Negative magnetoresistance in transverse and longitudinal magnetic fields in Bi nanowires

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Abstract. In this work the measurements of longitudinal (LMR) and transverse magnetoresistance (TMR) in Bi wires with 50<nm<d<500 nm in the interval 4.2 - 300 K and magnetic field up to 14 T were carried out. Was shown that, the maximum on LMR at \(H||I\) is suppressed due to quantum size effect. For the first time it was found that the field dependence of TMR \(R(H)\) at \(I \perp H\) in Bi wires with \(d<80\) nm contains the negative region \(R(H) < R_0\) at \(T<5\) K. This result was unexpected, because it is known that in bulk Bi samples the ”giant” increase of magnetoresistance in the case \(H \perp I\) is observed. We calculate the conductivity of nanowires in longitudinal and transverse magnetic fields on the basis of the Cubo formula for the conductivity. We use the model of quantum wires with a parabolic potential in the plane orthogonal to the axis of the size-quantized system. According to the model of such TMR and LMR were experimentally observed in the Bi quantum wires (QW) with \(d<80\)nm.

1. Introduction

Modern theoretical analysis [1,2] predicted the transition semimetal-semiconductor (SMSC) in Bi semimetal based nanowires due to the quantum size effect. The effect appears due to action of restrictions placed on particle motion, when characteristic dimension of the system (\(d\)) is comparable in value with the de Broglie wave length. Bulk bismuth is a semimetal in which three conduction band minima at the L-point overlap with the valence band maximum at the T-point by about 40 meV. Bismuth has the lowest effective mass, resulting in a long Fermi wavelength (\(\lambda \sim 60\) nm). Due to this property, quantum restriction is observed in Bi nanowires with diameters being significantly greater than in other materials. The SMSC transition will allow controlling Bi band structure by varying nanowire diameter. This may be one of the methods for obtaining of materials with new unusual properties.

The given paper presents peculiarities of manifestation of electron transport (LMR and TMR) in bismuth nanowires, when the wire diameter is comparable with the de Broglie wave length.
Lately, bismuth nanowires in form of nanowires arrays have been intensively studied, some new effects were found in them [1-12]. However, such researches as magnetoresistance at H \| I in the above mentioned case are ambiguous, since the magnetic field orientation (H \| I) relative to crystallographic directions could not be determined.

2. Sample preparation and experimental procedure

Samples were obtained by liquid phase casting and were the cylindrical single crystals in glass cover with the (10\{11\}) orientation along the wire axis with length up to several mm [13,14]. Wires diameter were from 50 nm up to 500 nm.

Measurements of LMR and TMR were carried out in the superconducting solenoid field up to 15 T in the temperature range 1.5-300 K in the International Laboratory of High Magnetic Fields and Low Temperatures (Wroclaw, Poland). For researches in the transverse magnetic field, a special insert (device) was applied, which allows rotating sample in two directions \perp and \parallel to the magnetic field.

3. Experimental results and discussions

Resistance of Bi nanowires was studied in the temperature range 4.2-300 K. It was found that at the diameters d<80 nm the resistance temperature coefficient (RTC) is negative, that is typical for the “semiconducting” character of the dependence R(T). RTC for the wires with d>80 nm is positive as in Bi bulk samples.

In the longitudinal magnetic field (H\|I) the magnetoresistance dependence in Bi wires has nonmonotonic behavior and significantly depends on wire diameter d (figure 1).

![Figure 1](image1.png)

**Figure 1.** Magnetic field dependence of normalized LMR for Bi wires with different diameters at 4.2 K: 1. d=50 nm, 2. d=75 nm, 3. d=160 nm, 4. d=350 nm, 5. d=480 nm. Insert: initial section of magnetic field dependence of LMR.

In the wires with (d>100 nm) in weak magnetic field (\mu H<1) the resistance increases forming a maximum \(H_{\text{max}}\) followed by the region of negative magnetoresistance [13,14]. The dependence of the maximum field \(H_{\text{max}}\) on the reciprocal diameter 1/d makes it possible to identify the onset of negative magnetoresistance on R(H) with the classical size effect MacDonald–Chambers [16,17]. It was established that the field \(H_{\text{max}}\) considers with the “cut off” \(H_{\text{cut}}\) of Shubnikov de Haas oscillations, which determined from the condition \(H_{\text{cut}}=D_{\text{max}}c/ed\), where \(D_{\text{max}}\) is the maximum diameter of the extremes section of the Fermi surface. Similar effect was observed in a consequence on nanowires arrays [5].

![Figure 2](image2.png)

**Figure 2.** Magnetic field dependence of LMR for Bi wire with d=110 nm at elastic tension \(\zeta=(l_{1}-l_{0})/l_{0}: 1. \zeta=0, 2. \zeta=0.5\%, 3. \zeta=0.8\%, 4. \zeta=1.6, 5. \zeta=2\%. Insert: dependence on quantum number of the ShdH oscillations on reverse field \(H^{-1}\) for curve 4.
Investigation of LMR of Bi nanowires with d<100 nm has shown the maximum suppression on R(H). This implicitly shows a decrease of contribution of L-electrons due to the quantum size effect (figure 1, curve 1.2).

Applying the method of elastic stretch of Bi wires [18], we have carried out an experiment that allowed observing change of behaviour of the R(H) dependence (H||I) in one sample at variation of the Fermi surface topology induced by deformation. Figure 2 presents the dependences R(H) of Bi wire with d - 90 nm both in absence of deformation and at various values of deformation in the magnetic fields up to 14 T.

It is known [14] that under elastic stretches of Bi wires (d>100 nm) of the given crystallographic orientation there occurs transfer of carriers (electrons) of one electron ellipsoid L₁ stretched along the wire axis into two others L₂,₃. This leads to an increase of their concentration by a factor of three at maximal stretch. In addition, the overlapping of L and T bands increases as well.

In the case of Bi wires with d<100 nm, wherein in the absence of stretch the overlapping of L and T bands decreases due to the quantum size effect, the elastic stretch results in the inverse effect: increase of the overlapping and appearance of the ShdH oscillations from the electron ellipsoids L₂,₃ lowering down the energy scale. Two frequencies with periods Δ₁(H⁻¹)=3,3*10⁻⁵ Oe⁻¹ and Δ₂(H⁻¹)=7,2*10⁻⁵ Oe⁻¹ are agree with data given in Bi wires with d>200 nm without deformation [13].

For the first time it was found that the field dependence of TMR R(H) at I||H in Bi wires with d<80 nm contains the negative region R(H)<R₀ at Т<5 K (figure 3).

This result was unexpected, because it is known that in bulk Bi samples the "giant" increase of magnetoresistance in the case H||I. In Bi wires with d>300 nm TMR increases with diameter growth d (figure 3, bottom insert) [19].

The negative magnetoresistance region at H||I is observed both at H||C₂ and at H||C₃ only on Bi wires with d<80 nm. As the wire diameter d decreases, the negative magnetoresistance region shifts into strong magnetic fields and the depth R/R₀ increases. It was found that at H||C₂ the negative

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**Figure 3.** Magnetic field dependence of normalized TMR for Bi wires with different diameters: 1,1’:d=50nm, 2,2’:d=75 nm at 4.2 K. 1’,2’ - H||Cₛ, 1,2 - H||C₂. Top insert: the initial section of TMR for Bi wires: 2. d=75 nm, 3. d=160 nm, 4. d=330 nm, 5. d=350 nm. Bottom insert: TMR, H||C₂ at T=1.7 K (curve 1) and T=4.2 K (curve 2).

**Figure 4.** Theoretical dependence of normalized TMR for size quantized Bi wires. µ₀ in the absence of magnetic field is situated: 1. significantly lower than the bottom of the second subband, 2. coincides or is situated just below the second subband bottom, 3. is just above the second subband bottom. Insert: the model of quantum subband and chemical potential µ₀.
magnetoresistance region is preceded by $R(H)$ increase with maximum formation on $R(H_{\parallel})$ (figure 3, curves 1' and 2').

Using the Cubo formula the electric conductivity of size-quantized Bi wires is calculated taking into account the scattering process carrier on the interface roughness and phonons [20]. Taking into account of the lowest subbands of size-magnetic quantization allows experimental explanation of the observed peculiarities in the dependence of TMR of Bi QW on $H$. If the level of the chemical potential $\mu_0$ in the absence of magnetic field is situated significantly lower than the bottom of the second subband (it is double degenerate in the magnetic field absence), (figure 4, insert) then with increasing magnetic field $H$ the chemical potential monotonously decreases and the resistance increases (figure 4, curve 1). If the chemical potential $\mu_0$ coincides or is situated just below the second subband bottom, then with increasing $H$ the chemical potential decreases and the resistance decreases at first and then monotonously increases (figure 4, curve 2). This is due to competitive influence of the magnetic field on the value of multiplier and exponent index in the expression for probability of carrier scattering on the Fermi level. If $\mu_0$ is just above the second subband bottom, then with increasing $H$ the resistance increases at first and then, while $\mu_0$ passing the subband bottom, falls rather sharply and monotonously increases at further increase of magnetic field (figure 4, curve 3). The given theoretical curves reflect fairly well the experimentally observed dependences (figure 4, curves 1 and 2).

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