"Anomalous" magnetoresistance of ionic semiconductors at low temperatures

É. M. Épshteĭn

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It is shown that although the time of electron relaxation on optical phonons at low temperatures is independent of energy, the corresponding transverse magnetoresistance (TMR) in classical magnetic fields can not only differ from zero, but can also greatly exceed the TMR corresponding to other scattering mechanisms.

It is well known[1,2] that in the case of electron scattering by optical phonons at low temperatures ($kT \ll \hbar\omega_0$, where ω_0 is the frequency of the optical phonons) it is possible to introduce a relaxation time that is furthermore independent of energy. It is equally well known that the TMR in classical magnetic fields ($\hbar\Omega < kT$, where Ω is the cyclotron frequency) differs from zero only in the presence of electron groups that differ in energy and correspond to different relaxation times. Therefore in the case of a monopolar conductor with an isotropic dispersion law and an energy-independent electron-relaxation time, there should be no TMR in the entire classical range of magnetic fields. It would seem to follow therefore that ionic semiconductors have no TMR at low temperatures, when electron scattering by optical phonons predominates and $\hbar\omega_0 \gg kT$. Such a statement is actually made in a number of known monographs (see, e.g., [2-4]).

In this article we wish to point out that in a definite region of (classical) magnetic field the TMR of a semiconductor with the indicated scattering mechanism not only differs from zero, but also greatly exceeds the TMR responsible to other electron-scattering mechanisms.[1)]

The cause of this anomaly is that electron scattering by optical phonons at low temperatures has a "composite" character,[6,2] viz., the electron absorbs an optical phonon and emits it immediately. In the energy region $0 < \epsilon < \hbar\omega_0$ (region 1) the scattering is accompanied by the absorption of an optical phonon, and in the region $\hbar\omega_0 < \epsilon 2\hbar\omega_0$ (region 2) it is accompanied by emission of a phonon, inasmuch as in region 2 the ratio of the absorption and emission probabilities is $\sim N_q/(N_q+1) \approx N_q \approx \exp(-\hbar\omega_0/kT) \ll 1$ (N_q are the occupation numbers of the phonon states). It follows therefore that the ratio of the corresponding relaxation times τ_2/τ_1 is exponentially small. If we add furthermore that the ratio of the carrier densities in the indicated regions is also small ($n_0/n_1 \sim \exp(-\hbar\omega_0/kT)$), then it becomes clear that the carriers in region 2 make no contribution to the transport processes, and the two-phonon process mentioned above can be regarded as a single scattering act.

This situation obtains also in the presence of any magnetic field, when $\Omega\tau_1 \ll 1$. In strong magnetic fields, however, the situation is different. At $\Omega\tau_2 \ll 1 \ll \Omega\tau_1$, the contribution of region 1 to the component of the conduction tensor σ_{xx} is equal to $\sigma_{xx}^{(1)} = n_1 e^2/m\Omega^2\tau_1$, where m is the effective mass of the electron (the x axis is directed along the current and the z axis along the magnetic field), so that this component decreases with increasing magnetic field and the exponentially large quantities (compared with the corresponding quantities for region 2) n_1 and τ_1 cancel each other. On the other hand, the contribution of region 2 is $\sigma_{xx}^{(2)} \sim n_2 e^2 \tau_2/m$, i.e., it is independent of the field. Therefore, as shown in [5], the main contribution to σ_{xx} is made at $(kT/\hbar\omega_0)^{1/2} < \Omega\tau_2 \ll 1 \ll \Omega\tau_1$ by region 2 (the reason is that in region 2 the density of states is larger by $\sim(\hbar\omega_0/kT)^{3/2}$ times). The same situation obtains also at $\Omega\tau_1 \gg \Omega\tau_2 \gg 1$. As to the component σ_{xy}, at $\Omega\tau_1 \gg 1$ it does not depend on the relaxation time, viz., $\sigma_{xy}^{(1)} = n_1 e^2/m\Omega$. Therefore the cancellation indicated above does not take place and the main contribution to σ_{xy} is made by region 1.

Thus, two groups of carriers with essentially different energies and relaxation times take part in transport processes in a magnetic field. The spread of the relaxation times is much larger than the thermal spread (since $\hbar\omega_0 \gg kT$), and we can therefore expect the TMR to be much larger than in the case of other scattering mechanisms.

Let us calculate by way of example the TMR in the case $\Omega\tau_1 \gg \Omega\tau_2 \gg 1$. According to [5] we have in this case

$$\sigma_{xx}(H) = \frac{2}{3}\frac{ne^2}{m\Omega^2 t_0}\frac{\hbar\omega_0}{kt}\exp\left(-\frac{\hbar\omega_0}{kt}\right), \qquad (1)$$

where n is the electron density, $t_0 = (2\alpha\omega_0)^{-1}$, and α is the electron-phonon interaction constant.[7]

The sought TMR is equal to

$$\frac{\Delta\rho}{\rho} = \frac{\rho_{xx}(H) - \rho_{xx}(0)}{\rho_{xx}(0)} = \frac{\sigma_{xx}(H)\sigma_{xx}(0)}{\sigma_{xx}^2(H) + \sigma_{xy}^2(H)} - 1 . \qquad (2)$$

Substituting here

$$\sigma_{xx}(0) = \frac{ne^2 t_0}{m} \exp(\hbar\omega_0 / kT),$$

$$\sigma_{xy}(H) = \frac{ne^2}{m\Omega} \quad \text{and} \quad \sigma_{xx}(H)$$

we obtain from (1)

$$\frac{\Delta\rho}{\rho} = \frac{2}{3}\frac{\hbar\omega_0}{kT} >> 1 . \qquad (3)$$

At other scattering mechanisms, when the TMR is due to the thermal spread, we have in strong magnetic fields ($\Omega\tau \gg 1$), as is well known,[2] $\Delta\rho/\rho \sim 1$.

We note that an anomalously large TMR was observed experimentally[8] in an ionic semiconductor (p-GaAs) at low temperatures (5–20 °K).

An analogous effect should take place also in nonpolar semiconductors in the case of low-temperature scattering by optical phonons.

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[1)]It should be noted that all the calculations needed to obtain this result are contained in the paper of Gurevich and Firsov.[5]

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