Magnetic and magnetotransport properties of Bi_2Se_3 thin films doped by Eu

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3D topological insulators are a novel research field in the condensed matter physics. In spite of its not so long history, the new lines of research have appeared even within itself, in particular, one of them is the study of properties of these materials with magnetic dopants, so called magnetic topological insulators. These studies have already given rise to the discovery of unusual quantum effects such as the quantum anomalous Hall effect and quantum magnetoelectric effect. However, specific features of electron transport and of magnetic phenomena in 3D magnetic topological insulators are still the scientific problem being the subject of great interest.

We will report on electron transport in magnetic field, including quantum antilocalization effects and linear magnetoresistance along with studies of magnetic state of Eu-doped Bi_2Se_3 within the wide range of magnetic fields (up to 18 T) and temperatures (0.3 – 300 K) as a function of Eu content. Eu content x in the $(Bi_{1-x}Eu_x)_2Se_3$ layers was regulated by Eu-cell temperature and deduced from the growth rates of the Bi_2Se_3 and EuSe reference layers. Thickness of the layers was obtained from XRR spectra and XRD Kiessig fringes. The films with the thickness of about 20–30 nm and Eu content $x = 0 – 0.2$ were obtained by MBE technology method. To protect surface of the films from exposure to the atmosphere and to stabilize their properties, films will be covered by the 30–40 nm thick layer of amorphous selenium. With the growth of Eu content x, HAADF STEM imaging and EDX spectroscopy analysis revealed Eu-riched nanoclusters with increasing lateral dimension (10 to 30 nm) and concentration $2\cdot10^{16}$ to $2\cdot10^{17}$ cm^{-3}.

SQUID magnetic measurements shows diamagnetic signal from substrate while sample demonstrate both paramagnetic and weak ferromagnetic contributions, which were obtained by subtracting the diamagnetic signal. The paramagnetic signal saturates at low temperatures and at high fields above 40–50 KOe. Ferromagnetic contribution saturates at fields less than 10 KOe, it could be extracted by subtraction of linear signal and for one of the samples (x=0.13) presented in Fig. 1. For samples with $x < 0.1$, the ferromagnetic signal is weak and originates from magnetic moments of isolated Eu-containing clusters, while for samples with $x = 0.13$ and $x = 0.2$, it seems that the long-range ferromagnetic state is established.

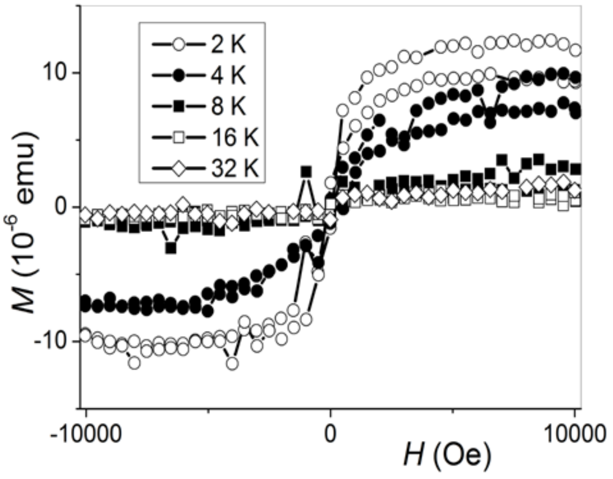

Figure 1. Magnetization versus magnetic field for $(Bi_{1-x}Eu_x)_2Se_3$ sample with $x = 0.13$ at various temperatures.

Magnetotransport measurements was performed at various orientations of magnetic field both perpendicular to the sample plane and in plane, while in the latter case, the magnetic field was directed both perpendicular and parallel to the current. From these measurements we found that the main part of magnetoresistance is due to the surface states. At weak magnetic field, we have observed antilocalization, which at low Eu content ($x < 0.07$) (see fig. 2) was not followed by weak localization in agreement with the predictions for nontrivial topological states.

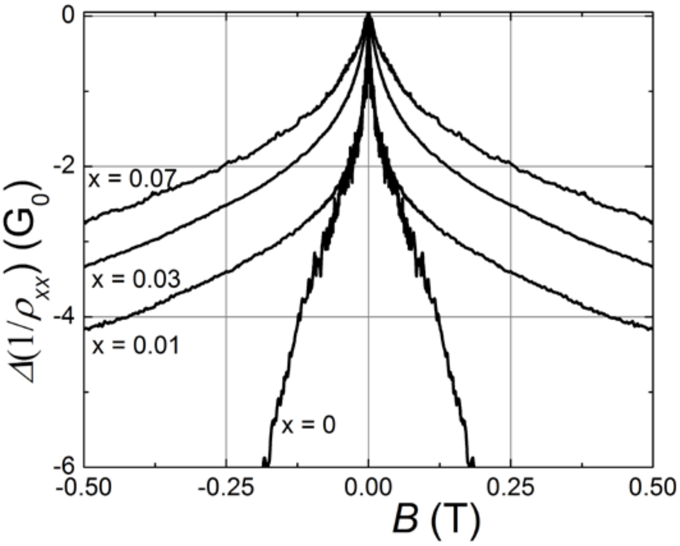

Figure 2. Magnetoresistance curves for Bi_2Se_3 samples doped by Eu with various Eu content x shown at the curves. The curves demonstrate quantum corrections to conductivity due to weak antilocalization without any sign of weak localization.

Standard Hikami–Larkin–Nagaoka formula was used to calculate the dephasing length l_φ. All samples with Eu content $x < 0.13$ demonstrate square-root-like inversed temperature dependence of l_φ suggesting dominant role of e–e scattering as a dephasing mechanism. However, this dependence takes place within the whole temperature range of measurements for undoped samples ($x = 0$), while for Eu doped samples, l_φ starts to saturate at $T < 1.5$ K as it is seen in Fig. 3.

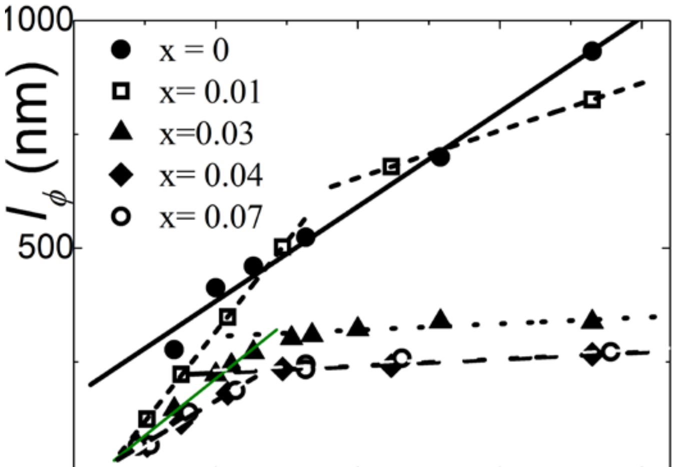

Figure 3. Dephasing length versus inversed square-root temperature for the samples with various Eu content.

Unlike undoped samples, the Eu doped samples demonstrate linear magnetoresistance, which changes according to the standard parabolic-like magnetoresistance behavior at fields higher than $B = B_{\max}$. The $B_{\max}$ value increases with Eu content up to $x \approx 0.05$ as well as the dephasing length. The slope of linear magnetoresistance increases with temperature lowering down to about 1 K and then saturates like the dephasing length does.

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