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LETTER

Signatures of Quantum Transport Steps in Bi_2Se_3 Single Crystal

Rabia Sultana [1,2] · Deepak Sharma [1,2] · R. S. Meena [1,2] · V. P. S. Awana [1,2]

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Abstract

We report signatures of quantum magneto transport steps in a Bi_2Se_3 single crystal. The Bi_2Se_3 crystal is grown by self-flux method through solid-state reaction. Details of its structural analysis along with physical properties in terms of low temperature and high field transport, thermal (heat capacity), Raman, X-ray photo electron and angle resolved photo electron spectroscopy were reported earlier (J. Sup. Novel. Mag. 30, 2031 2017). In a present short letter, we show the details of its 2 K and up to 14 Tesla magneto transport, exhibiting quantum transport (QT) like steps above say 11 Tesla field. The possible QT steps cannot be modelled with the SdH (Shubnikov-de Haas) or other possible quantum oscillations. The observed QT like steps are possibly the result of the mixed out-of-plane R_{xy}(H) and in-plane R_{xx}(H) contributions from the misaligned [00*l*] planes of the studied crystal and this may happen with other studied topological insulator (TI) crystals as well. Our careful assessment of crystal XRD data shows the same.

Keywords Topological insulators · Magneto resistance · Quantum properties

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Topological insulators (TI) are known for quantum properties due to their quantized surface state carriers spins being locked in right angle to their momentum [1–4]. It is clear by now that the role of both spin and momentum along with their time reversal symmetry (TRS)-driven-protected states are important. The outline of surface driven quantum transport was started decades before, when quantum Hall effect (QHE) was discovered with protected momentum states, which paved the path for QSHE (quantum spin Hall effect), and thus the TI. The TIs are the most discussed topic today in condensed matter physics including both the theoreticians and experimentalists [1–6].

As far as quantum transport is concerned, which is a key fundamental property of a TI, the same is evidenced from the fact though these are insulator in their beneath bulk but with high conductivity at surface due to momentum and spin locked TRS protected quantum states. Under applied magnetic field, the TRS breaks, and thus exhibiting high magneto resistance (MR) [1–8]. The MR is maximum when applied field is out-of-plane and minimum in-plane [8]. The surface conductivity of a TI is quantum mechanically driven, and the same often exhibits several interesting phenomenon such as the periodic oscillations at high fields (above say 10 Tesla) and low temperatures (below 2 K) [9–11] .

The Bi_2Se_3 sample is grown via self-flux method in an evacuated sealed quartz tube heating up to a temperature of 950 °C (2 °C/min) and then cooling down slowly to 650 °C (2 °C/h), further details along with structural/micro-structural and spectroscopic studies on the same are given elsewhere [7]. The magnetic measurements were done using the quantum design physical property measurement system (PPMS) down to 2 K and under applied magnetic field of up to 14 Tesla.

Figure 1 represents the X-ray diffraction (XRD) patterns of the as grown Bi_2Se_3 single crystal exhibiting the [00*l*] alignment. Though on a normal scale of intensity, the unaligned peaks were not visible [7], the log-scale data plotted in Fig. 1 clearly shows the mixing of [00*l*] with [10*l*]. For reference, the normal-scale data from ref. [7] is shown in inset of Fig. 1. The [105] and [1010] XRD peaks are clearly seen with the prominent [00*l*] log-scale plot. Seen are other minor intensity peaks as well, but these are not unreacted ones because the detailed Reitveld analysis of the powder XRD of the crystal showed the same to be free of impurities within XRD limits [7]. These

✉ V. P. S. Awana
awana@nplindia.org; https://www.awanavps.webs.com

1 National Physical Laboratory (CSIR), Dr. K. S. Krishnan Road, New Delhi 110012, India

2 Academy of Scientific and Innovative Research (AcSIR), Ghaziabad 201002, India

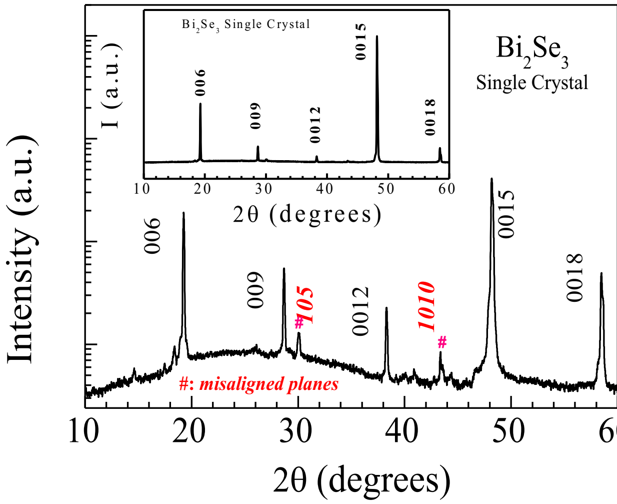

Fig. 1 X-ray diffraction pattern for Bi_2Se_3 single crystal on a log scale, inset shows the same for a normal scale

may be another very minor crystallographic planes contributions besides the major [00*l*] and minor [10*l*] planes.

The magneto transport of the studied crystal is reported in ref. [12], where though QT steps were seen at 2 K but not at 100 K and 200 K until 14 Tesla. In order to further elucidate on this, the 2 K, isothermal magneto transport [ρ(H)] data are shown with the enlarged steps part in Fig. 2, along with the same in entire field range of 0 to 14 Tesla in upper inset of the same figure. Although the ρ(H) data (upper inset Fig. 2) is completely linear until 11 Tesla, the quantum steps (QT) at around 11.5, 12.5 and 13.5 Tesla are clearly visible from main panel Fig. 2. Further, it is inferred from Fig. 2 that the width of the steps increases with increase in field. However, there is a

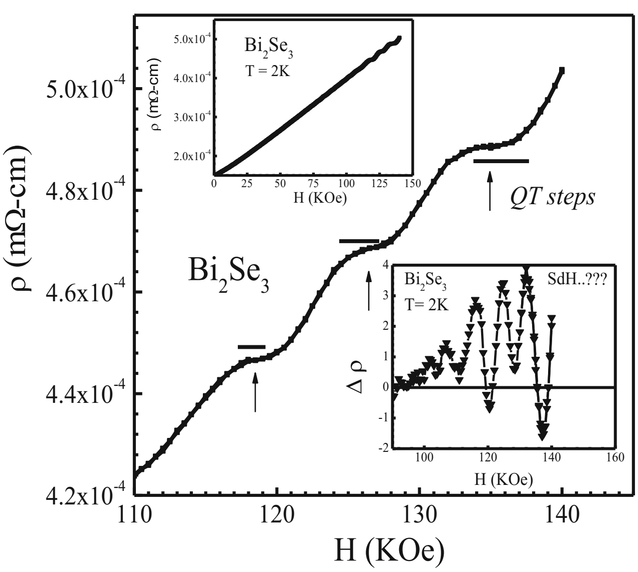

Fig. 2 Isothermal magneto transport [ρ(H)] data for Bi_2Se_3 in the enlarged steps part; the upper inset shows the same in entire field range of 0 to 14 Tesla, and the lower inset shows the possible SdH behaviour at 2 K

problem that is the transition from one step to another is not sharp but slightly linear. In fact, in an earlier attempt, we tried to fit the data with Shubnikov-de Haas (SdH) oscillations quantum transport model but failed [12]. The diversion of resistivity from linear behaviour (Δρ) and magnetic field plot is shown here in a lower inset of Fig. 2. It is clear that the oscillations are not symmetric through the base line of *y*-axis, i.e., along $y = 0$, again showing that the observed QT steps and resultant oscillations are away from the ideal one [9, 10]. This prompted us to look again at the data and find for possible solutions. The reasoning behind such a behaviour can be understood in terms of misaligned single crystal, where the applied field is not absolutely perpendicular to crystallographic planes of the same. The TI growth crystal plane is [00*l*], and hence one presumes that the electrical transport takes place along *ab* plane, i.e. [*hk*0] and the applied magnetic field is perpendicular, i.e. in [00*l*]. The crystal transport measurement schematic is shown in Fig. 3. However, what about the situation when, both crystallographic planes gets mixed up at the conducting surface of the crystal, for example in present case the [00*l*] and [*h*0*l*] are mixed, and hence the ρ_{xy}(H) and ρ_{xx}(H) gets interfering each other. In such a situation neither the ρ_{xx}(H) steps nor the ρ_{xy}(H) SdH oscillations are perfect. Also, the absence of clear quantitative oscillations calls for the steps to be of quantum Hall (QH) nature, though this is only speculative at this juncture. It had already been reported that strained TI with low mobility of carriers exhibit the QHR steps [11]. In this direction, mixed topological insulators having low mobility with partially aligned crystallographic planes could be a good choice for QHR. One could focus on mixed topological insulators like $Bi_{2-x}Sb_xTe_{3-y}Se_y$ and quench them after growth from say 400 °C to induce disorder and misalignment of crystallographic planes.

Summarily, in the current letter, we stressed upon the fact that though our Bi_2Se_3 single crystal exhibited the quantum transport (QT) steps, the same is yet not perfect due to non-unidirectional growth of the crystal, giving rise to [00*l*] and [*h*0*l*] intermixing on the conducting surface. The possibility of QH steps also cannot be ruled out and future steps to be taken are proposed.

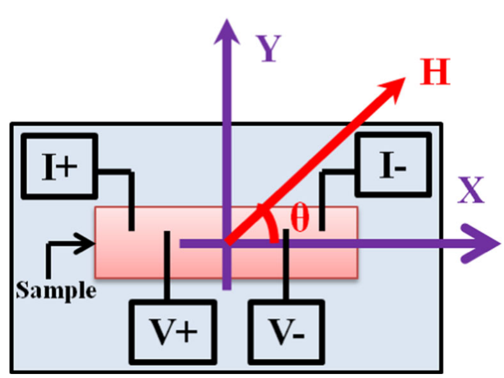

Fig. 3 Crystal transport measurement schematic

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