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Abstract

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E. G. Tsitsishvili

On Some Features of the Faraday Effect in Heavily Doped Semiconductors

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In paper (1), the dependence of the ellipticity near the absorption edge on the carrier concentration in GaAs was investigated. A decrease in the magnitude of the ellipticity with increasing concentration and a change of its sign at concentration $n > 2 \cdot 10^{18}$ cm^{-3} were observed. According to (2), the change in the magnitude and sign of the ellipticity may be connected with the degeneration of the electrons and caused by a different Burstein shift for right- and left-polarized waves.

In paper (2), the difference $(n_+\alpha_+ - n_-\alpha_-)$ ($n_\pm$ are the refractive indices) was calculated in the simple-band model with allowance for Fermi filling. In heavily doped semiconductors, in addition to this effect, the interaction of charge carriers with randomly distributed impurity atoms may also play a role. Allowance for this interaction in the classical approximation is straightforward. Proceeding as in paper (3) and summing over Landau levels, we obtain

$$\alpha_+(\omega) - \alpha_-(\omega) = A\sqrt{\hbar\omega - \mathcal{E}_g}\left\{2\,\frac{g\beta\mathcal{H} - \dfrac{m}{m_c}g\beta\mathcal{H}}{kT}\,J_1 - \frac{2g\beta\mathcal{H}}{\hbar\omega - \mathcal{E}_g}\,J_2\right\}, \quad (1)$$

where

$$J_1 = \frac{1}{\sqrt{\pi}}\int_{-\infty}^{+\infty} dx\,\frac{e^{-x^2}}{\mathrm{h}^2\left[\dfrac{\sqrt{\bar{v}}}{kT}\left(x + \dfrac{\mu - \dfrac{m}{m_c}(\hbar\omega - \mathcal{E}_g)}{\sqrt{\bar{v}}}\right)\right]}, \quad (2)$$

$$J_2 = \frac{1}{\sqrt{\pi}}\int_{-\infty}^{+\infty} dx\,\frac{e^{-x^2}}{1 + \exp\left[\dfrac{\sqrt{\bar{v}}}{kT}\left(x + \dfrac{m}{m_c}(\hbar\omega - \mathcal{E}_g)\right)\right]}. \quad (3)$$

Here $g = g_c + g_v$; $\bar{v} = \langle (v - \bar{v})^2 \rangle$ is the root-mean-square fluctuation of the screened impurity potential; the Fermi level μ is measured from the lower Landau band; A is a quantity containing the band parameters: $m = m_c m_v/(m_c + m_v)$.

The appearance of the first term in formula (1) is connected precisely with the fact that the Burstein shift is different for waves of different polarization.

For $(\sqrt{\bar{v}}/kT)^{-1} \gg 1$, relation (1) goes over into an expression analogous to that obtained in paper ([2]).

For $\sqrt{\bar{v}}/kT \gg 1$, the ellipticity does not depend on temperature, but depends on the impurity concentration (the determining role is played not by the change in Fermi filling, but by the interaction of charge carriers with the impurity).

In this case

$$\alpha_+(\omega) - \alpha_-(\omega) = A\sqrt{\hbar\omega - \mathcal{E}_g}\left\{ \frac{2}{\sqrt{\pi}} \frac{g_c\beta\mathcal{H} - \dfrac{m}{m_c} g\beta\mathcal{H}}{\sqrt{\nu}} \times \right.$$

$$\left. \times \exp\left[-\frac{\left(\mu - \dfrac{m}{m_c}(\hbar\omega - \mathcal{E}_g)\right)^2}{\nu} \right] - \frac{g\beta\mathcal{H}}{(\hbar\omega - \mathcal{E}_g)} \left[1 - \Phi\left(\frac{\mu - \dfrac{m}{m_c}(\hbar\omega - \mathcal{E}_g)}{\sqrt{\nu}} \right) \right] \right\}. \tag{4}$$

Here $\Phi(x)$ is the probability integral. Formula (4) was also obtained in Ref. ([4]).

In the absence of degeneracy ($\mu < 0$, $|\mu| \gg kT$), the sign of the ellipticity is opposite to the sign of the sum of the g-factors (the first term in (4) is exponentially small). In the case of degeneracy, the first term begins to play an essential role in the frequency region near the absorption edge.

Let $m_c \ll m_v$. Near the absorption edge ($\hbar\omega - \mathcal{E}_g \simeq \mu$),

$$\alpha_+(\omega) - \alpha_-(\omega) = A\sqrt{\hbar\omega - \mathcal{E}_g}\left\{ -\frac{2}{\sqrt{\pi}} \frac{g_v\beta\mathcal{H}}{\sqrt{\nu}} - \frac{g\beta\mathcal{H}}{\hbar\omega - \mathcal{E}_g} \right\}. \tag{5}$$

Consider the following cases:

1. $g < 0$, $g_v > 0$, $|g| \gg g_v$ (a case typical of InSb, where $g_c < 0$ and $|g| \sim g_c$). In this case the difference in the Burstein shifts for right- and left-polarized waves is small, as a result of which the ellipticity does not change sign. However, the presence of filling leads to a decrease in the magnitude of the ellipticity in comparison with a pure sample, where

$$\alpha_+(\omega) - \alpha_-(\omega) \simeq -2Ag\beta\mathcal{H}/\sqrt{\hbar\omega - \mathcal{E}_g}. \quad (6)$$

2. $g_v \gg |g|$. Near the absorption edge in this case

$$\alpha_+(\omega) - \alpha_-(\omega) \simeq \frac{2A}{\sqrt{\pi}}\sqrt{\hbar\omega - \mathcal{E}_g}\,\frac{g_v\beta\mathcal{H}}{\sqrt{\nu}}. \quad (7)$$

Let now $m_c \sim m_v$ (a case typical of lead compounds). Then near the absorption edge

$$\alpha_+(\omega) - \alpha_-(\omega) \simeq \frac{A\sqrt{\hbar\omega - \mathcal{E}_g}}{\sqrt{\pi\nu}}\,(g_c - g_v)\beta\mathcal{H}, \quad (8)$$

and if the g-factor and the difference $(g_c + g_v)$ have the same sign, then the ellipticity changes sign. It should be noted (see formulas (4), (5), (7), (8)) that an experiment measuring ellipticity can serve to determine one of the characteristic parameters arising in the theory of degenerate doped semiconductors—the parameter ν.

The influence of the impurity potential on the interband Faraday effect was investigated in Ref. ([3]). It was shown that simultaneous allowance for the impurity potential and for the fact of filling leads to a change in the frequency dependence of the rotation angle near each maximum and minimum ($\hbar\omega > \hbar\omega_g$).

In the present note the long-wavelength limit is calculated ($\omega \ll \omega_g$), which, as shown in ([2]), is different from zero if the gas of charge carriers is degenerate.

If, along with band filling, one takes into account the interaction of charge carriers with the impurity ([3]), then at sufficiently low temperatures ($kT \ll \sqrt{\nu}$) the long-wavelength limit is equal to a finite quantity independent of frequency and temperature and, like the ellipticity, containing the parameter ν:

$$\theta(0) = \frac{2e^2 m^{1/2}|p_{cv}|^2}{c\sqrt{\varepsilon}\,m_0^2\hbar^{3/2}\sqrt{\pi\nu}}\sqrt{\omega_g}\left[\frac{g\beta\mathcal{H}}{\hbar\omega_g} - 2\left(\mu + \frac{m}{m_c}\hbar\omega_g\right)\frac{\left(\frac{m}{m_c}g\beta\mathcal{H} - g_c\beta\mathcal{H}\right)}{\nu}\right]\times$$

$$\times\exp\left[-\frac{\left(\mu + \frac{m}{m_c}\hbar\omega_g\right)^2}{\nu}\right].$$

Let us note in conclusion that everything set forth above is equally applicable to a degenerate system of electrons moving in any random Gaussian field.

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Institute of Cybernetics
Academy of Sciences of the Georgian SSR
Tbilisi

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Note: Figure translations are in progress. See original paper for figures.