Berry's phase manifestation in Aharonov-Bohm oscillations in single Bi nanowires

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Abstract. Here we report on Aharonov-Bohm oscillations of magnetoresistance (MR) of the single Bi nanowires with diameter d<80 nm. The samples were prepared by Ulitovsky technique and represented cylindrical single crystals with the 1011 orientation along the wire axis. Due to semimetal-to-semiconductor transformation and big density of surface states with strong spin-orbit interactions Bi nanowire should effectively become a conducting tube. The equidistant oscillations of the MR have been observed in a wide range of magnetic fields up to 14 T at various temperatures (1.5 K<T<4.2 K) and angles θ (0<θ<90°) of the sample orientation relative to the magnetic field. We have obtained longitudinal MR oscillations with periods ΔB1=Φ0/S and ΔB2=Φ0/2S, where Φ0=h/e is the flux quantum and S is the wire cross section. From B≈8 T down to B=0 the extremums of Φ0/2S oscillations are shifted up to 3π at B=0 which is the manifestation of Berry phase shift due to carriers moving in inhomogeneous magnetic field. An interpretation of the MR oscillations in terms of a subband structure in the surface state band caused by quantum interference is presented.

1. Introduction

Bismuth is a particularly favourable material to study the electronic properties of quantum wires due to its small electron effective mass and high carrier mobility. Quantum confinement effects decrease the effective band overlap energy E0, detailed calculations [1] show that a semimetal-to-semiconductor (SMSC) transition occurs for d~55 nm for wires oriented along the trigonal direction.

It is well known that quantum interference effects are present in superconducting devices and in very small pure metallic rings and cylinders. In particular, in the presence of magnetic flux Aharonov-Bohm (AB) oscillations [2] may occur in doubly connected systems. For a normal metal the period of these oscillations is Φ0=h/e (the flux quantum). There are two types of quantum interference effects in normal conductors of long carrier’s mean free path that cause a magnetoresistance oscillation with a period ΔB that is proportional to Φ0/ΔS, where S is the wire cross section. The first effect is a Dingle oscillation [3] which results from quantization of the electron energy spectrum. The second type of

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oscillation, with a period $\Delta B = \Phi_0/S$, is caused by electrons undergoing continuous grazing incidence at the wire walls. This type of longitudinal magnetoresistance oscillations have been observed at 4.2 K in single nanowires grown by Ulitovsky technique with diameter 0.2<d<0.8 $\mu$m [4] and in a Bi nanowire arrays 270 nm in diameter [5]. For the disordered cylindrical samples with short mean free path (compare with the circumference of the cylinder) the new type of AB oscillations with period $\Delta B = \Phi_0/2S$ was predicted by Al’tshuler, Aronov and Spivak (AAS) [6]. These oscillations were observed by Sharvin and Sharvin [7] on the Mg cylinder 1 $\mu$m in diameter and 1 cm long.

Figure 1. Magnetic field dependence of the longitudinal MR for a 55 nm and 73 nm Bi nanowires, T=1.5 K. Insert: Temperature dependences of the resistance for a 55 nm and 73 nm Bi nanowires.

Since the introduction of the AB effect, the phase factor has been studied intensively. Berry [8] showed that, even in the absence of electromagnetic fields, when a quantum state undergoes an adiabatic evolution along a closed curve in parameter space, it develops a phase which depends only on this curve. To observe Berry’s phase in an electronic system with spin, Loss et al. [9] proposed to study transport in a mesoscopic ring structure in the presence of an orientationally inhomogeneous magnetic field. This can be experimentally implemented via fabricating the ring from a material with inversion asymmetry and spin–orbit (SO) interaction.

In this paper we present our results for observation of AB oscillations with periods $\Delta B = \Phi_0/S$ and $\Delta B = \Phi_0/2S$ on single Bi nanowires with diameter d < 80 nm. The manifestation of Berry phase shift for $\hbar/2e$ oscillations will be discussed.

2. Experimental
The Bi nanowires were fabricated using the Ulitovsky technique, by which a high-frequency induction coil melts a 99.999%-pure Bi boule within a borosilicate glass capsule, simultaneously softening the glass. Glass capillaries containing Bi filament were produced by drawing material from the glass [4,10]. The Bi in the microwires can be viewed as cylindrical single crystals with the (1011) orientation along the wire axis. In this orientation the wire axis makes an angle of 19.5° with the bisector axis $C_1$ in the bisector-trigonal plane. The samples used in this work are, to date, the smallest diameter single Bi wires for which the electronic transport at low temperatures has been reported.

All measurements were performed at the High Magnetic Field Laboratory (Wroclaw, Poland) in superconducting solenoid in magnetic fields up to 14 T at temperatures 1.5 K - 4.2 K.

3. Results and discussion
Figure 1 shows the magnetic field dependence of the longitudinal MR for Bi nanowires d= 55 nm and 73 nm. R(B) decreases for increasing magnetic field it is typical for Bi nanowires of large and small
diameters [1,10,11]. This phenomenon is a Chambers effect, which occurs when the magnetic field focuses electrons toward the core of the wire, thereby avoiding surface collisions. We have observed the non monotonic changes of longitudinal MR that are equidistant in the magnetic field. The insert in Figure 1 presents the temperature dependence of resistance $R/T_{300}$ for Bi nanowires $d=55$ nm and 73 nm. The $R(T)$ dependencies have “semiconductor” character, i.e. the resistance grows in the whole range of temperatures. For $T>100$ K, the nanowires’ resistance $R(T)\sim \exp(\Delta/2k_B T)$. The energy gap between the electron and hole band in the core of the nanowires, $\Delta$, is found to be $10\pm 5$ meV for both the 55 nm and 73 nm wires.

Figure 2. Magnetic field dependence of derivative of longitudinal MR for a 55 nm Bi nanowires, $T=1.5$ K (the monotonic part is subtracted). Insert (a): FFT spectra of the oscillations; (b): changes of maxima positions versus $B$ for $h/2e$ oscillations which were converted into the values of phase shift of high field harmonic oscillation.

Figure 2 shows the oscillation part of magnetic field derivative of the longitudinal MR of 55 nm nanowire. The inset (a) shows Fast Fourier Transform (FFT) spectra of this oscillation. Longitudinal MR oscillations that are equidistant in the magnetic field and decrease in amplitude have been observed for the first time in magnetic fields up to 14 T in Bi single crystal nanowires $d<80$ nm at $T=1.4 \div 4.2$ K [12,13]. In contrast to oscillations that have been observed in thick Bi microwires ($0.2<d<0.8$ µm) they exist in wide range of magnetic field (up to 14 T) and have two periods: $\Delta B_1=h/e$ and $\Delta B_2=h/2e$. Due to SMSC transition in our nanowires the carrier concentration in the wires core is very small, it's unlikely that they excite these oscillations. Angle-resolved photoemission spectroscopy (ARPES) studies of planar Bi surfaces have shown that they support surface states, with carrier densities $\Sigma$ of around $5\times 10^{12}$ cm$^{-2}$ and large effective masses $m_\Sigma$ of around 0.3[14]. The observed effects are consistent with theories of the surface of nonmagnetic conductors whereby Rashba spin-orbit interaction gives rise to a significant population of surface carriers [15]. Given the bulk electron $n$ and hole $p$ densities (in undoped Bi, $n=p=3\times 10^{17}$ cm$^{-3}$ at 4 K) and the surface density $\Sigma$ measured by ARPES one expects the surface carriers to become a clear majority in nanowires with diameters below 100 nm at low temperatures. At that point, the nanowire should effectively become a conducting tube.

Using FFT analysis we have separated every frequency for longitudinal MR of 55 nm nanowire. As it has appeared $h/e$ oscillation is harmonic but the extrema of $h/2e$ oscillation lie on a straight line only for $B > 8$ T and step-by-step deviate from it at low magnetic fields. After converting the low field extrema positions to the phase shift of high field harmonic oscillations the phase shift curve (Figure 2, insert (b)) was obtained. Mathematic simulation was used for testing of this method. From $B \sim 8$ T down to $B=0$ the extremums of $h/2e$ oscillations are shifted up to $3\pi$ at $B=0$ which is the manifestation of Berry phase shift due to electron moving in nonuniform magnetic field.
Derivative of MR for 55 nm bismuth nanowire was measured at various inclined angles up to $90^\circ$ of magnetic fields relative to nanowire’s axis in two mutually perpendicular planes. The observed angle variation of the periods are not in the agreement with theoretical dependence $\Delta(\alpha)=\Delta(0)/\cos\alpha$ of the size effect oscillations of the “flux quantization” type when period of oscillations in magnetic field depends only on the component $B_X$, parallel to the axis of the cylindrical sample. According to the experimental data the shifts of oscillation frequencies at the same angles depend on plane of sample rotation. Derivative of MR was measured at various rotational angles of nanowire when axis of the wire was mounted perpendicularly to the magnetic field. Even in this case the equidistant oscillations of MR exist in transverse magnetic fields under certain rotation angles. This means that oscillations nature connected with Bi Fermi surfaces and very complicated. We connect the existence of h/2e oscillations with weak localizations on surface states of Bi nanowires according to the AAS theory.

4. Conclusions
To conclude, the MR in single crystal Bi nanowires with glass coating with diameter $d< 80$ nm was studied. The $R(T)$ dependencies for Bi nanowires have “semiconductor” character. For $T>100$ K, the nanowires’ resistance $R(T)=\exp(\Delta/2k_B T)$, where $\Delta$ is the energy gap between the electron and hole bands in the core of the nanowires; $\Delta$ is found to be 10±5 meV for both the 55 nm and 73 nm wires. Due to Rashba spin-orbit interaction Bi surfaces support surface states with carrier densities $\Sigma$ of around 5x10$^{12}$ cm$^{-2}$. Taking into account the above properties, the Bi nanowire should effectively become a conducting tube. The longitudinal MR oscillations with period $\Delta B=h/e$ and $\Delta B=h/2e$ were observed. According to FFT from $B \sim 8$ T down to $B=0$ the extremums of h/2e oscillations are shifted up to $3\pi$ at $B=0$ which is the manifestation of Berry phase shift due to electron moving in nonuniform magnetic field. We connect the existence of h/2e oscillations with weak localizations on surface states of Bi nanowires according to the AAS theory. The observed angle variation of the periods are not in the agreement with theoretical dependence $\Delta(\alpha)=\Delta(0)/\cos\alpha$ for the “flux quantization” oscillations. Moreover the equidistant oscillations of MR exist in transverse magnetic fields under certain rotation angles. This means that oscillations nature connected with Bi Fermi surfaces and very complicated.

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