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Semiconductor-metal transition in doped topological insulators

Bismuth selenide (Bi_2Se_3) is a typical topological insulator [1,2] which is characterized by insulating bulk state with an energy gap and conducting surface state with linear energy-momentum dispersion relation. Bi_2Se_3 has two-dimensional layered structure which consists of a stack of Se-Bi-Se-Bi-Se units (quintuple layers, QLs) with week van der Waals interaction. The resistance of Bi_2Se_3 usually decreases with decreasing temperature. This metallic behavior shows that Bi_2Se_3 is *n*-doped, *i.e.*, the Fermi level, E_F, is located in the bulk conduction band (BCB) due to natural deficiency of Se atoms. Doping of Bi_2Se_3 with impurity atom M is effective to change electronic property of Bi_2Se_3 not only by tuning E_F but also inducing ordered states. Here, notice two roles of impurity doping. One is *p*-doping by substituting mono- or bi-valent M for trivalent Bi atom. The other is *n*-doping by intercalating M into the van der Waals gap between QLs. Thus, to lower E_F, M must be substituted for Bi. Actually, substitution of bivalent Ca [3] or Cd [4] for Bi decreases E_F in the bulk valence band (BVB). On the other hand, Sr intercalation in Bi_2Se_3 increases electron density, thereby inducing the superconductivity [5].

In this presentation, we report interesting transport property observed in Ag-doped Bi_2Se_3 [6]. The resistance increased with decreasing temperature, and this semiconducting behavior is explained by the decrease in E_F due to the substitution of Ag for Bi atom. With decreasing temperature, however, the resistance abruptly dropped at critical temperature T_c of 35 K, showing semiconductor-metal (S-M) transition (Fig. 1(a)). Measurement of Hall effect showed that the carrier type was electron and the decrease in resistance was accompanied with the increase in carrier density and mobility (Fig. 1(b) and (c)). The carrier density exceeds the maximum capacity of the surface state, indicating the carrier of Ag-doped Bi_2Se_3 mainly results from bulk. Furthermore, electric-field effect was studied by measuring conductivity σ against bottom gate voltage V_g. As shown in Fig. 2, the inflection of $\sigma(V_g)$ curves was found around $V_g = 0$, *i.e.*, the mobility is larger at negative V_g than at positive V_g. Provided that E_F is pinned at the bottom of BCB, the above result means that the mobility is larger in bulk than at surface. This is because depletion layer produced at negative V_g is generally much thicker than accumulation layer at positive V_g. The pinning of E_F at the bottom of BVB implies the detailed balancing between *p*-doping by substituted Ag and *n*-doping by intercalated Ag. To summarize, the S-M transition is due to the increase in bulk carrier with large mobility, which can be induced by depinning of E_F below T_c. The splitting of BCB is one possible origin of the depinning of E_F and the S-M transition.

References

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Figures

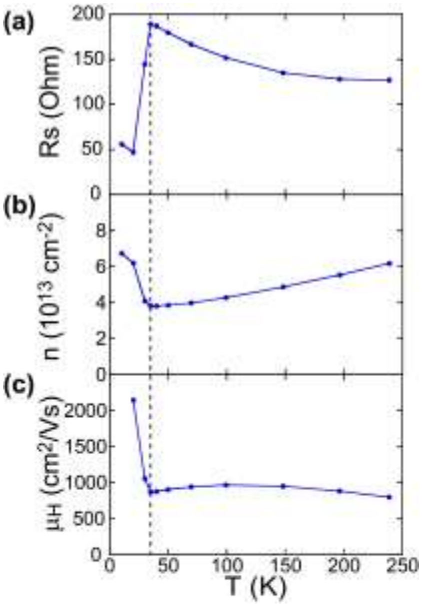

Figure 1: Temperature dependence of (a) sheet resistance, (b) carrier (electron) density per area, and (c) Hall mobility of $Ag_{0.05}Bi_2Se_3$ [5]. A dashed line shows T_c where S-M transition occurs.

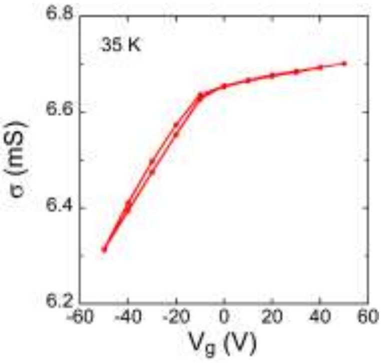

Figure 2: Gate voltage dependence of sheet conductivity of $Ag_{0.05}Bi_2Se_3$ at 35 K.