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Epitaxial Growth of Bi_2Te_3 Topological Insulator Thin Films with Persistent Linear Magnetoresistance Behaviors

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Abstract

We report the growth of a high-quality Bi_2Te_3 thin film on an Al_2O_3 substrate using physical vapor deposition. Using a carefully selected temperature gradient between two separately controllable heaters inside a furnace, an unstrained Bi_2Te_3 thin film with *c*-axis orientation and domains bonded by van der Waals epitaxy is formed, as confirmed by X-ray diffraction. The stoichiometry of the film determined by X-ray photoelectron spectroscopy shows that the film has only slight surface oxidation and few contaminants, and the estimated ratio of the atomic densities of bismuth and tellurium is 1.49. A relatively low carrier concentration of 4.83×10^{18} cm^{-3} and electron mobility of 192.4 cm^2/Vs at 3 K allow clear observation of the weak anti-localization effect. Using a traditional two-dimensional (2D) localization analysis with the original Hikami–Larkin–Nagaoka (HLN) equation, we find clear evidence for the existence of topological surface states, and the temperature dependence of the phase coherence length exhibits 2D material behavior. Pronounced linear magnetoresistance at medium and high fields, which shows the interplay between three characteristic lengths, is also analyzed.

1. Introduction

Since their discovery, three-dimensional (3D) topological insulators (TIs) have been drawing much attention [1]. TIs have a full bandgap in their bulk and a Dirac cone surface state protected by strong spin–orbit interactions and time-reversal symmetry [2]. High-quality TI samples have been grown by several methods including molecular beam epitaxy (MBE) [3], pulsed laser deposition (PLD) [4], vapor–liquid–solid (VLS) growth [5], metal–organic chemical vapor deposition (MOCVD) [6], and the solvothermal method [7]. All of these methods are able to grow either thin films or nanostructures depending on the substrates and environment during growth. In this work, we demonstrate the growth of Bi_2Te_3 thin films on *c*-Al_2O_3 through a simple but effective PVD method. We use a fast heating technique, where the temperature is increased at a rate of ~100 °C/min in both source and substrate regions, to avoid incongruent sublimation during the initial stage of growth. Although these parameters may fluctuate because of the environment inside the quartz tube and the choice of different substrates, our results provide guidance for the growth of related materials using similar methods.

2. Results and Discussion

We make a remark on two generally adopted models which also give a reasonable explanation to LMR: Abrikosov's quantum model, and Parish and Littlewood's classical model. The research on this effect has been started in the research on doped silver chalcogenides $Ag_{2+\delta}Se$ and $Ag_{2+\delta}Te$, which are gapless semiconductors with a linear energy spectrum. The quantum model suggests that LMR will occur either by following the linear Dirac surface dispersion, where all the electrons are populated into the lowest Landau level when the quantum limit, $n_0 \ll (eH/\hbar c)^{3/2}$ is satisfied, or in a highly inhomogeneous sample where segregations of domains with different carrier concentrations exist. The criterion rules out the applicability for our data since LMR should begin at a relatively high field (~10^5 T) according to this model, if the estimation is made by $n_0 = 4.8\times10^{18}$ cm^{-3} at T = 3 K. Our data, however, show LMR at a relatively much smaller field, where *MR%* shift into a linear dependence at H = 0.31 T for T = 3 K, and H = 0.72 T for T = 30 K. These crossover fields H_c can be identified clearly in a double logarithmic scale figure plotted in Figure 8. Polycrystalline grains with more than 10^5 cm^{-3} carrier

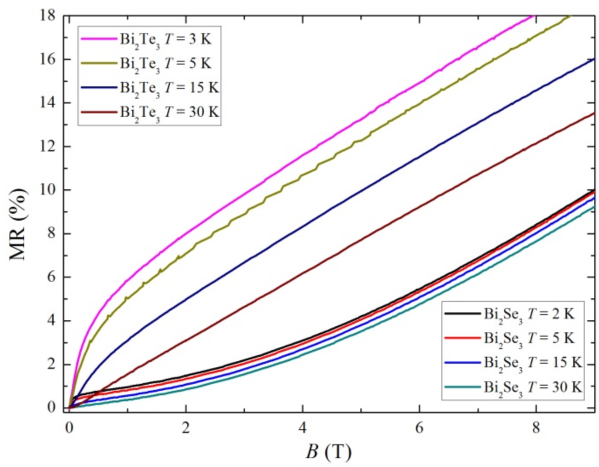

Fig. 1 Normalized magnetoresistance (*MR*%) for both Bi_2Se_3 and Bi_2Te_3 at four different temperatures ranging from 0-9 T. The *MR*% of Bi_2Se_3 is presented as a reference.

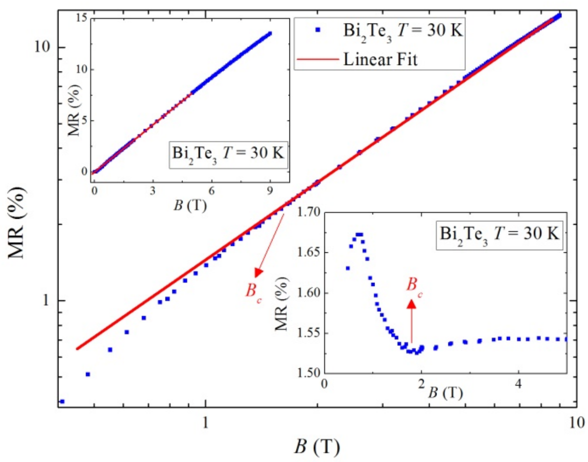

Fig. 2 Methods used to determine the crossover field B_c, which starts the linear magnetoresistance.

concentrations differences, as Abrikosov's model suggested, would also seem inappropriate in our sample since the morphology and stoichiometry surveys showed a homogeneous, single crystal film, even though small amount of disorder and impurities exist. Segregation usually occurs in samples grown or processed by chemical methods, and it can be avoided in a carefully controlled PVD system with slow deposition rate. Furthermore, the quantum model indicated that *MR%*, as shown in Fig. 1, depends strongly on the carrier concentration, while in our sample, n_{3D} barely changed from T = 3 K to T = 30 K. Therefore, we conclude that the quantum model is not suitable in our PVD grown Bi_2Te_3. The classical approach, on the other hand, focused on the relation between carrier mobility and LMR, and the basic principle is to consider an inhomogeneous surface as a network of four-terminal resistors. The model predicts that, at sufficiently large magnetic fields, $MR\% \propto \langle\mu\rangle$ for $\Delta\mu/\langle\mu\rangle < 1$, and $MR\% \propto \Delta\mu$ for $\Delta\mu/\langle\mu\rangle > 1$, where $\langle\mu\rangle$ is the average mobility, and $\Delta\mu$ is the width of the mobility disorder. Also the crossover field B_c calculated via the methods described in Fig. 2 should be linear proportional to μ^{-1}. We analyzed our data to check its applicability, with the results shown in the inset of Fig. 3. We found that the temperature dependence between $1/\mu$ and B_c, as well as μ and d*MR*%/d*H*, show a clear linear dependence. Our results fall in the $MR\% \propto \langle\mu\rangle$ category, which is reasonable since in a homogeneous single crystal the mobility should be greater than the its spatial fluctuation. We treat the classical model as a good approximation.

3. Conclusions

Epitaxial growth of Bi_2Te_3 thin films on *c*-plane Al_2O_3 substrates was achieved by PVD. The topological surface state was observed as a clear WAL effect and unsaturated LMR in the transport measurements. The WAL is analyzed by using the HLN equation and LMR can be well approximated by the classical model. All the above measurements show the effectiveness of a carefully controlled temperature gradient inside the PVD furnace, allowing the energies of vapor molecules to be suitable for vertical and horizontal growth.

Acknowledgements

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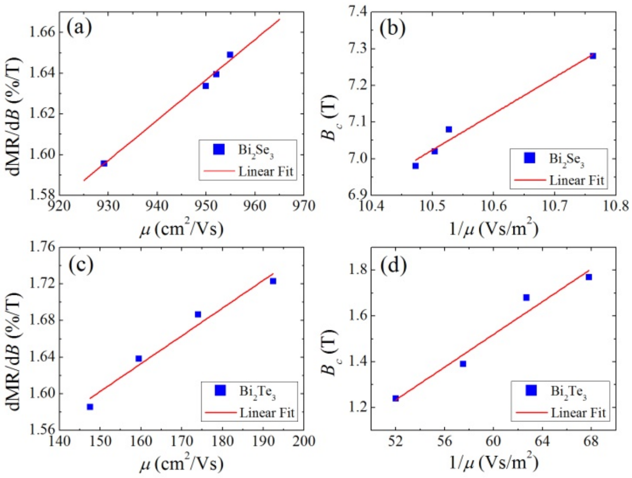

Fig. 3 The relation between the slope of *MR*% (d*MR*/d*B*) and the Hall mobility for (a) Bi_2Se_3 and (c) Bi_2Te_3, and the relation between the crossover field B_c and the inverse of the Hall mobility for (b) Bi_2Se_3 and (d) Bi_2Te_3. The *MR*% of Bi_2Se_3 is presented as a reference.