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Quantum electrical transport properties of topological insulator Bi_2Te_3 nanowires

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ABSTRACT

We investigate the quantum transport properties of surface electrons on a topological insulator Bi_2Te_3 nanowire in a magnetotransport study. Although the nanowires are synthesized by using a relatively coarse method of electrochemical deposition, clear Aharonov–Bohm oscillations of phases 0 and π are observed, owing to the highly coherent surface electron channel. The oscillation amplitude exhibits exponential temperature dependence, suggesting that the phase coherence length L_φ is inversely proportional to the temperature, as in quasi-ballistic systems. In addition, a weak antilocalization analysis on the surface channel by using a one-dimensional localization theory, enabled by successful extraction of the surface contribution from the magnetoconductance data, is provided in support of the temperature dependence of L_φ.

1. Introduction

Topological insulators (TIs) exhibit a novel gapless spin-resolved edge (or surface) electronic state [1,2] that is located within the bulk insulating energy gap, with spin-momentum locking due to a strong spin–orbit interaction. The TI system is highly promising not only for fundamental studies on topological nature in condensed matter physics, but also for potential applications in future information technologies such as topological quantum computing and spintronics [1–4]. A two-dimensional (2D) topological insulating state was theoretically predicted for HgTe quantum well structures [3], and experimentally verified by using a transport study [5]. Later, $Bi_{1-x}Sb_x$ alloys were determined to be three-dimensional (3D) TIs [4] with a topological surface state (TSS) by an angle-resolved photoemission spectroscopy (ARPES) study [6]. Recently, additional materials, such as Bi_2Se_3, Bi_2Te_3, and Sb_2Te_3, have also been identified as 3D TIs, of which the surfaces have single Dirac cone band structures protected by time-reversal symmetry [7–9]. In addition, the existence of a spin-helical state, in which the electron spin is aligned parallel to the surface and normal to the momentum, has been verified from spin-resolved ARPES studies [8,10].

TIs may sustain highly coherent charge- and spin-transport by virtue of the spin-momentum helical locking and the protection from backscattering by time reversal symmetry in the TSS; hence, they can constitute an attractive platform for spintronic device applications. Further progress in developing TI-based applications needs to be preceded by experimental studies on their electrical transport characteristics for determining the surface state properties. However, the contribution from the residual bulk carriers due to material imperfection makes it difficult to isolate the genuine transport properties of the TSS. This issue has been tackled with methods such as tuning the Fermi level to the bulk band gap by chemical doping [11–13] or external gate control [14,15], and by using nanostructures of TIs, which cause the surface state contribution to dominate the charge transport, owing to the large surface-to-volume ratio [16–18].

Conduction electrons in the TSS of TIs exhibit strong quantum interference effects. Weak antilocalization (WAL) [19] occurs in TIs

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as a result of a strong spin–orbit interaction, which is known to disturb the weak localization effect caused by constructive interference between time-reversed electron paths in diffusive media. Analyses of magnetoconductance (MC) data for WAL have been performed to investigate the phase coherence and spin–orbit interaction of conduction electrons in one-dimensional (1D) TI nanostructures [16–18]. Aharonov–Bohm (AB) conductance oscillations, characterized by the oscillation period of a single flux quantum $\Phi_0 = h/e$, have also been observed for TI nanoribbons and nanowires [20–23]. The AB oscillations in mesoscopic ring geometry are usually explained by the interference between partial waves encircling the magnetic flux enclosed by the electron paths. However, the AB oscillations from surface electrons in nanoribbons or nanowires under axial magnetic fields can be understood more properly in terms of the formation of 1D subbands, quantized along the circumference (with integer indices n) and modulated by the magnetic flux Φ threading the cross-sectional area of the quasi-1D nanostructure [24–27]. The dispersion relation for the 1D subbands in the TSS of TIs, as a function of the momentum k along the nanowire, is as follows: [25,27].

$$E(n,k,\Phi) = \pm h v_F \sqrt{\left(\frac{k}{2\pi}\right)^2 + \left(\frac{n+1/2-\Phi/\Phi_0}{L_p}\right)^2}, \tag{1}$$

where h is the Planck constant, L_p is the perimeter length, and v_F is the Fermi velocity that is assumed to be the same in both the azimuthal and axial directions. Electronic phase coherence is especially important for this 1D subband picture to hold, because the model explicitly relies on the existence of well-defined quantum eigenstates. Another important point is that the conductance maxima due to the AB oscillations can occur either for integer flux quanta ($\Phi = 0, \pm\Phi_0, \pm2\Phi_0, \ldots$) or for half-integer flux quanta ($\Phi = \pm1/2\Phi_0, \pm3/2\Phi_0, \ldots$), depending on the location of the Fermi level and disorder strength in the nanowire [26,27].

In this work, we have observed the phase-coherent quantum interference effects in magnetoconductance (MC) of devices made of Bi_2Te_3 single nanowires grown by using electrochemical deposition. The AB oscillations exhibiting both of the possible phases were clearly observed under magnetic fields parallel to the nanowire axis, verifying the existence of a highly coherent surface electron channel. The oscillation amplitude was found to decrease almost exponentially with increase in temperature T, implying that the phase coherence length $L\varphi$ is inversely proportional to T. This suggests that the surface electron channel is in the quasi-ballistic regime. After carefully extracting the surface contribution from the MC measured in perpendicular magnetic fields, a WAL analysis was performed using a 1D localization theory. Our results demonstrate that the diameter-controlled Bi_2Te_3 nanowires, although synthesized by using a relatively coarse method of electrochemical deposition, exhibit a highly coherent surface electron channel that is essential for possible next-generation TI-based information technologies.

2. Experiments

Bi_2Te_3 nanowires were grown by electrochemical deposition by using porous anodic aluminum oxide membrane nanotemplates [28]. The cylindrical nanowires had a typical diameter and length of ~60 nm and 8–10 μm, respectively (Fig. 1(a)). Fig. 1(b) is a scanning electron microscopy (SEM) image of the Bi_2Te_3 nanowires taken after removal of the AAO template. High-resolution transmission electron microscopy (HRTEM) and selected area electron diffraction (SAED) images show that the nanowires grow as single crystals in the [110] direction, normal to the c-axis (Fig. 1(c)). It is evidently shown that the nanowire is covered by a ~5-nm-thick native oxide layer, making the actual diameter of the nanowire conducting part ~50 nm. The X-ray diffraction (XRD) measurements on the nanowire array generate a strong peak from the (110) planes (Supplementary data Fig. S1), implying that the nanowires have a highly textured structure along the [110] direction, in accordance with the HRTEM result. For device fabrication, the nanowires were deposited onto highly p-doped silicon substrates, covered by a 300-nm-thick oxide layer. Metal (Pt or Ni) electrodes with a thickness of 100 nm are patterned by using standard electron beam lithography and electron beam evaporation to connect the nanowires to the Au bonding pads preformed on the substrates. The length L of the nanowire channel between the metal contacts was ~800 nm for all samples used in this study. A SEM image of a Bi_2Te_3 nanowire device (Pt1) is shown in Fig. 1(d). The electrical conductance G of single nanowire devices was measured by using a four-probe standard lock-in technique, using a physical property measurement system from Quantum Design, which provides a high-field (±9 T) and low-temperature (2 K) environment for device measurements.

3. Results and discussion

Fig. 2(a) shows the differential MC ($\Delta G \equiv G(B) - G(0)$) measured for the sample Pt2, with the magnetic field B applied parallel to the nanowire axis. It is apparent that conductance oscillations are superimposed on the slowly varying background MC drawn in solid curves, which is obtained by a fitting process. Each of the MC background curves consists of a polynomial and a Lorentzian, which has been used for convenience to simulate the conductance peak due to the WAL near $B = 0$ T. We note that the general shape of the MC background for $|B| > 1$ T does not change even when the magnetic field is applied perpendicular to the nanowire axis (Supplementary data Fig. S3). This suggests that the MC background is mainly determined by the magnetic field modulation of the electronic states in the nanowire bulk [22].

The background MC has been subtracted from the MC data, and the residues denoted by δG are shown in Fig. 2(b). It is clear that the residual MC is mainly comprised of a periodic oscillation. Fig. 2(c) shows the fast Fourier transform (FFT) amplitudes of δG. A strong peak is observed at $1/B = 0.549$ T^{-1}, which corresponds to the oscillation period of $\Delta B = 1.82$ T. This oscillation period yields 54 nm as the diameter d, according to the relation for AB oscillations in a nanowire with a circular cross-section, $\pi(d/2)^2\Delta B = \Phi_0$. This value of d exactly matches the actual diameter of the conducting part of the nanowire deduced from the external diameter (64 nm) measured by using atomic force microscopy (AFM), and the oxide shell thickness (~5 nm) obtained from the HRTEM result (Fig. 1(c)). Besides the AB oscillations, the Altshuler–Aronov–Spivak (AAS) oscillations with a period of $h/2e$ [29], caused by the weak localization effect around the circumference, are also expected in a phase-coherent cylindrical surface electron system in the diffusive limit. However, Fig. 2(c) does not show a significant Fourier component of periodicity $h/2e$. It has been demonstrated that the AAS oscillations in TSS of TI can be easily disrupted by weak perpendicular magnetic fields [27]. It is possible that the absence of the AAS oscillations in our sample is caused by a slight misalignment of the applied field direction.

Fig. 2(d) shows the AB oscillation amplitude (δG_{AB}) as a function of T. Evidently the temperature dependence does not follow the ~$T^{-1/2}$ relation [29], which is attributed to thermal averaging in diffusive systems over energy scales larger than the correlation energy E_c, that is, for $k_BT >> E_c$. Depending on the type of system, the correlation energy could correspond to either the mean difference between the energy levels in the system or the Thouless