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**Semiconductor-metal transition in doped topological insulators**

Bismuth selenide ($\text{Bi}_2\text{Se}_3$) 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. $\text{Bi}_2\text{Se}_3$ 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 $\text{Bi}_2\text{Se}_3$ usually decreases with decreasing temperature. This metallic behavior shows that $\text{Bi}_2\text{Se}_3$ 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 $\text{Bi}_2\text{Se}_3$ with impurity atom M is effective to change electronic property of $\text{Bi}_2\text{Se}_3$ 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 $\text{Bi}_2\text{Se}_3$ increases electron density, thereby inducing the superconductivity [5].

In this presentation, we report interesting transport property observed in Ag-doped $\text{Bi}_2\text{Se}_3$ [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 $\text{Bi}_2\text{Se}_3$ mainly results from bulk. Furthermore, electric-field effect was studied by measuring conductivity $\sigma$ 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**


**Figures**

**Figure 1:** Temperature dependence of (a) sheet resistance, (b) carrier (electron) density per area, and (c) Hall mobility of Ag$_{0.05}$Bi$_2$Se$_3$ [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$_2$Se$_3$ at 35 K.