Terahertz Probing of Surface Electron States in Topological Crystalline Insulators $Pb_{1-x}Sn_xSe$

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***Abstract*— We suggest a method for detection of highly conductive surface electron states including topological ones. The method is based on measurements of the photoelectromagnetic effect using terahertz laser pulses. In contrast to conventional transport measurements, the method is not sensitive to the bulk conductivity. The method is demonstrated on an example of topological crystalline insulators $Pb_{1-x}Sn_xSe$. It is shown that highly conductive surface electron states are present in $Pb_{1-x}Sn_xSe$ both in the inverse and direct electron energy spectrum.**

I. INTRODUCTION

THEORETICAL prediction of existence of gapless electron states on the surface of topological insulators stimulated extensive experimental studies directed to detection of these states. By now, the main tools of these studies are ARPES measurements. On the other hand, ARPES does not provide direct information on the surface conductivity, and the main interest to topological surface states was stimulated by hopes to use the electron transport via these states. In most of the cases, however, this surface electron transport is shunted by conductivity via the bulk of a sample.

We suggest a method for detection of highly conductive surface electron states including topological ones which is not sensitive to the presence of charge carriers in the bulk of a sample. This method uses the photoelectromagnetic effect induced by pulses of laser terahertz radiation.

II. RESULTS

The method is demonstrated by an example of topological crystalline insulators $Pb_{1-x}Sn_xSe$. $Pb_{1-x}Sn_xSe$ form a continuous range of solid solutions for all tin content values $0 < x < 1$. The energy gap varies with x passing through zero at $x = 0.15$ at $T = 0$ K. In the low tin content range $x < 0.15$, these semiconductors are classified as trivial insulators. At $x > 0.15$, instead, the inverted energy spectrum is realized, and non-trivial topologically protected surface electron states appear.

The samples under study were single crystals of $Pb_{1-x}Sn_xSe$ grown by the Bridgman method. All samples possessed the *n*-type conductivity with the free electron concentration varying from 10^{17} cm^{-3} to $3*10^{19}$ cm^{-3}.

The photoelectromagnetic (PEM) effect is appearance of a voltage drop U_{PEM} between sample contacts oriented perpendicular to the incident radiation direction and to the magnetic field. The signal magnitude and sign are defined by the magnetic field and by the direction and value of the diffusive carrier flux. 100 ns – long pulses of an optically pumped NH_3 terahertz laser with the wavelengths of 90, 148 and 280 μm were used to excite the PEM effect.

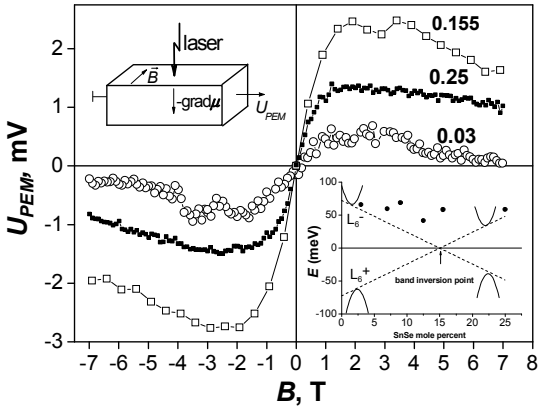

Fig. 1. Dependence of the PEM effect amplitude as a function of magnetic field applied for $Pb_{1-x}Sn_xSe$ samples of different compositions x (figures near the curves). The sample temperature is 4.2 K, the laser wavelength is 148 μm, the maximal power in a pulse is 30 kW. The inserts show the composition dependence of the conduction and valence band positions relative to the middle of the bandgap at $T = 0$ K together with the calculated positions of the Fermi level in the samples studied and the experiment geometry.

Figure 1 shows dependence of the PEM effect amplitude on the magnetic field. The effect is odd in magnetic field. The PEM effect was detected in all samples, both with $x > 0.15$ and with $x < 0.15$ as well. The sign, amplitude and characteristic features of the effect do not vary substantially with x.

The sign of the effect corresponds to the net diffusion of charge carriers from the surface to the sample bulk. The origin of appearance of the diffusive electron flux comes from the difference in charge carrier mobility of excited electrons nearby the sample surface and the electron mobility in the sample bulk. The excited electrons diffuse to the sample bulk while losing their energy. This leads to counter diffusion of "cold" electrons from the bulk to the surface. In course of this process, the electron mobility gradient gives rise to a net flux of electrons. The only option to explain this behavior is appearance of extended surface electron states with enhanced free electron mobility compared to the bulk.

It is shown that highly conductive surface electron states are present in the topological crystalline insulators $Pb_{1-x}Sn_xSe$ both in the direct and inverse energy spectrum. Therefore it is demonstrated that even if existence of the topological states is confirmed by ARPES experiments, observation of highly conductive surface electron states in electronic transport does not necessarily mean that these states are topological. There may exist other highly conductive surface electron states that hinder the topological states in transport measurements.