Transport properties in topological materials

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Topological materials are a new quantum material in which only topology is responsible for unusual transport properties. The materials differ from non-topological materials, topological insulators have a conductive surface which is protected by topology. Different categories of topological materials have different topologies. Very recently, NbP has been predicted as a topological Weyl semimetal (WSM) with a peculiar gapless state and massless relativistic electrons. We found that NbP shows 850,000% unsaturated magnetoresistance (MR) accompanied by strong Shubnikov-de Haas (SdH) oscillations at 1.85 K (250% at room temperature) in 9 T and an ultrahigh carrier mobility of 5,000,000 cm^2 V^{-1} s^{-1}. With the help of high-field MR measurements at HLD, Dresden and HFML, Nijmegen, we also found that these MR are non-saturating up to 62T. Bi_2Te_2Se topological insulator single crystals grown by the modified Bridgman method possess a high bulk resistivity of > 20 Ωcm below 20 K, whereas the bulk is mostly inactive and surface transport dominates. We designed a special measurement geometry to measure the resistance and found that single-crystal Bi_2Te_2Se exhibits a crossover from bulk to surface conduction at 20 K. Another materials class are Heusler topological insulators that show a very high hole mobility of 35,900 cm^2 V^{-1}s^{-1} and unsaturated MR. A tentative relationship between the linear MR and mobility was established, which indicates that the mobility controls the linear part of MR in Heusler topological insulators.

Topological materials are recent members in a series of quantum materials, and their properties are controlled by topology. Topological insulators (TIs) are insulating in the bulk and conducting at the surface. In another class of topological materials, the bulk of the material is a semimetal, and the valence and conduction bands touch near the Fermi level. Depending on whether the bands are nondegenerate or doubly degenerate, a topological material is called a topological Weyl semimetal or a topological Dirac semimetal. The field dependence of the Hall resistivity $\rho_{xy}(H)$ that exhibits a nonlinear behavior indicates the involvement of more than one type of charge carrier in the transport properties. From the inset of Fig. 1, NbP exhibits a negative Hall coefficient, R_H, up to 125 K, which changes sign for temperatures above 125 K. We use the single-carrier Drude band model, $n_{e,h}(T)=1/[eR_H(T)]$, to calculate the carrier density and $\mu_{e,h}(T) = R_H(T)/\rho_{xx}(T)$ to estimate the mobility, where n_e (n_h) and μ_e (μ_h) are the charge density and mobility of the electrons (holes), respectively. The electron carrier concentration was found to be 1.5 ×10^{18} cm^{-3} at 1.85 K and increases slowly with temperature, exhibiting a semimetal-like or very small gap-like behavior (see Fig. 1). The mobility plays a major role in the charge transport in a material and consequently determines the efficiency of various devices. Here, NbP exhibits an ultrahigh mobility of 5×10^6 cm^2 V^{-1}s^{-1} at 1.85 K. A large MR is usually associated with a high mobility. We now focus on the MR measurement in NbP. Fig. 1 shows the MR measured in transverse magnetic fields up to 9 T at different temperatures. We find that NbP exhibits an extremely large MR 8.5×10^5% at 1.85K in

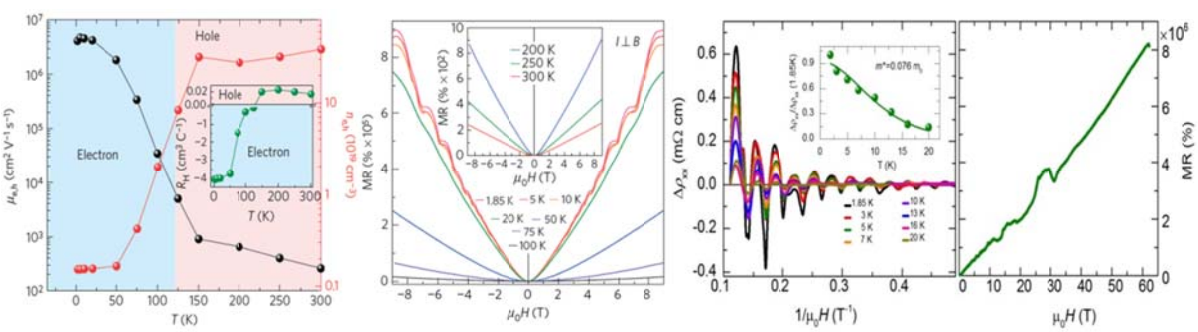

Fig. 1: Temperature dependence of the mobility (left axis) and the carrier density (right axis). Transverse magnetoresistance measured at different temperatures. SdH oscillations after subtracting the background from ρxx measurements. The inset shows the temperature dependence of the relative amplitude of Δρxx for the SdH oscillation at 8.2 T. The solid line is a fit to the Lifshitz–Kosevich formula for effective mass. The right-hand graph shows the MR measured in field up to 62 T.

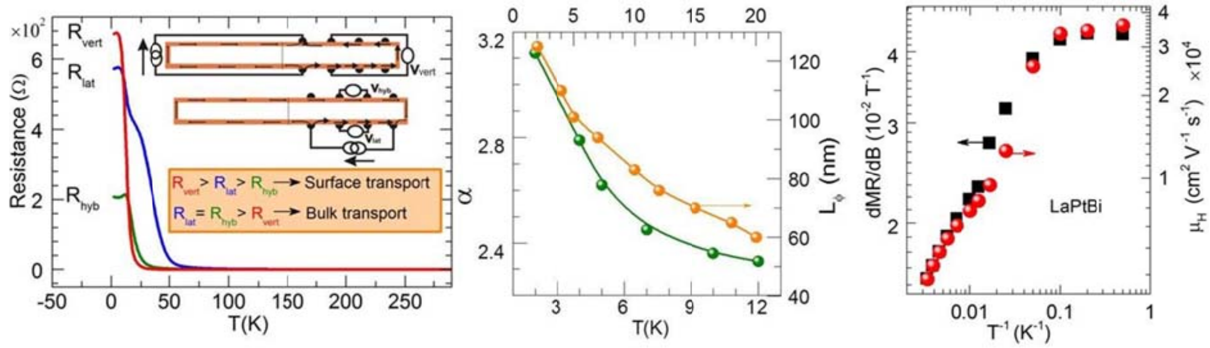

Fig. 2: Temperature dependence resistances, R_{vert}, R_{lat}, and R_{hyb}, measured in a special geometry (inset). Temperature dependence of the weak anti-localization coefficient, α, and the magnetic phase coherence length, Lϕ. Linear part of the slope of the MR, dMR/dB, and mobility as a function of inverse temperature.

a field of 9 T. Interestingly, the MR continues to increase and reaches the value of 8×10^6 % at 1.5 K in magnetic fields up to 62 T.

Another category of topological material is topological insulators. We grew a series of different types of topological insulators, e.g., Heusler topological insulators and Bi-based topological insulators. We synthesized very high quality Bi_2Te_2Se single crystals by using a modified Bridgman method that possess a high bulk resistivity of >20 Ωcm below 20 K, whereas the bulk is mostly inactive and surface transport dominates. To extract the surface transport from that of the bulk, we designed a special measurement geometry to measure the resistance and found that $R_{lat} > R_{hyb} > R_{vert}$, as would be expected for bulk conduction at high temperature. However, for surface conduction or the TI case below 30 K, where current is forced to flow through the surface, the R_{lat} value becomes larger than R_{hyb} and follows the order $R_{vert} > R_{lat} > R_{hyb}$, which was verified by surface transport (upper inset of Fig. 2). We fitted the measured magnetoconductance by using a well-known Hikami-Larkin-Nagaoka (HLN) model and fitted values of α and L_ϕ plotted against temperature. According to the middle graph of Fig. 2, high values of α (-1 for perfect 2D) indicate some contribution from bulk channels. After extracting the bulk contribution by measuring it in rotating fields, we found the value of α to be exactly -1, which indicates perfect surface transport. The temperature dependence of $1/L^2_\phi$ exhibits a linear behavior, indicating the dominant inelastic electron-electron scattering in the surface conducting channels of our Bi_2Te_2Se bulk single crystal. We synthesized a series of Heusler compounds RPtBi, where R is a rare-earth element, and found that these are topological insulators. Besides the topological property, RPtBi (R= La, Y, and Lu) show superconductivity below 1 K. Heusler topological insulators exhibit a very high mobility of 3.5×10^4 $cm^2V^{-1}s^{-1}$ and unsaturated MR. These ultrahigh values of the mobility are not only due to gaplessness but also to the presence of linear dispersion of the bands close to the Fermi energy, where charge carriers behave like relativistic particles. From Fig. 2, slope of the linear MR and mobility follow the same trend with temperature, indicating that the mobility controls the linear part of the MR in this series of compounds. The high mobility is important for further device applications of these materials such as image magnetic monopoles, detection of Majorana fermions, and giant magneto-optical effects.

References

[1] [1 *C. Shekhar, A. K. Nayak, Y. Sun, M. Schmidt, M. Nicklas, I. Leermakers, U. Zeitler, Y. Skourski, J. Wosnitza, Z. Liu, Y. Chen, W. Schnelle, H. Borrmann, Y. Grin, C. Felser and B. Yan, Nat. Phys. (doi:10.1038/nphys3372), (2015).*

[2] *C. Shekhar C. E. Viol Barbosa, B. Yan, S. Ouardi, W. Schnelle, G.-H. Fecher, and C. Felser, Phys. Rev. B* ***90****, 165140 (2014).*

[3] *C. Shekhar, S. Ouardi, A. K. Nayak, G.-H. Fecher, W. Schnelle, and C. Felser, Phys. Rev. B* ***86****, 155314 (2012).*

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