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Application of an electric field-effect magnetoconductance method to quantum-size semimetal Bi films

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Abstract. The electric field-effect magnetoconductance (EFE-MC) method was applied to study the quantum-size effect in semimetal Bi films. This method uses a magnetic field to adjust the quantum-size characteristics of a semimetal film—in particular, the ratio of the mobilities of the electrons and holes. We present a theoretical analysis of the EFE-MC method and demonstrate its strength experimentally. The characteristic of the quantum-size state of Bi films, namely the ratio of the densities of states of the electron and hole bands, g_n/g_p, and its relation to the ratio of the hole and electron mobilities, μ_p/μ_n, was obtained by determining the crossover magnetic field H_0, at which the EFE-MC changes sign. We demonstrate also that the EFE-MC results prove the absence of charge-carrier trapping by showing that all of the extra charge carriers introduced by the EFE contribute to the conductance. The results obtained are in excellent agreement with those obtained in the absence of a magnetic field, and provide an independent confirmation of the latter interpretation.

1. Introduction

The recent development of novel preparation methods [1, 2], resulting in improved, high-quality, thin films of bismuth [3], has led to an increase in the research effort devoted to experimental and application-oriented aspects. The semimetal bismuth films, due to their characteristic electron energy band spectrum, are uniquely suited for the investigation of the galvanomagnetic coefficients under the electric field-effect (EFE) conditions in quantum-size (QS) systems with degenerate electron gas.

The EFE method is a well known way of studying interface electrical properties of solids. Experimentally, this amounts to measuring the change in the electrical conductance of a sample due to a change in the concentration of the charge carriers when charging the sample.

The EFE has been studied extensively in semiconductors, metals and even in superconductors; however, we have only sparse information on the EFE in semimetals. In the few experimental works published on the EFE in semimetal films [4], none of the authors have proposed a mechanism for the EFE, based on the specific features of semimetals. Recently we have shown [5] that the explanation for the EFE in semimetal films is based on two factors: the presence of two types of charge carrier in weakly overlapping electron and hole bands [6] and the QS state [7, 8] of the film.

Usually the EFE is investigated using a standard capacitor configuration with the QS Bi film serving as one of the capacitor plates (figure 1). Let the thickness of the sample be L and

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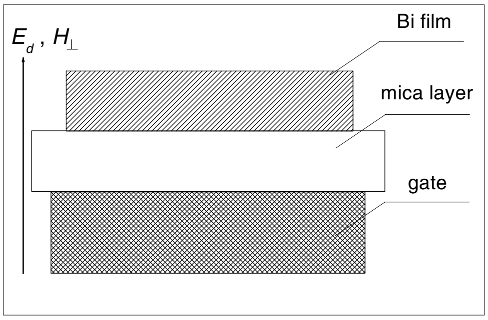

Figure 1. The experimental capacitor unit for EFE measurements.

the strength of the applied electric field within the dielectric layer be E_d. A constant probing electric current is applied in the direction parallel to the film surface, and from the measured voltage drop along the film we derive the change of the conductance $\Delta\Sigma$, as a function of E_d, at a given film thickness L:

$$\Delta\Sigma(L, E_d) = \Sigma(L, E_d) - \Sigma(L, 0) = e\left[\mu_p\, \Delta P(L, E_d) + \mu_n\, \Delta N(L, E_d)\right] \tag{1}$$

where ΔN and ΔP are the total increments (per unit area) of the free electrons and holes in the sample.

By the EFE we will mean the quantity Θ, defined by

$$\Theta = \frac{\mathrm{d}}{\mathrm{d}E_d}\, \Delta\Sigma(L, E_d). \tag{2}$$

The total electric charge induced in the QS film, provided that none of the charge is captured by surface or defect states, is distributed between the conduction band and the valence band. The increase in the number of the free charge carriers of one sign (corresponding to the polarity of the electric field), and the decrease in the number of the free charge carriers of the opposite sign in a QS film [5] are proportional to the corresponding densities of states, $g_n(L)$ and $g_p(L)$, at the electron and hole Fermi levels (for a given film thickness L), i.e.

$$\left|\frac{\Delta N}{\Delta P}\right| = \frac{g_n(L)}{g_p(L)}. \tag{3}$$

For the QS film, g_n and g_p are step-like functions of the carrier energy. It should be noted, though, that the step lengths are markedly different, due to the strong anisotropy of the electron spectrum [9] and due to the difference in the effective masses.

Thus the function

$$G(L) = \frac{g_n(L)}{g_p(L)} \tag{4}$$

(which is the ratio of the statistical weights of the conduction band and the valence band) governs the distribution of the induced charge among them. This function was measured for the QS Bi films and, as shown in reference [5], it is an oscillating function of the film thickness.

According to the Gauss theorem, the total charge (per unit area), Q, in the Bi film is

$$Q = -\varepsilon_d\varepsilon_0 E_d = -e(\Delta N - \Delta P) \tag{5a}$$

where ε_d is the dielectric constant of the dielectric layer in the capacitor. It is important to stress that, ΔN and ΔP being the increments in the numbers of the free electrons and holes, equation (5a) is valid only if the carriers introduced by the EFE are not trapped.

From equations (5a) and (3) it follows immediately that

$$\Delta N = \frac{\varepsilon_d \varepsilon_0 E_d}{e} \frac{G}{1+G} \tag{5b}$$

$$\Delta P = -\frac{\varepsilon_d \varepsilon_0 E_d}{e} \frac{1}{1+G}. \tag{5c}$$

From equations (1), (2), (3), and (5a), the EFE can be written as

$$\Theta = \varepsilon_d \varepsilon_0 \mu_n \frac{M - G}{1+G} \tag{6}$$

where

$$M(L) = \frac{\mu_p(L)}{\mu_n(L)} \tag{7}$$

and where μ_p and μ_n are the hole and electron mobilities in the QS film, which are oscillating functions for the QS film [10]. Thus, the EFE is governed by both the 'statistical' function $G(L)$ and the 'transport' function $M(L)$.

Since the mobilities in the QS Bi film do not depend upon the applied electric field [5], the function $M(L)$ is likewise electric field independent. Therefore, Θ does not depend on E_d, i.e. $\Delta\Sigma(L, E_d)$ is a linear function of E_d. This is an attribute of the EFE in the QS film.

The main experimental result of reference [5] is that over the whole thickness range investigated (200 Å–2000 Å) the difference between the functions $G(L)$ and $M(L)$, determining the magnitude of the EFE in the QS Bi film, is small:

$$|M(L) - G(L)| \lesssim 0.01\text{–}0.1. \tag{8}$$

The property (8) can be formulated as follows: *the ratio of the mobilities in the QS film follows closely the ratio of the densities of states*. This result is the key to the understanding of the EFE in Bi films, and therefore requires an independent decisive experimental test.

We now show that such an independent test of the proposed physical picture of the EFE in semimetal films can be obtained by measuring the magnetoconductance of the Bi films under EFE conditions (EFE magnetoconductance, or EFE-MC), since a magnetic field normal to the film changes the relation between the functions $G(L)$ and $M(L)$, as shown in the following section.

2. Magnetoconductance: theoretical analysis

The function $M(L)$ can be varied by changing the magnitude of the applied magnetic field $\boldsymbol{H}_\perp$ directed normal to the film surface (figure 1). It is important to note that in Bi the strong classical magnetic field, directed along the trigonal axis, is separated sufficiently from the region of Landau quantization [11]. As is known, Bi films grow on the mica substrate with the trigonal axis perpendicular to the film surface [12]. Therefore, in the case considered here the function $G(L)$ remains unchanged.

We define now

$$M(L, H_\perp) = \frac{\mu_{pH}}{\mu_{nH}} \tag{9}$$

where the magnetic field-dependent mobilities are

$$\begin{aligned} \mu_{pH} &= \frac{\mu_p}{1 + \mu_p^2 H_\perp^2} \\ \mu_{nH} &= \frac{\mu_n}{1 + \mu_n^2 H_\perp^2}. \end{aligned} \tag{10}$$

Hence,

$$M(L, H_\perp) = M(L)\frac{1 + \mu_n^2 H_\perp^2}{1 + \mu_p^2 H_\perp^2}. \tag{11}$$

This function is calculated using the parameters for the two samples described in this work (presented below in table 1) and shown in figure 2. The carrier mobilities were extracted from the measurements of the conductance and Hall constant without an applied electric field.

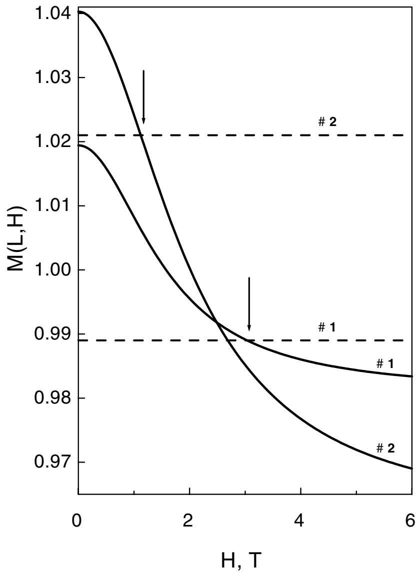

Figure 2. The magnetic field dependence of the function $M(L, H_\perp)$, calculated for two samples: (1) $L_1 = 685$ Å and (2) $L_2 = 725$ Å. The horizontal lines represent the corresponding values of $G(L)$ for the two samples.

Table 1. Parameters of the films and a summary of the results.

Parameter	Sample 1	Sample 2
L (Å)	685	725
μ_n (m^2 V^{-1} s^{-1})	0.603	0.490
μ_p (m^2 V^{-1} s^{-1})	0.615	0.512
$M = \mu_p/\mu_n$	1.020	1.045
M^{-1}	0.980	0.957
H_0 (T)	3.1	1.2
$G_{MC}(L)$	0.989	1.021
$G_\Sigma(L)$ $(H_\perp = 0)$	0.985	1.009

The conductance of the film, under the combined influence of the electric and magnetic fields, is given by

$$\Sigma(L, E_d, H_\perp) = e\left[\mu_{pH} P(L, E_d) + \mu_{nH} N(L, E_d)\right] \tag{12}$$

where P and N are the total numbers (per unit area) of holes and electrons in the film. Thus the magnetoconductance in an applied electric field is defined by

$$\Delta\Sigma(L, E_d, H_\perp) = \Sigma(L, E_d, H_\perp) - \Sigma(L, E_d, 0) = e\,\Delta P(E_d)\,\mu_{nH}\,[M(L, H_\perp) - G(L)]\,. \tag{13}$$

ε_d is the dielectric constant of the dielectric, and the EFE-MC in a magnetic field is

$$\Theta(L, H_\perp) = \frac{\varepsilon_d \varepsilon_0 \mu_{nH}}{[1 + G(L)]} \left[M(L, H_\perp) - G(L) \right]. \tag{14}$$

Formula (14) is then used to extract $G(L)$ from the measured $\Theta(L, H_\perp)$ (at each magnetic field), and from the corresponding values of $M(L, H_\perp)$ calculated from (11). A particular case of this method is the choice of $H_\perp = H_0$, where H_0 is the crossover magnetic field (the magnetic field at which the EFE changes sign), defined by the condition $\Theta(L, H_0) = 0$. Then,

$$G(L) = M(L, H_0). \tag{15}$$

From (15) and (11) we get H_0:

$$H_0^2 = \frac{1}{\mu_n \mu_p} \frac{M(L) - G(L)}{M(L)G(L) - 1}. \tag{16}$$

Thus a physical solution for the magnetic field H_0 exists when either one of the following conditions is fulfilled:

$$\begin{aligned} &M > G(L) > M^{-1} \qquad \text{for } M > 1 \\ &M < G(L) < M^{-1} \qquad \text{for } M < 1. \end{aligned} \tag{17}$$

Since in QS Bi films $G(L) \approx M(L) \approx 1$ [5], condition (17) is very strong and is satisfied for only a limited range of film thickness. Analysing the oscillating dependencies of $G(L)$ and $M(L)$ allows us to identify the narrow thickness ranges for which condition (17) is valid. The samples belonging to these film thickness ranges are described in the next section.

3. Experimental results and discussion

The EFE-MC measurements were carried out on the standard capacitor structure (figure 1). Mica sheets of 10–20 μm thickness were used as substrates for the Bi films, at the same time serving as the capacitor dielectric. The Bi films were prepared by thermal evaporation in a vacuum of (1–3) $\times$ 10^{-7} Torr with a rate of 10 Å s^{-1} and subsequently annealed near the melting temperature of bismuth. The sample length/width ratio was 4. The measurements of the EFE-MC were carried out at 4.2 K, in magnetic fields up to 6 T and at several constant electric fields E_d up to 0.5×10^8 V m^{-1} for both polarities.

The experimental dependencies of $\Sigma(L, H_\perp)$ are shown in figures 3(a) and 3(b) for two films having different thicknesses, L_1 and L_2, for which condition (17) is satisfied and, hence, H_0 exists. The crossing of the magnetoconductance curves in the magnetic field H_0 is equivalent to the change of the sign of $\Theta(L, H_\perp)$ in this field. The definition of H_0 is made clear in the insets of these figures, showing the difference $\Delta\Sigma = \Sigma(H_\perp, E_d) - \Sigma(H_\perp, 0)$. These values of $H_0(L_{1,2})$ were substituted in equation (16) and, using μ_n and μ_p, the values of $G_{MC}(L_{1,2})$ were determined (the index MC indicates that the function $G_{MC}(L_{1,2})$ was obtained by magnetoconductance measurements).

We would like to point out the following features:

(1) The consistency of the method requires that this $G_{MC}(L_{1,2})$ coincides with the value of $G_\Sigma(L_{1,2})$ calculated using equation (6) from the independently measured EFE value of $\Theta(L, H_\perp = 0)$. This is indeed the case as seen in table 1, which also summarizes all the other important experimental parameters of the sample films.

(2) $H_0(L)$ does not depend on E_d. In fact this is equivalent to the statement that $M(L, H_\perp)$ and $G(L)$ do not depend on E_d. Therefore, in accordance with equation (14) for the QS Bi film, $\Theta(L, H_\perp)$ is also independent of the electric field. This result agrees with the measurements of the EFE of the samples investigated without a magnetic field.

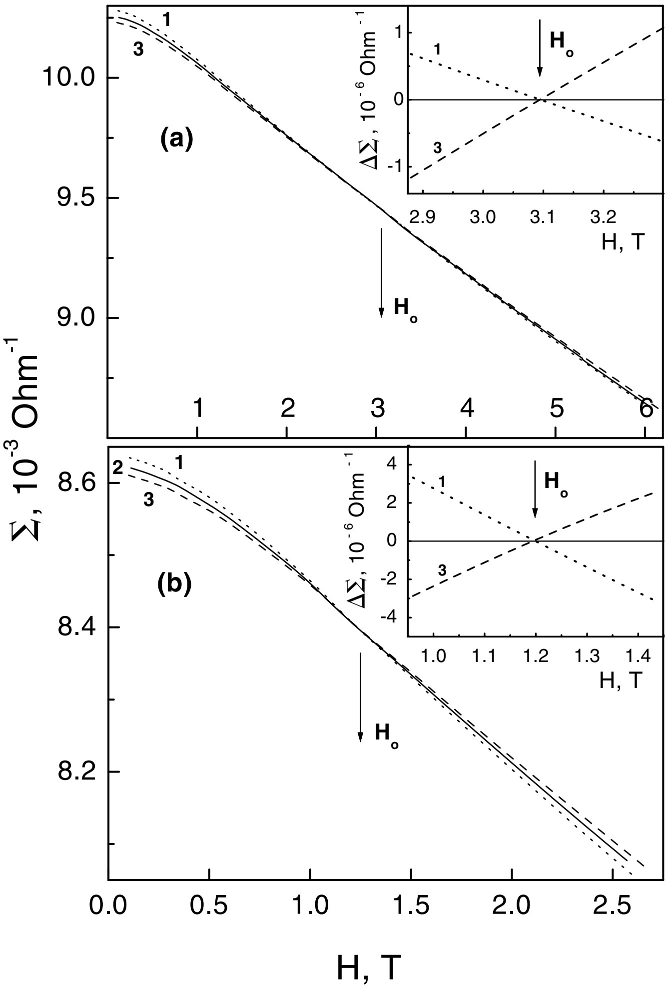

Figure 3. Experimental graphs of $\Sigma(H_\perp)$ for two samples: (a) $L_1 = 685$ Å, $H_0 = 3.1$ T and (b) $L_2 = 725$ Å, $H_0 = 1.2$ T. Curve (1) corresponds to $E_d = -0.3 \times 10^8$ V m^{-1}; curve (2) corresponds to $E_d = 0$; curve (3) corresponds to $E_d = 0.3 \times 10^8$ V m^{-1}. The insets show the difference $\Delta\Sigma = \Sigma(H_\perp, E_d) - \Sigma(H_\perp, 0)$.

(3) Following from the range of the physically possible values of H_0, equation (17), the corresponding intervals for $G_{MC}(L_{1,2})$ are

$$M^{-1}(L_1) = 0.980 < G_{MC}(L_1) < M(L_1) = 1.020$$
$$\left|M(L_1) - M^{-1}(L_1)\right| = 0.04$$

for sample 1 and

$$M^{-1}(L_2) = 0.957 < G_{MC}(L_2) < M(L_2) = 1.045$$
$$\left|M(L_2) - M^{-1}(L_2)\right| \simeq 0.1$$

for sample 2. Thus, condition (8) is also satisfied.

(4) The thicknesses L_1 and L_2 differ only by 6% while the corresponding values of $H_0(L_1)$ and $H_0(L_2)$ differ by a factor of 2.5. Such strong dependence of $H_0(L)$ is found, according to equation (16), because $M(L_{1,2})G(L_{1,2}) \simeq 1$.

(5) The vanishing of the EFE-MC at H_0 and the equality $G_{MC}(L_{1,2}) = G(L_{1,2})$ actually prove that all the carriers introduced by the EFE contribute to the conductance, i.e. that there is no trapping of the carriers in the Bi films. Indeed, $G(L)$ can be determined from equation (16) *independently* of ΔP. Then, the value of ΔP (or ΔN) can be determined using equation (13). It turns out that these values of ΔP (or ΔN) exactly coincide with the values derived from equation (5*c*) (or (5*b*)). This is possible only in the absence of capture, as noted above in the comment on equation (5*a*).

In conclusion, the experimental results on the EFE-MC are in good agreement with the predictions of the above analysis and confirm the interpretation of the results obtained at $H_\perp = 0$. Thus, the EFE-MC method is an effective way of determining the ratio of the electron and hole densities of states $G(L)$ in QS Bi films. We have also established the absence of charge trapping in these samples. Thus, the present work can be considered as an independent and decisive test of the interpretation of the nature of the EFE, and, in particular, of the cause of the anomalously small magnitude of the EFE on the conductivity of QS semimetal films.

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