Hikami Larkin Nagaoka Analysis of Topological Insulators

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Abstract. We report the WAL related magneto-conductivity analysis of topological insulators (Bi_2Te_3 and Bi_2Se_3) fitted using the Hikami Larkin Nagaoka (HLN) equation. At lower applied magnetic fields and temperatures, the studied topological insulators (Bi_2Te_3 and Bi_2Se_3) followed the HLN equation. Further, the extracted values of the fitting parameters i.e., phase coherence length (l_φ) and the pre-factor (α) suggested that the electronic conduction mechanism in these topological insulators is dominated by both surface states driven weak anti localization (WAL), as well the bulk WL (weak localization) states. Summarily, the short letter discusses briefly on the competing effect of WAL and WL conduction mechanism of topological insulators analyzed by the HLN model.

INTRODUCTION

Topological insulators (TIs) are unique materials exhibiting both bulk insulating states and mass-less Dirac-cone like surface states protected by time reversal symmetry (TRS), relevant for futuristic novel applications such as quantum computation, spintronics, low – dissipation electronics and many others [1-6]. Three dimensional (3D) TIs with TRS protected topological surface states coupled with spin momentum locking property exhibits a number of exotic and interesting surface transport properties [1-6]. Recently, one of the fascinating transport features of TIs i.e., weak anti-localization (WAL) have grabbed the attention of the entire condensed matter physics community. WAL is intrinsic to TIs exhibiting gapless surface states and appears as the negative magneto-conductivity with a sharp v-type cusp in small magnetic fields [7-8]. Another, interesting feature of the quantum transport in disordered electron system is the weak localization (WL) effect which occurs when the intrinsic TIs are doped with magnetic impurities resulting in the breaking of TRS and opening of a gap. WL appears as a positive low field magneto-conductivity at low temperatures [7-8].

However, there are currently many practical challenges that limit the study of the topological surface state properties and surface conduction in TIs. This is due to the significant contributions from the bulk states to the overall electronic conduction mechanism occurring from defects, impurities, or intersite occupancy [7-9]. In order to investigate the quantitative analysis of the WAL behaviour and to know the contribution of the surface versus bulk conduction to the overall conduction process, one need to fit the magneto-conductivity of TIs to the standard Hikami Larkin Nagaoka (HLN) equation [10]. In the present work, we discuss briefly about the fitting parameters (α and l_φ) and the resultant conduction process of TIs (Bi_2Te_3 and Bi_2Se_3) analyzed by the HLN equation.

EXPERIMENTAL DETAILS

The single crystals of Bi_2Te_3 and Bi_2Se_3 were grown using the standard self flux method via the conventional solid state reaction route. The detailed crystal growth mechanism of Bi_2Te_3 and Bi_2Se_3 and their physical property characterization has been previously reported by some of us [11-12]. In brief, high purity (99.99%) elements were weighed precisely and mixed according to the stoichiometric ratio. The homogeneous mixtures of Bi_2Te_3 and Bi_2Se_3 were then enclosed in evacuated quartz glass tubes and kept inside an automated programmable tube furnace. The mixture was heated to 950˚C followed by slow cooling to 650˚C at a rate of 2˚C/hour and then to room temperature

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at a rate of 120˚C/hour. The as-grown crystals obtained were in the form of one piece which was further mechanically cleaved along the basal plane exhibiting silvery shiny mirror like surface. The magneto-transport measurements were carried out using the 14Tesla down to 2K, Quantum Design Physical Property Measurement System (PPMS).

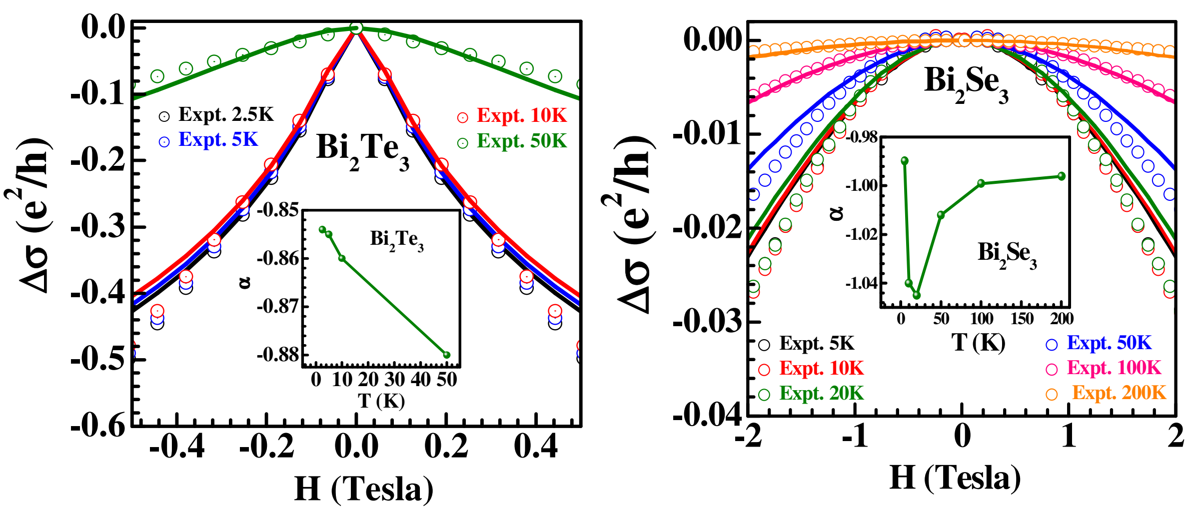
RESULTS AND DISCUSSION

In order to investigate the surface versus bulk conduction contributions to the overall conductivity of Bi_2Te_3 and Bi_2Se_3 single crystals, the magneto-conductivity is fitted using the HLN equation [10]:

$$\Delta\sigma(H) = -\frac{\propto e^2}{\pi h}\left[\ln\left(\frac{B_\varphi}{H}\right) - \Psi\left(\frac{1}{2}+\frac{B_\varphi}{H}\right)\right] \qquad (1)$$

where, Ψ signifies the digamma function, $B_\varphi = \frac{h}{8e\pi H l_\varphi}$ is the characteristic magnetic field, h represents the Planck's constant, H is the applied magnetic field, α is the pre-factor and l_φ is the phase coherence length. The phase coherence length (l_φ) is defined as the distance travelled by an electron before its phase is changed and the pre- factor (α) is a coefficient signifying the type of localization (WL, WAL or both WL and WAL). The pre-factor α = 0.5 for a single coherent conduction channel. Here, the values of the fitting parameters i.e., pre-factor (α) and the phase coherence length (l_φ) is obtained by fitting the experimentally observed magneto-conductivity data using the HLN equation. The HLN equation has already been used to describe the WAL behaviour in various topological systems (thin film, bulk single crystals, nano flakes, nano–wires) and the experimentally fitted value of α lie between -0.4 and -1.1, for single surface state, two surface states, or intermixing between the surface and bulk states [13-16] .

Figure 1(a, b) displays the change of magneto-conductivity defined as $\Delta\sigma(H) = \sigma(H) - \sigma(0)$, of as synthesised Bi_2Te_3 and Bi_2Se_3 single crystals measured in perpendicular magnetic fields at different temperatures. To extract the values of the fitting parameters more accurately, we have fitted the magneto-conductivity of Bi_2Te_3 and Bi_2Se_3 single crystals under lower applied magnetic fields of up to ± 0.25Tesla and ± 1Tesla respectively. For both Bi_2Te_3 and Bi_2Se_3 single crystals the experimentally observed magneto-conductivity data is represented by circles whereas, the solid lines within ± 0.25Tesla (Bi_2Te_3) and within ± 1Tesla (Bi_2Se_3) are the HLN fitted curves [Fig. 1(a, b)]. Fig. 1(a, b) clearly shows that all the magneto-conductivity curves follow the HLN behaviour.



(a) (b)

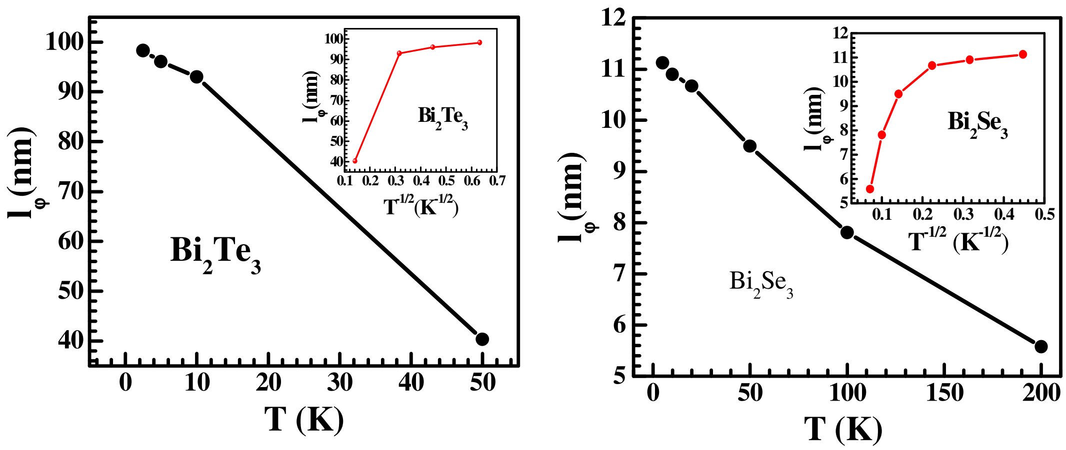
FIGURE 1. Magneto–conductivity of (a) Bi_2Te_3 and (b) Bi_2Se_3 single crystals measured in perpendicular magnetic fields at different temperatures. The inset shows the temperature dependence of pre-factor (α) obtained from HLN fitting of the magneto-conductivity for (a) Bi_2Te_3 and (b) Bi_2Se_3 single crystals.

The inset of Fig. 1(a, b) shows the temperature dependence of pre-factor (α) obtained from HLN fitting of the magneto-conductivity for Bi_2Te_3 and Bi_2Se_3 single crystals. The inset of Fig. 1(a) shows that as the temperature increases from 2.5K to 50K the value of α tends to decrease from -0.854 to -0.88. However, in case of Bi_2Se_3 [inset of Fig. 1(b)] as the temperature is increased from 5K to 200K the value of α tends to decrease at first, then sub linearly increases and further enters into saturation. The resultant value of α for both Bi_2Te_3 and Bi_2Se_3 single crystals are depicted in Table 1. Henceforth, we can say that both the WAL and WL contribute to the conduction process in case of Bi_2Te_3 and Bi_2Se_3 single crystals.

TABLE 1. HLN fit values of the pre-factor (α) and the phase coherence length (l_φ) obtained at different temperatures for Bi_2Te_3 and Bi_2Se_3 single crystals.

Temperature (K)	**Bi_2Te_3**		**Bi_2Se_3**	
	α	**l_φ (nm)**	**α**	**l_φ (nm)**
2.5	-0.854	98.266	-	-
5	-0.855	96.045	-0.9897	11.125
10	-0.86	92.979	-1.040	10.895
20	-	-	-1.045	10.667
50	-0.88	40.314	-1.012	9.496
100	-	-	-0.999	7.805
200	-	-	-0.996	5.576

Figure 2 (a, b) shows the temperature dependence of the phase coherence length (l_φ) as obtained from the HLN fitting of the magneto-conductivity for Bi_2Te_3 and Bi_2Se_3 single crystals. The extracted values of phase coherence length (l_φ) at different temperatures for both Bi_2Te_3 and Bi_2Se_3 single crystals are depicted in Table 1. The phase coherence length (l_φ) for both Bi_2Te_3 and Bi_2Se_3 single crystal is observed to decrease with increase in temperature. In case of Bi_2Te_3 (Fig. 2a) the phase coherence length (l_φ) is observed to reduce drastically from 98.266nm to 40.314nm as the temperature is increased from 2.5K to 50K whereas, for Bi_2Se_3 (Fig. 2b) the phase coherence length is seen to decrease from 11.125 nm to 5.576 nm at 5K and 200K respectively. Accordingly, the phase coherence length for Bi_2Te_3 decreases to nearly half from around 98 to 40nm as the temperature increased from 2.5 to 50K whereas, for Bi_2Se_3 the decrease in l_φ is very small. The decrease in phase coherence length as a function of temperature is expected since the probability of inelastic scattering due to electron-electron interaction increase with temperature.



(a) (b)

FIGURE 2. Temperature dependence of the phase coherence length (l_φ) obtained from HLN fitting of the magneto-conductivity for (a) Bi_2Te_3 and (b) Bi_2Se_3 single crystals. Inset represents the extracted phase coherence length (l_φ) as a function of temperature ($T^{-1/2}$) for (a) Bi_2Te_3 and (b) Bi_2Se_3 single crystals.

The inset of Fig. 2(a, b) shows the phase coherence length (l_{φ}) as a function of temperature ($T^{-1/2}$) for Bi_2Te_3 and Bi_2Se_3 single crystals. Clearly, the phase coherence length (l_{φ}) for both Bi_2Te_3 and Bi_2Se_3 single crystal is seen to follow the $T^{-1/2}$ dependence. A single slope is observed for topological systems exhibiting only WAL behaviour. However, in our case we observe two slopes, as seen from inset Fig. 2(a, b). The possible reason may be due to the competing WAL and WL effect contributing to the overall conduction process.

CONCLUSION

In conclusion, we studied and analyzed the magneto-conductivity data of Bi_2Te_3 and Bi_2Se_3 single crystal in terms of HLN equation and found that both WAL and WL contribute to the conduction mechanism. The extracted fitting parameters pre-factor (α) and phase coherence length (l_{φ}) displayed values which further showed the robustness of the system in terms of conduction.

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