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Electrical properties of $Pb(Bi,Sb)_2Te_4$ topological insulators

Topological insulators (TIs) are known to exhibit characteristic 2D surface states similar to graphene and other Dirac materials. TIs' surface states are spin-polarized, and immune to scattering at impurities. These unique properties make TIs promising materials for future applications as novel spintronic devices [1] for sustainable society. However, the detection and practical use of the surface states are currently a bit difficult. The reason is that the bulk bandgap is narrow in most of the TIs identified so far (Figure 1a), and characteristic surface conduction is masked by bulk conduction [2]. Therefore, many efforts have been made to improve bulk insulation in this field. In our research, we chose $Pb(Bi,Sb)_2Te_4$ TI, which has twice higher density of surface carriers than ordinary BSTS-TI [3]. By changing Bi/Sb ratio precisely, we succeeded in obtaining bulk insulating samples for the first time in this system, and resistivity value at T=2K was about 100 higher than previous research [4]. Remaining bulk conduction was considered to be contributed by impurity bands in the bulk band gap [5]. Magnetoresistance observed in this system was quite well interpreted as 3D-WAL scheme [5]. We then proceeded to investigate surface states using such high resistivity samples.

Total conduction in TIs should be the sum of bulk and surface contributions [6] (2-channnel model, Figure 1b). Equivalent circuit is also shown. Then, total resistance R and resistivity ρ_{xx} can be expressed by surface resistivity ρ_s , bulk resistivity ρ_b , surface thickness t_s, bulk thickness t_b, sample length l and sample width w, as follows.

$$R = \frac{1}{\frac{1}{R_s}+\frac{1}{R_b}} = \frac{1}{\frac{wt_s}{\rho_s l}+\frac{wt_b}{\rho_b l}} = \frac{\rho_s\rho_b l}{(t_s\rho_b+t_b\rho_s)\cdot w} \tag{1}$$

$$\rho_{xx} = \frac{(t_b+t_s)w}{l}R = \frac{\rho_s\rho_b(t_b+t_s)}{t_s\rho_b+t_b\rho_s} = \frac{\rho_s(1+t_s/t_b)}{t_s/t_b+\rho_s/\rho_b} \tag{2}$$

Here, t_b can be changed by sample thickness and t_s is constant (about 5nm [6]). In the limit of $t_s/t_b \to 0$ (thick sample), then $\rho_{xx} \to \rho_b$, and if $t_s/t_b \to \infty$ (thin samples), $\rho_{xx} \to \rho_s$. So, by reducing thickness, surface conduction can be made dominant. AFM image of typical device is shown in Figure 1c. Sample thickness is $t = t_s + t_b = 190nm$, and other size factors can be measured by AFM data. The temperature dependence of resistivity measured in nano-flake is shown in Figure 1d (blue line). The resistivity at T=2K is ρ_{xx} =25.3 mΩcm, considerably lower than thick sample with ρ_b=164mΩcm. Therefore, this can be attributed to surface conductance. ρ_s can be calculated by eq. (2) and its value is ρ_s= 0.78 mΩcm. In BSTS-series TI, the reported ρ_s is about 2.2 mΩcm [6], so surface conductivity is higher in our samples. As surface electrons n_s of $Pb(Bi,Sb)_2Te_4$ is reported to be twice as many as that of BSTS, lower $\rho_s = \sigma_s^{-1} = (qn_s\mu_s)^{-1}$ can be attributed to higher surface carrier density. In addition, the contribution of surface conduction to total conduction is about 85% in thin flakes(190nm), while 0.5% in thick samples(200μm). If quantum oscillation originating from surface states can be detected, more quantitative analysis of surface properties, such as surface carrier density, n_s fermi wavenumber k_F, mobility μ_s , etc., can be conducted

References

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Figures

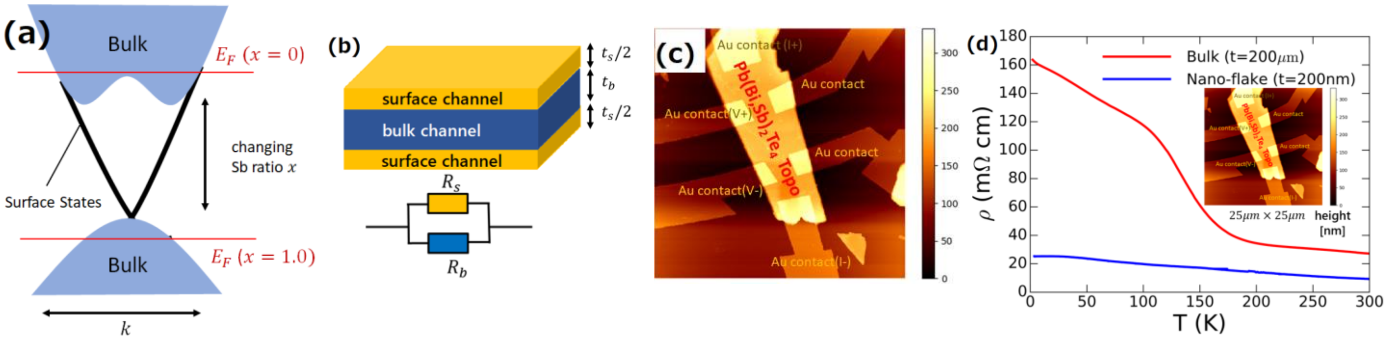

Figure 1:

(a) Schematic picture of Pb(Bi,Sb)2Te4's band structure (BS). Bulk and surface states have different BS.

(b) schematic picture of transport channels in TIs.
In order to reduce bulk contribution, efforts have been made to enhance bulk resistivity and reduce bulk thickness t_b

(c) AFM image of typical device for electrical measurements. Sample is in the center, and Au probe is contacted.

(d) Temperature dependence of resistivity of nano-flake(blue) and bulk(red) sample.
Resistivity significantly reduces when reducing sample thickness.