Photoelectric Hall effect in semiconductors for intraband light absorption

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The low-inertia photoelectric Hall effect in semiconductors, due to dynamic action of light on carrier scattering, is considered. It is shown that in sufficiently strong magnetic fields the dynamic effect exceeds the heating effect.

The influence of light on the conductivity of semiconductors in intraband carrier transitions can be due, as is well known, to two factors: first, to a change in the average carrier energy (heating) and, second, to the dynamic effect of the light field on the scattering. The most essential difference between the outward manifestation of these mechanisms is the large gap between the times characterizing their inertia. Thus, the heating mechanism corresponds to a delay time on the order of the carrier energy relaxation time, while the time corresponding to the dynamic mechanism is of the order of the momentum relaxation time. In this sense, the dynamic mechanism has a noticeable advantage. Usually, however, the relative magnitude of the dynamic effect is quite small. In this communication we wish to call attention to the possible existence of a photoelectric Hall effect in intraband carrier transitions, due to the dynamic action of the light on the scattering. As will be shown below, this effect turns out to be stronger than the corresponding heating effect. This is caused by the interesting circumstance that in strong magnetic field ($\omega_c\tau \gg 1$, where ω_c is the cyclotron frequency and τ is the momentum relaxation time) the Hall constant, in first-order in the scattering, is independent of the carrier mobility in the direction perpendicular to the magnetic field. At the same time, the dynamic effect appeared already in the first order. Thus, the sensitivity of the Hall constant to the heating is characterized by a quantity on the order of $(\omega_c\tau)^{-2}$, and the contribution of the dynamic mechanism to this constant is of the order of $(\omega_c\tau)^{-1}$.

Let us consider an electronic semiconductor placed in a strong magnetic field. We assume that

$$\Omega,\ \omega_c >> \tau^{-1}. \tag{1}$$

Here Ω is the frequency of the light, which is assumed to be monochromatic for simplicity. We can then write for the correction to the Hall current, necessitated by the quasielastic scattering of the electrons by the impurities and acoustic phonons[1]

$$\Delta j_y = \frac{2\pi e L^2}{\hbar} \sum_{\mu,\nu,q} \frac{1}{2} q_x [f(\epsilon_\mu) - f(\epsilon_\nu)] \sum_{l=-\infty}^{\infty} G_l(\xi) \times |U_q|^2 |<\mu| e^{iqr} |\nu>|^2 \delta(\epsilon_\mu - \epsilon_\nu + l\hbar\Omega - eEL^2 q_y), \tag{2}$$

where U_q are the matrix elements of the scattering potential, $f(\epsilon_\mu)$ are the diagonal elements of the density matrix of the electrons in the Landau representation $[\mu = (N,\ k_y,\ k_z)]$, $\epsilon_\mu = \epsilon(k_z) + (N+1/2)\hbar\omega_c$, and $L = (c\hbar/eH)^{1/2}$ is the magnetic radius. The z axis is directed along the magnetic field and the x axis along the drawing electric field. The quantities $G_l(\xi)$, which describe the influence of the light on the scattering, depend in general nonlinearly on the light intensity and are different for radiation fields with different degrees of coherence. In particular, for coherent radiation we have $G_l(\xi) = J_l^2(\xi)$, whereas for thermal radiation $G_l(\xi) = \exp(-\xi^2/2) I_l(\xi^2/2)$, where $J_l(\xi)$ and $I_l(\xi)$ are Bessel functions of the real and imaginary argument, respectively. In the case $\Omega < \omega_c$ considered below, to which we confine ourselves for simplicity, we have $\xi^2 = L^2(\mathbf{q} \times \mathbf{e})^2(\mathcal{E}/\bar{\mathcal{E}})^2$, where $\mathbf{e}$ is the radiation-polarization vector, $\mathcal{E}$ is the radiation field intensity, and $\bar{\mathcal{E}} = H\Omega L/c$ ($\mathbf{e} \perp \mathbf{H}$). In the absence of radiation, i.e., as $\mathcal{E} \to 0$, expression (2) vanishes, in agreement with previously known results (e.g.,[1]). At not too high light intensities, when $\mathcal{E} < \bar{\mathcal{E}}$, we can confine ourselves in (2) to terms quadratic in $(\mathcal{E}/\bar{\mathcal{E}})$, i.e., linear in the intensity of the incident radiation. This yields for the increment to the Hall current

$$\Delta j_y \sim \sigma_{xx} E \sin 2\theta\, (\mathcal{E}/\bar{\mathcal{E}})^2. \tag{3}$$

Here σ_{xx} is the "dark" transverse conductivity, and θ is the angle between the high-frequency radiation field and the static electric field. In the case of unpolarized light, expression (3) must be averaged over the angle θ, as a result of which it vanishes.

The presence of Hall photoconductivity causes the Hall constant R to depend on the light intensity

$$\frac{\Delta R}{R} \sim \frac{\sigma_{xx}}{\sigma_{xy}} \left(\frac{\mathcal{E}}{\bar{\mathcal{E}}}\right)^2 \sim (\omega_c\tau)^{-1} \left(\frac{\mathcal{E}}{\bar{\mathcal{E}}}\right)^2. \tag{4}$$

Let us examine $\bar{\mathcal{E}}$. Let $H \sim 2\times10^4$ G and $\Omega \sim 5\times10^{12}$ sec^{-1}. Then $\bar{\mathcal{E}} \sim 10^3$ V/cm.

We compare the dynamic change in the Hall constant (4) with the corresponding change due to the change in the dissipative conductivity transverse to the magnetic field. Assuming that the change of the latter is due to heating of the electron gas by the radiation,[2] we obtain for the ratio $(\Delta R)_{dyn}/(\Delta R)_{heat}$

$$\frac{(\Delta R)_{dyn}}{(\Delta R)_{heat}} \sim \omega_c\tau \left(\frac{s}{\Omega L}\right)^2 \tag{5}$$

at $\Omega < T/\hbar$ and

$$\frac{(\Delta R)_{dyn}}{(\Delta R)_{heat}} \sim \omega_c\tau \left(\frac{s}{\Omega L}\right)^2 \left(\frac{\hbar\Omega}{T}\right) \tag{6}$$

at $\Omega > T/\hbar$. Here s is the speed of sound and T is the electron temperature. We have assumed for the sake of argument that $T < \hbar\omega_c$.

It follows from the last relations that in sufficiently strong magnetic field, when the parameter $\omega_c\tau$ is large, the dynamic effect turns out to be stronger than the heating effect. Assuming $\Omega \sim 5\times10^{12}$ sec^{-1}, $s \sim 3\times10^5$ cm/sec, $T \sim 4$ °K, and $\tau \sim (10^{-11} - 10^{-12})$ sec, we find that the dynamic action of the light exceeds the heating action in magnetic fields $H > (1-2)\times10^4$ G, if $m \sim 10^{-29}$g. We note that in the case of rapidly alternating processes, when heating does not manage to "follow" the radiation-field amplitude, the time variation of the Hall constant is determined by the dynamic action under even less stringent conditions.

[1]E. N. Adams and T. Holstein, J. Phys. Chem. Sol. 10, 254 (1959).
[2]V. I. Ryzhii, Fiz. Fverd. Tela 15, 486 (1973) [Sov. Phys.-Solid State 15, 341 (1973)].