highly sensitive to electron and hole scattering in the crystal. It was found in Ref. 1 that as a result of scattering the envelope $\Phi(w,\mathscr{E})$ of the oscillating part of the ER spectrum decreases exponentially with increasing photon energy $E = \hbar w$

$$\Phi_{l,h}(w, \mathscr{E}) = A_{l,h}\hbar\theta_{l,h}\Delta^{-1}\exp\left[-(\hbar\theta_{l,h})^{-3/2}\int_0^{\Delta}\Gamma_{l,h}(E)E^{-1/2}dE\right], \tag{1}$$

$$\Gamma_{l,h}(E) = \Gamma^{(c)}\left(\frac{\mu_{l,h}}{m_c}E\right) + \Gamma^{(v)}_{l,h}\left[\left(1-\frac{\mu_{l,h}}{m_c}\right)E\right] \tag{2}$$

where $\Gamma^{(c)}$ is the damping of the electron; $\Gamma^{(v)}_{l,h}$ is the damping of the light and heavy holes, respectively; $\hbar\theta_{l,h} = (e^2\mathscr{E}^2/2\mu_{l,h})^{1/3}$; $\mu_{l,h}$ is the reduced effective mass of the electron and hole in the direction along the electric field $\mathscr{E}$; $A_{l,h}$ is an amplitude factor; $\Delta = (E - E_g)$, E_g is the width of the forbidden band; $\Gamma_{l,h}(E) = \sum_j \hbar/\tau_{jl,h}(E)$, and j is the scattering.

For quasielastic scattering, the damping is a power-law function of the energy E:

$$\Gamma_{j\,l,h}(E) = C_{jl,h}E^{r_j} \tag{3}$$

where $r = -3/2$ for impurity ions, $r = 0$ for impurity neutrals, and $r = 1/2$ for phonon scattering. Substitution of (3) into (1) for the three types of scattering gives

$$\ln\{A^{-1}_{l,h}\Delta(\hbar\theta_{l,h})^{-1}\Phi_{l,h}(w, \mathscr{E})\} = (\hbar\theta_{l,h})^{-3/2}[C_{\text{ion}\,l,h}\Delta^{-1} + 2C_{\text{neut}\,l,h}\Delta^{1/2} + (C_{\text{ac}\,l,h} + C_{\text{opt}\,l,h})\Delta]. \tag{4}$$

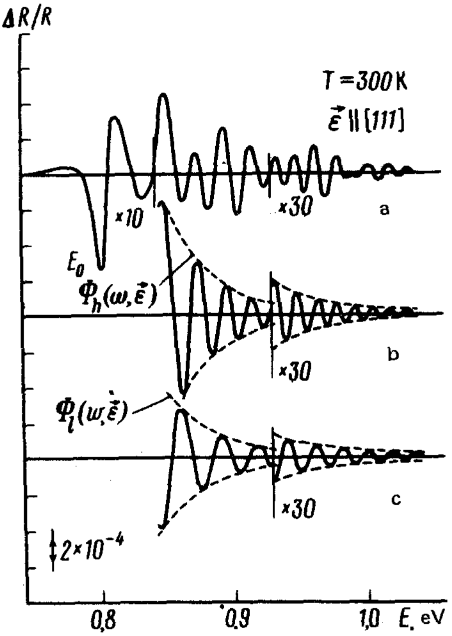

FIG. 1. a) Experimental ER spectrum of n-type germanium, 30 Ω·cm, $\vec{\mathscr{E}}\|[111]$, $\mathscr{E}=2\times10^4$ V/cm; b) and c) oscillating parts of the ER spectra for transitions from the heavy and light hole bands, respectively; $\Phi_h(w,\vec{\mathscr{E}})$ and $\Phi_l(w,\vec{\mathscr{E}})$ are their envelopes.

It is evident that the dominant mechanism of scattering of the charge carriers and the coefficients $C_{jl,h}$ appearing in (3) can be determined from the dependence of the logarithm of the envelope of the photon energy Δ; in this case, the hyperbolic dependence corresponds to scattering by ionic impurities, a square-root dependence corresponds to scattering by neutral impurities with $\Gamma=$ const, and the linear dependence corresponds to scattering by acoustical and optical phonons.

In the present work, we investigated ER spectra at room temperature for the transitions $\Gamma_8^+ - \Gamma_7^-$ at the center of the Brillouin zone in germanium for three orientations of the electric field $\mathscr{E}^8\|[100]$, [110], and [111]. The experimental procedure is described in Ref. 2.

The experimental ER spectrum for $\mathscr{E}\|[111]$, is illustrated in Fig. 1a and the oscillating parts of the spectra are illustrated separately in Figs. 1b and 1c for transitions out of the heavy and light hole bands, obtained from the total spectra taking into account the ratio of the contributions of the light and heavy hold bands.[3] Figure 2 shows the dependence of the logarithms of the amplitudes of oscillations of these spectra as a function of $(E-E_g)$. It is evident that dependence (4) is linear for both heavy and light holes and, therefore, the oscillations are damped due to scattering by acoustical and (or) optical phonons. It is also evident that the angles that these graphs form with the abscissa axis and, therefore, the coefficients $C_{\text{phonon}\ l,h}$, which are determined from the tangent of these angles, differ. This means that the relaxation times of

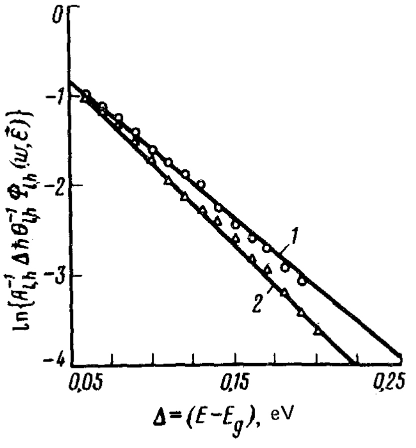

FIG. 2. Logarithm of the envelope of the oscillations of ER spectra shown in Figs. 1b and 1c as a function of the photon energy $(E - E_g)$;1) for transitions from the light hole band; 2) from the heavy hole band.

the light and heavy holes also differ. These coefficients, as well as the coefficients given analogously for $\mathscr{E}\|[100]$ and [110], are listed in Table I.

Thus the mechanism of scattering and the energy dependence of the relaxation time of electrons and holes for different crystallographic directions can be determined from an analysis of the envelope of oscillations of ER spectra using the theory in Ref. 1.

Under certain assumptions, the interaction constants of light and heavy holes interacting with optical phonons can be obtained for three directions in the Brillouin zone from these same data.

Assuming in (2) $\Gamma^{(c)} = \Gamma^{(c)}_{ac}$ and $\Gamma^{(v)}_{l,h} = \Gamma^{(v)}_{l,h\,ac} + \Gamma^{(v)}_{l,h\,opt}$, we obtain

$$C_{\text{phonon}\,l,h} = C^{(c)}_{ac}\left(\frac{\mu_{l,h}}{m_c}\right)^{1/2} + (C^{(v)}_{ac\,l,h} + C^{(v)}_{opt\,l,h})\left(1 - \frac{\mu_{l,h}}{m_c}\right)^{1/2}, \quad (5)$$

where C_{ac} and C_{opt} are known functions[4] of the acoustical and optical deformation potentials of the conduction and valence bands, as well as the effective masses of the

TABLE I.

Orientation of field	$C_{\text{фон.}\,l,h}$, eV$^{1/2}$		$D^{(v)}_{l,h} \cdot 10^{-11}$, eV/m	
	$C_{\text{phonon}\,l}$	$C_{\text{phonon}\,h}$	$D^{(v)}_l$	$D^{(v)}_h$
$\mathscr{E}\|[100]$	0,039	0,034	2,30	2,84
$\mathscr{E}\|[110]$	0,040	0,027	2,30	2.90
$\mathscr{E}\|[111]$	0,041	0,031	2,30	3,36

density of states of the conduction (m_{dc}) and of the valence (m_{dv}), bands; in addition, $m_{dv}^{3/2} = m_{dl}^{3/2} + m_{dh}^{3/2}$.

The first term in (5) is due to scattering of electrons by acoustical phonons in the conduction band from the minimum at $\mathbf{k} = 0$ in the valley [111] on the boundary of the Brillouin zone and in the valley [100] with identical interaction constants equal to 2×10^{10} eV/m and equivalent phonon temperatures of 320 K.[5] This term is two orders of magnitude smaller than the other terms in (5) and it can be ignored. Ignoring, further, the anisotropy of scattering of holes by acoustical phonons,[6] we shall use for them the average deformation potential constant equal to 5.7 eV.[5] Substituting into (5) the measured values of the coefficients $C_{\text{phonon}\,l,h}$ for three directions in the Brillouin zones and using the relations in Ref. 4, we determine the constants of the optical deformation potentials $D_{l,h}^{(v)}$ for light and heavy holes for these directions (Table I). It should be noted that the observed constants are approximately two times greater than the value 1.25×10^{11} eV/m, obtained in Ref. 7 at 78 K from the conductivity of charge carriers heated by light.

We have thus been able to show that the study of multioscillatory ER spectra is a new, efficient method for investigating mechanisms of scattering of charge carriers. The high sensitivity of this method has made it possible to determine for the first time the magnitude of the anisotropy of the optical deformation potentials of holes.

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