Influence of Electric Field Effect on Quantum Oscillations in Single Crystal Bi Nanowires

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***Abstract* — We report the results of studies of the magnetoresistance (MR) and electric field effect (EFE) of single-crystal Bi nanowires with diameter 40 nm<*d*<800 nm at low temperatures. Single-crystal nanowire samples were prepared by the Taylor-Ulitovsky technique; they were cylindrical single crystals with the $(10\bar{1}1)$ orientation along the wire axis where the C_3 axis was inclined at an angle of 70° to the wire axis. According to theory of S. Murakami, bismuth bilayers can exhibit the quantum spin Hall effect. A Bi crystal can be viewed as a stacking of bilayers with a honeycomblike lattice structure along the [111] direction. Using electric field effect in measurements of quantum magnetic oscillations we have confirmed the dependence of the surface states on the diameter of the Bi nanowires.**

***Index Terms* — bismuth, nanowires, magnetoresistance, Aharonov-Bohm oscillations, field effect.**

I. INTRODUCTION

Nanowire systems have become the focus of intense experimental and theoretical investigation due to their scientific and technologic interest. The most exciting prospect is that of an ideal quantum wire with diameter d that is less than Fermi wavelength λ_F where the Fermi level is chosen such that nanowire transport is mediated by a single conduction channel. The properties of this one-dimensional system or quantum wire have been investigated theoretically. A particular case of Bi nanowires was studied by Hicks and Dresselhaus [1]. Bismuth has a Fermi surface consisting of small hole and electron pockets at *T* and *L* points of the Brillouin zone, respectively; therefore, the Fermi wavelength λ_F is very long (about 50 nm). Bismuth is a particularly favorable material to study the electronic properties of quantum wires due to its small electron effective mass and high carrier mobility [2].

Angle-resolved photoemission spectroscopy (ARPES) studies of planar Bi surfaces showed that they support surface states with carrier densities Σ of about 5×10^{12} cm^{-2} and large effective masses m_Σ of around 0.3 [3]. The observed effects are consistent with theories of the surface of nonmagnetic conductors whereby the Rashba spin-orbit interaction gives rise to a significant population of surface carriers.

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 a magnetic flux, Aharonov-Bohm (AB) oscillations [4] can occur in doubly connected systems. For a normal metal, the period of these oscillations is $\Phi_0=h/e$ (flux quantum). These effects should vanish once the elastic mean free path of the electrons is smaller than the system size. For the disordered cylindrical samples with a short mean free path (compared with the circumference of the cylinder) the AB oscillations with a period proportional to *h/2e* was predicted by Altshuler, Aronov, and Spivak (AAS) [5]. This effect arises from the interference of pairs of coherent electron waves circumscribing the cylinder. AB and AAS oscillations have been observed in various conducting rings, tubes, and solid cylinders that consist of tubes, such as multiwall carbon nanotubes (MWNTs), and arrays of a 270-nm Bi nanowire [6].

Experimental investigation of the magnetoresistance (MR) of thin single-crystal bismuth nanowires in glass coating obtained by the Ulitovsky method in the diameter range of 200 - 800 nm with a large mean free path *l* revealed MR oscillations with period *h/e* in a longitudinal magnetic field at r_L, $l > d/2$, where r_L is the Larmor radius of the electron trajectory [7]. In this case, theoretical studies have been focused on the whispering gallery model of low-effective-mass electrons that define a highly conducting tube in the boundary of the solid cylinder. The period of oscillations depends on the angle α between the sample axis and the direction of magnetic field as $\Delta B(\alpha) = \Delta B(0)/cos\alpha$, which is a characteristic feature of the size effect oscillations of the flux quantization type [8]. In addition to the *h/e* period of MR oscillations, the period equal to 1.4 *h/e* also was observed. The additional period was connected with Dingle oscillations, which results from quantization of the electron energy spectrum [9].

The study of the MR of thin single-crystal bismuth nanowires with diameter d < 80 nm [10] in glass coating, which were obtained by the Ulitovsky method, revealed the Aharonov-Bohm oscillations derived from the longitudinal magnetoresistance (LMR) with two periods ΔB proportional to *h/e* and *h/2e*; the development of a Berry phase shift [11] owing to electrons moving in the nonuniform magnetic field $\vec{B}_\Sigma=\vec{B}+\vec{B}_{SC}$, where B_{SO} is the Zeeman-like effective magnetic field, was found in *h/2e* oscillations. The fact that the *h/2e* oscillations exhibit a phase shift only in one direction means that, as in topological insulators [12], the surface states of Bi nanowires have only one spin degree of freedom.

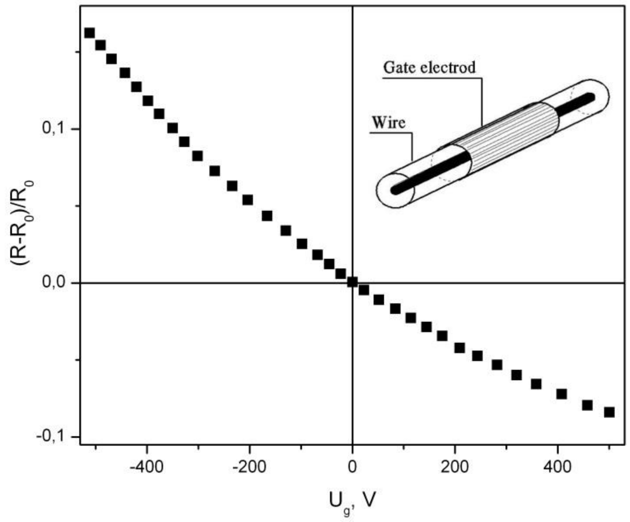

Fig. 1. Relative changes in resistance $(R-R_0)/R_0$, where R_0 – resistance at U_g=0, of the 180-nm Bi nanowire versus potential U_g on the top-gate electrode at T=4.2 K; Insert: Schematic drawing of the EFE experiment, external voltage was applied to the top-gate relative the core of the nanowire.

Electrical field effect (EFE) is a very powerful tool to control the surface properties of semiconductors; it changes the electronic properties of a sample by electrical charging. The surface effects would be difficult to observe if the sample were heavily doped. It is easily implemented in the capacitor structure where the sample is used as one of the plates. It seems very useful to apply EFE to influence the electronic properties of surface layers of semimetals [13, 14].

To understand the occurrence of MR equidistant oscillations in Bi nanowires, we have investigated the LMR of Bi nanowires in the geometry of the EFE.

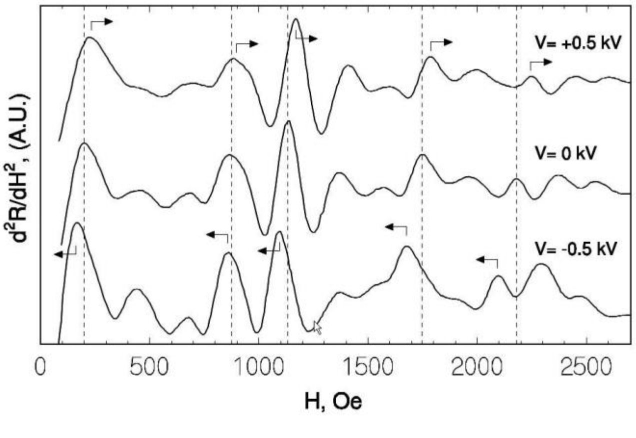

Fig. 2. Dependence of phase displacement of the quantum size oscillations in bismuth single crystal microwire with D=17.3 μm and d=0.45 μm at T=4.2 K on transverse electric field $E=\pm 6.1\cdot10^6$ V/cm.

II. SAMPLES AND EXPERIMENT

Individual nanowire samples were prepared by high-frequency liquid phase casting in a glass capillary using an improved Ulitovsky technique [15]; they were cylindrical single-crystals with the $(10\bar{1}1)$ orientation along the wire axis. In this orientation, the wire axis makes an angle of 19.5° with the bisectix axis C_1 in the bisectrix-trigonal plane the trigonal C_3 axis is inclined to the wire axis at an angle of ~70°, and one of the binary C_2 axes is perpendicular to it. Diameter D of nanowire glass insulation was in a range of 15 - 20 μm. The glass coating reliably protects the sample from mechanical damage while mounting and from oxidation. The samples were then cut from long nanowires, the length l of the samples was 0.5 - 0.8 and 3 - 5 mm for nanowires with d < 100 nm and d > 150 nm, respectively. Electrical connections to the nanowires were performed using the InGa eutectic. This type of solder consistently makes good contacts compared to other low-melting-point solders. The samples are characterized by electronic diameter $d=\sqrt{\rho_{Bi} l / R_0}$, where $\rho_{Bi} = 1.14\text{x}10^{-4}$ Ohm*cm is the bulk resistivity at 300 K, l is the wire length, and R_0 is the wire resistance at T=300 K. The actual diameter d_{SEM} of the samples was measured with a scanning electron microscope (SEM). We found that $d_{SEM}=d$ within experimental error and that there is a trend toward $d_{SEM} < d$ for smaller diameters, consistent with an increase in resistance due to size effects at room temperature [16].

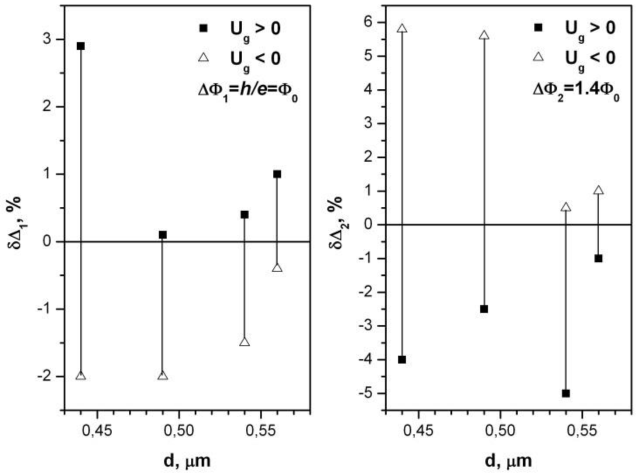

Fig. 3. Dependence of the change of the period of quantum size oscillations in the nanowires of bismuth under EFE on the diameter of the nanowires.

We used samples with 45 nm<d<800 nm. Shubnikov–de Haas (SdH) oscillations of LMR are observed in the thick (d>150 nm) Bi nanowires; this shows that the bismuth material in the nanowires has the required high purity and high mobility. However, in the thin samples (d<80 nm) the conditions for observing SdH oscillations are not optimal because of large AB oscillations. The observed periods of SdH oscillations are consistent, within the experimental errors (3%), with the well-known periods for this particular crystalline orientation with respect to the magnetic field for intrinsic Bi. We surmise that our nanowires are intrinsic and do not undergo strain from the glass coating upon cooling. For measurements of EFE in thick nanowires (d > 150 nm) the long samples with l of about 5 mm were cut from long nanowires. In this case, a top-gate electrode was prepared by painting the surface of the glass coating with liquid Ga (Insert of Fig. 1). Owing to the coaxial geometry of our samples, the highest electric field value above 10^7 V/cm on the surface of the Bi wire was achieved: $E=2U_g/(d\ln(D/d))$, where U_g is the top-gate electrode potential, d and D represent the diameter of the Bi nanowire and the diameter of the glass coating, respectively. A back-gate electrode was prepared for thin Bi samples with $d < 100$ nm and $l = 0.5 – 0.8$ mm; a schematic diagram of a back-gate electrode is shown in the inset of Fig. 4. The calculated capacitance of a coaxial nanowire is an order of magnitude higher than the back-gate capacitance; therefore, the electric field on the surface of the Bi nanowire is much smaller for the case of the back-gate electrode.

Magnetic field-dependent resistance *R(B)* measurements in a range of 0 to 14 T were carried out at the International Laboratory of High Magnetic Fields and Low Temperatures, Wroclaw, Poland.

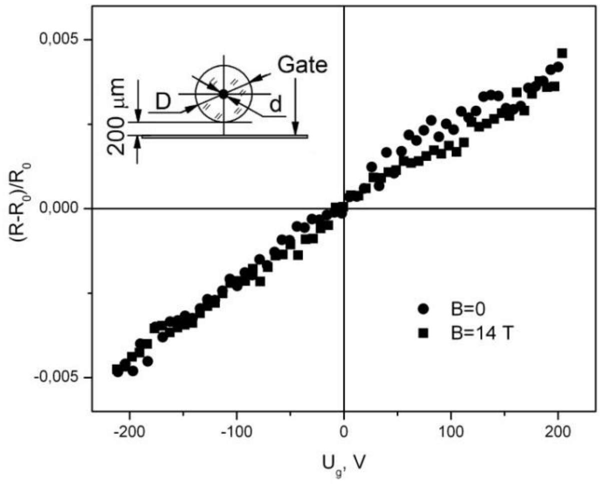

Fig. 4. Relative changes in resistance $(R-R_0)/R_0$, where R_0 – resistance at U_g=0, of the 45-nm Bi nanowire versus potential U_g on the back-gate electrode at longitudinal magnetic fields B=0 and 14 T, T=1.5 K; Insert: Schematic drawing of the EFE experiment, external voltage was applied to the back-gate relative the core of the nanowire.

III. RESULTS AND DISCUSSION

Relative changes in resistance $(R-R_0)/R_0$, where R_0 is the resistance at U_g=0, at helium temperatures of the Bi nanowire versus potential U_g on the gate electrode are shown in Fig. 1. (for the 180-nm Bi nanowire and top-gate electrode) and Fig. 4 (for the 45-nm Bi nanowire and back-gate electrode). The figures clearly show that the change in the resistance of thin bismuth wires is much less than in thicker wires. The most important fact is that the dependence of $\Delta R = f(U_g)$ fundamentally changes, which means that the properties of the Bi nanowire surface strongly depend on nanowire diameter. According to calculated theoretical EFE of the Bi film [13] the sign of the slope of EFE at U_g=0 is determined by the sign of the term $(\mu_n - \gamma\mu_p)$, where μ_n is the electron mobility, μ_p is the hole mobility, and coefficient γ is on the order of 1.5. This represents the fact that with decreasing nanowire diameter, in the surface region of the nanowire, the density of electrons increases or their mobility increases compared to holes; this is probably due to the growing influence of the helical edge states of the Bi bilayer [17], this will be further discussed below.

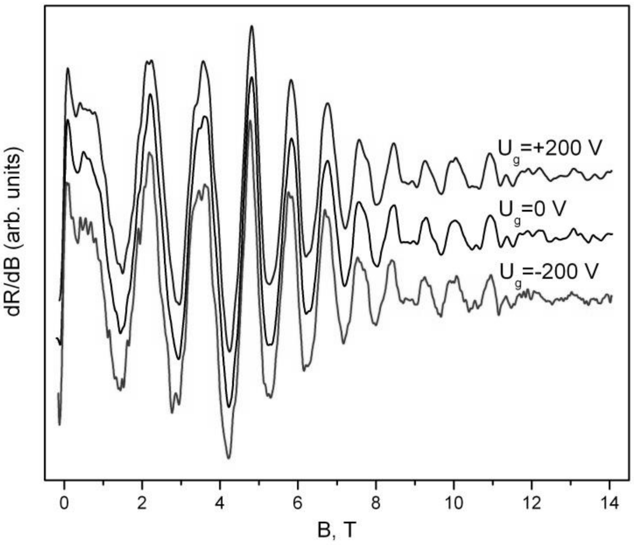

Fig. 5. Magnetic field dependences of the LMR for 45-nm Bi nanowires, T=1.5 K (the monotonic parts are subtracted); Potentials are applied to the back-gate electrode relative to the core of nanowire.

The oscillation parts of the LMR of the 45-nm nanowire at different potentials on the back-gate electrode are shown in Fig. 5. It is clear that the changes in potential (+200 V, 0, -200 V) do not alter the pattern of oscillations. For thicker nanowires with d = 450 nm, the EFE led to a significant change in the LMR oscillation frequency (Fig. 2). Theoretical studies of LMR oscillation for thick nanowires were focused on the whispering gallery model of low-effective-mass electrons that define a highly conducting tube in the boundary of a solid cylinder [18]. In this case, the EFE is shown in a modification of the effective diameter of this tube in the range of the penetration depth of the electric field $L_e \approx 100$ Å which leads to a change in the oscillation frequency $\Delta F \sim 1$-5% (Fig. 3). Invariance of the LMR oscillation for the 45-nm nanowire (Fig. 5) confirms our interpretation [19] of the *h/e* oscillations of LMR observed in the 55-nm Bi nanowire in our earlier work [10] (as in carbon nanotubes [20]) in terms of oscillations in the density of surface states. The high-frequency nonmonotonicity observed in the oscillations of LMR can be a manifestation of the conductance fluctuations which were observed in Bi nanowires [21].

In terms of the band structure, Bi is classified as a trivial topological insulator, and surface states are not protected from dissipation. It was recently suggested that Bi(111) bilayers can exhibit the quantum spin Hall effect [17]. A bismuth crystal can be viewed as a stacking of bilayers with a honeycomblike lattice structure along the [111] direction. According to calculation of Murakami [17] Z_2 topological number I is odd which guarantees stability of the helical edge states against backscattering. As the sample becomes thicker, the helical edge states are expected to transform to 2D surface states on 3D bulk Bi. In 45-nm nanowire, the self-organization of helical edge states results in the appearance of AB oscillations in TMR.

In conclusion, using electric field effect in measurements of quantum magnetic oscillations we have confirmed the dependence of the surface states properties on the Bi nanowires diameter.

ACKNOWLEDGMENTS

This work was supported by the STCU Grant # 5373.

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