Change of the topological surface states induced by ferromagnetic metals deposited on BiSbTeSe$_2$

A K Kaveev$^1$, A N Terpitskiy$^1$, O E Tereshchenko$^{2,3}$, V A Golyashov$^2$, D A Estyunin$^4$, A M Shikin$^4$ and E F Schwier$^5$

$^1$Ioffe Institute, Saint-Petersburg, 194021, Russia
$^2$Rzhanov Institute of Semiconductor Physics, Novosibirsk, 630090, Russia
$^3$Novosibirsk State University, Novosibirsk, 630090, Russia
$^4$Saint-Petersburg State University, Saint-Petersburg, 198504, Russia
$^5$Hiroshima University, Higashi Hiroshima, 739-8527, Japan

kaveev@mail.ioffe.ru

Abstract. The energy gap was revealed in the Dirac cone of the BiSbTeSe$_2$ topological insulator after the submonolayer deposition of a ferromagnetic metal. As a ferromagnet, cobalt and manganese were used. Such way of the energy gap opening is novel in comparison to the bulk ferromagnetic doping of topological insulators.

1. Introduction
The control of the spectrum of surface topological states of topological insulators is attractive from the point of view of possible applications in spintronics. In particular, the influence of the proximity effect when depositing or introducing a magnetic impurity into the surface layer can remove the topological protection of states by removing the inversion with respect to time reversal symmetry [1].

2. Experimental
Co and Mn were deposited on the BiSbTeSe$_2$(0001) surface with use of both conventional and laser molecular beam epitaxy methods. BiSbTeSe$_2$ mono-crystalline substrates were made from bulk single crystals grown by the modified vertical Bridgeman method from the previously synthesized mixture of 5N pure Bi, Sb, Te and Se.

Clean TI surfaces were obtained by the cleaving with a scotch tape and a subsequent vacuum annealing at 330°C under the 10$^{-8}$ mbar pressure. Ferromagnetic atoms were deposited on the substrate at 330°C in vacuum. The effective thicknesses were between 0 and 2 Å for Co and between 0 and 1.4 Å for Mn, respectively. It should be taken into account that these are sub-monolayer coverages.

The electronic structure of the grown samples was studied both by synchrotron and by laser-based microfocused angle-resolved photoelectron spectroscopy (BL-1 and Laser-ARPES setups, HiSOR synchrotron, Hiroshima, Japan). The measuring system is based on a 3.3 W Ti:Sa mode-locked laser (Tsunami, Spectra Physics) with a 17 W green laser pumping (Millenia eV, Spectra Physics). High harmonic generator (HarmonIXX, A.P.E.) allows obtaining UV radiation at a 191-210 nm wavelength with a power of 0.1-0.7 mW.

3. Results and discussion
The effect of the displacement of the Dirac point due to the band bending downwards (electron doping) was revealed using the same materials (cobalt and manganese) as adsorbates deposited at room temperature. This band bending leads to a shift of the Dirac point below the Fermi level, which made it possible to observe the region near the Dirac point by ARPES (figure 1). The energy gap width was estimated as 15–25 meV for the case of cobalt deposition (figure 2), and 30–45 meV for the case of manganese deposition (figure 3).

**Figure 1.** (a) - electronic structure of BiSbTeSe$_2$ surface, measured using Laser ARPES (hν = 6.3 eV, T = 20 K, Γ-K direction), after cleaving the sample in vacuum. (b, c) – the result of bending of the surface bands after deposition of 0.1 Å of Co (b) or Mn (c) at room temperature: Dirac point is observed by ARPES.

**Figure 2.** The result of bending of the surface bands after deposition of 0.1 Å of Co adsorbate at room temperature (Dirac point is observed) (a) and the band gap opening (b) in the spectrum of Dirac surface states in the Co / BiSbTeSe$_2$ system. Figure (b) corresponds to the deposition of 0.6 Å of Co at 300 °C.
Figure 3. The result of bending of the surface bands after deposition of 0.1 Å Mn adsorbate at room temperature (Dirac point is observed) (a) and the band gap opening (b) in the spectrum of Dirac surface states in the Mn / BiSbTeSe$_2$ system. Figure (b) corresponds to the deposition of 0.7 Å of Mn at 300ºC. (c) - ResPES energy distribution cuts in the vicinity of the topological surface state at the Dirac point in 0.7 Å of Mn / BiSbTeSe$_2$ system measured at photon energies 47, 50 and 52 eV.

Measurements of resonance photoelectron spectroscopy (ResPES, see figure 3(c)) using synchrotron radiation of 47 eV for Mn-BiSbTeSe$_2$ samples (corresponding to the 3p-3d manganese transition) demonstrated the absence of electronic states of manganese in the region of the Dirac point. The revealed spectral features lie above the Dirac point by more than 100 meV. This result confirms the absence of manganese states inside the energy gap, and, as a consequence, the inapplicability of the resonance scattering mechanism [2] in determining the nature of the band gap.

Temperature measurements above 15 K showed the stability of the band gap to an increase in temperature. A mechanism is known for the formation of a gap of a nonmagnetic nature, which can be associated with the hybridization of surface states from two opposite surfaces of a topological insulator arising from the penetration of metal atoms into the van der Waals gaps between the atomic quintiles of topological insulators based on chalcogenides and that destroy the van der Waals bond [3]. However, in our case, this mechanism is not applicable because of the small amount of precipitated substance (less than one monolayer), which is not sufficient for diffusion through at least 4-5 quintuple-layers of the substrate to open a gap of similar width (~ 50 meV in [3]). Thus, we can make an assumption about the magnetic nature of the gap.

4. Conclusions
We have shown the energy gap in the spectrum of surface topological states of the BiSbTeSe$_2$ during the deposition of submonolayer Co and Mn coatings. Managing the opening of an energy gap of a magnetic nature can be considered as a tool for controlling the topological states of a topological insulator. A large number of experimental works are devoted to opening a gap in the spectrum of surface states, for example, [4]. But most of them describe the bulk doping of TIs by magnetic impurity. In contrast, in our work we obtained the gap opening by the TI surface doping after the magnetic metal deposition. The work is a result of the series of experiments on metal deposition on different TIs [5-8]. The further studies of the TI topmost layer are underway.

Acknowledgments
The project was supported by the RFBR grant № 18-29-12094.
References
[1] Qi X-L, Hughes T L and Zhang S-C 2008 Phys. Rev. B 78 195424
[2] Sánchez-Barriga J et al. 2016 Nat. Commun. 7 10559
[3] Zhang Y et al. 2010 Nature Phys. 6 584–588
[4] Rienks E D L et al. 2019 Nature 576 423–428
[5] Kaveev A K, Suturin S M, Sokolov N S, Kokh K A and Tereshchenko O E 2018 Tech. Phys. Lett. 44 3 184–186
[6] Kaveev A K, Sokolov N S, Suturin S M, Zhiltsov N S, Golyashov V A, Kokh K A, Prosvirin I P, Tereshchenko O E and Sawada M 2018 CrystEngComm 20 3419-3427
[7] Kaveev A K, Golyashov V A, Klimov A E, Schwier E F, Suturin S M, Tarasov A S and Tereshchenko O E 2020 Mat. Chem. and Phys. 240 122134
[8] Kaveev A K, Suturin S M, Golyashov V A, Kokh K A and Tereshchenko O E 2019 J. Phys.: Conf. Ser. 1400 055016