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To the inhomogeneous bulk state of the $Bi_{1.08}Sn_{0.02}Sb_{0.9}Te_2S$ topological insulator as revealed by ESR of the charge carriers

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Studies of topological insulators (TI) are currently marked by a growing interest to the origin of strong impact of various defects and local charge inhomogeneities existing in the insulating region between conducting surfaces or edges on the fundamental properties of surface current carriers. Much of this interest is due to the intriguing results obtained for two-dimensional TI, which reveal the failure of conductance quantization [1–4] in two-dimensional topological insulators despite of topological protection and the absence of magnetic impurities.

One of the possible ways to explain the spoiling of conductance quantization and the emergency of backscattering in 2D topological insulators is the coupling of edge modes to charge puddles, naturally present in real samples [5, 6]. The edge current carriers can penetrate into these puddles due to tunneling and interact inelastically with current carriers located in them. Then, after spending some time there, they can tunnel back to the edge which, undoubtedly, should affect their transport properties and, in particular, lead to non-zero backscattering.

An important issue is the detection and analysis of similar inhomogeneities in real three-dimensional TIs, where their presence seems also to be very probable. One of the promising tools for solving such problems is spin resonance of current carriers, which can be used to study local inhomogeneities in the distribution of charge and spin excitations.

The main aim of the present paper is the study of electron spin resonance (ESR) of the bulk charge carriers in one of the most perfect 3D topological insulator $Bi_{1.08}Sn_{0.02}Sb_{0.9}Te_2S$ in order to elucidate the electronic properties and local charge inhomogeneities in the insulating region between conducting surfaces of this compound.

1. In topological insulators, spin excitations, as well as charge ones, can be divided into two types: surface and bulk. The corresponding Hamiltonians were obtained in [7]. The adjustment of these general expressions for the needs of spin-based experiments was carried out in [8, 9]. An important feature of surface spin excitations is that, due to the "spin-momentum locking" effect, even in zero magnetic field, the spin sublevels are split at a distance of the order of hundreds of meV comparable with a bulk gap value, and the observation of spin resonance with a standard ESR spectrometer is impossible. Nevertheless, interesting physical properties as well as some parameters of the Hamiltonian [7–9] can be determined from analysis of the spin resonance on bulk current carriers, which will be presented below.

The spin splitting for them is proportional to the applied magnetic field and may be described by a corresponding effective g-factor in the Zeeman term. The total g-factor includes three contributions. The main contribution results from the strong spin-orbit coupling in TI, which is inherently included within the Hamiltonian [7, 8]. Second (minor) correction come from the free electron g-factor and the third one is due to perturbative contribution from remote energy bands [7].

2. Our investigations of electron spin resonance in the topological insulators were carried out for the isostructural version of Bi telluride compound $Bi_{1.08}Sn_{0.02}Sb_{0.9}Te_2S$ (BSSTS). The studied single crystals were grown using the procedure described in [10]. It is necessary to indicate that the compensation for the last of native defects present was achieved through 1 % Sn substitution for Bi. The comprehensive characterization of the grown single crystals revealed [11, 12] that their structure, transport and magnetotransport properties were similar to that published in [10].

3. ESR spectra were recorded using the standard X-band ($9.2 \div 9.6$ GHz) spectrometer Bruker BER-418s in the temperature range from 1.4 up to 100 K. The weak spin resonance signals were observed in fields of

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150–250 Oe at temperatures below 15 K. ESR in such weak magnetic fields corresponds to unusually large values of the g-factors of current carriers, which indicates a strong spin-orbit interaction characteristic of topological insulators. While the positions of the observed ESR signals are independent on the orientation of external field in the ab plane they strongly depend on its orientation relative to the crystal axis c normal to surface of the crystalline sample.

It should be noted that in some samples we observed two ESR signals at the fields in the vicinity of 150 and 170 Oe correspondingly. The positions of these signals strongly depend on the orientation of the magnetic field relative to the basal ab plane of the crystal. We assign them to holes and to electrons correspondingly.

4. Let us turn now to the angular dependence of the spin resonance spectra on the orientation of the magnetic field relative to the c axis (characterized by the angle θ) for samples which clearly reveal the superposition of two different ESR lines corresponding to holes and to electrons. From the analysis of the observed spectra using for the angular dependence of g-factor of each superimposed line the standard expression $g^2 = g_{\|}^2 \cos^2\theta + g_{\perp}^2 \sin^2\theta$ it follows that for holes $g_{\perp} = 28.3 \pm 1$; $g_{\|} = 47.4 \pm 1$ and for electrons $g_{\perp} = 26.4 \pm 1$; $g_{\|} = 44.7 \pm 1$. The strong temperature dependence of the lines should be noted, the intensity of which rapidly decreased with increasing temperature. At temperatures above 15 K, the lines became unobservable.

The analysis of the integral ESR signal intensity reveals very interesting circumstance. Instead of the temperature independence expected in accordance with the Pauli law, the integral intensity of the spin resonance signal from the current carriers grows rapidly upon lowering temperature in a way similar to Curie-like dependence. For the system without any local magnetic moments such an unusual behaviour may be considered as an indication that the bulk charge carriers are arranged into the ensemble of nanosized metal particles (droplets) randomly distributed in the bulk of sample. Indeed, as it was shown by Gor'kov and Eliashberg [14], that if the size of droplets is small enough to lead to discreteness of the energy levels of the quasiparticles forming them, then at temperatures smaller than the spacing between the levels, their magnetic susceptibility obeys the Curie law.

5. The droplets can appear due to compensating doping of topological insulators, which suppresses bulk conductivity. As a result, charged defects appear in the TI structure giving rise to local distortions of the forbidden gap, which are anomalously strong when the screening is suppressed due to the small number of current carriers [13].

It is not excluded that such droplets when residing near the surface may influence the surface current carriers.

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