Direct observation of magnetization distribution
in a magnetic heterostructure of topological insulator

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## 1. Introduction

A topological insulator is a material processing a conducting surface state while its bulk interior is an insulator [1]. The presence of the surface state is ascribed to the non-trivial topology of the band structure. The dispersion relation of the topological surface state is gapless unless the time reversal symmetry is broken. In other words, the opening of the energy gap on the topological surface states can be controlled by introducing ferromagnetic order. This unique situation leads to a variety of fascinating physical phenomena, such as quantum anomalous Hall effect (QAHE). Chang *et al.* demonstrated the QAHE using Cr-doped topological insulator thin films of $(Bi,Sb)_2Te_3$ (BST). They observed the quantization of Hall resistivity to $h/e^2$ at low temperatures [2], where $h$ and $e$ are the Planck's constant and the charge of an electron, respectively. The square shaped hysteresis loop of $\rho_{yx}$ centered at $H$=0 (Fig. 1) indicates that the magnetic moments of doped Cr ions achieved the long-range ferromagnetic order, and that the quantized Hall resistivity was obtained owing to the spontaneous magnetization at zero magnetic field.

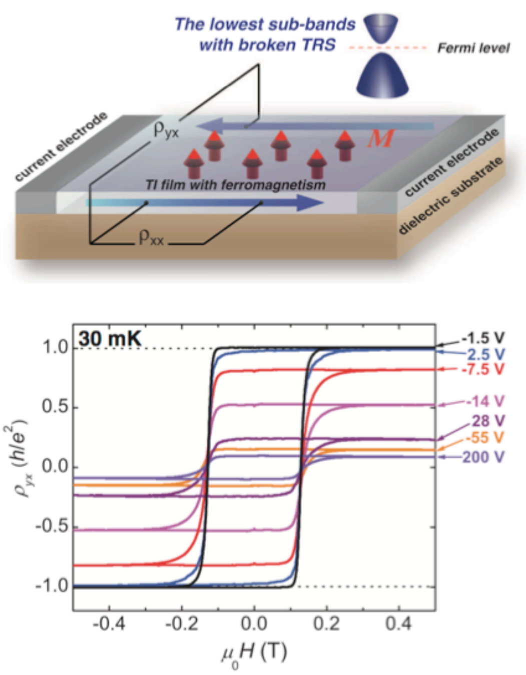


Fig. 1: A schematic of magnetically doped TI film and typical field dependence of Hall resistivity of the film [Cited from Ref. 2]

Another root to introduce the time reversal symmetry breaking is to exploit magnetic proximity effect. By preparing a topological insulator (TI) / magnetic insulator (MI) heterostructure, the surface electrons in TI can be magnetically polarized via magnetic exchange coupling from the MI layer. Quite recently, our collaborators have grown a heterostructure of BST and a ferromagnetic insulator $Cr_2Ge_2Te_6$ (CGT), which has a relatively high ferromagnetic ordering temperature of 61 K. Furthermore, CGT has a layered structure, which has a very flat surface and good structural matching with BST. This is a favorable situation to realize a large proximity effect on the interface with TI. In the present study, we have thus investigated magnetization distribution and possible magnetic proximity effect in a BST/CGT heterostructure by means of polarized neutron reflectivity (PNR) measurements at SHARAKU in MLF of J-PARC.

## 2. Experiment

The thin film sample of CGT/BST heterostructure was grown by molecular beam epitaxy (MBE) on the InP(111) substrate. Nominal thicknesses of each layer are as follows: InP substrate/BST(1 nm)/CGT(13 nm)/BST(9 nm)/CGT(13 nm)/$Al_2O_3$(3 nm). The surface area of the film was 7 x 15 mm$^2$.

In the present PNR measurements, we employed a closed-cycle He refrigerator and an electromagnet. We measured PNR spectra in magnetic field of 1 T without analyzer, at 300 and 3 K. We also performed x-ray reflectivity (XRR) measurement using the identical sample at room temperature. The PNR and XRR spectra are simultaneously analyzed using the GenX software.

**3. Results**

Figures 2(a) and 2(b) show the observed XRR and PNR data. Because the difference in nuclear scattering length density (SLD) between BST and CGT is relatively small, the PNR data at 300 K does not exhibit clear fringe patterns. On the other hand, we observed distinct fringe pattern in the XRR data owing to the difference in charge density between CGT and BST. At 3 K, where the magnetic moments in CGT layers are supposed to achieve long-range ferromagnetic orders, we observed clear splitting between $R+$ and $R-$, which are neutron reflectivity measured when the incident neutrons have up and down spins, respectively. The XRR and PNR data have been analyzed using the GenX software, and we finally found a structural model simultaneously satisfying all the reflectivity data. The nuclear and magnetic SLD profiles are shown in Figs. 2(c) and 2(d). We found that the interfaces between CGT and BST are relatively sharp (roughness is about 1 nm), and that the magnitude of magnetization in the CGT layer is 2.4(3) $\mu_B/Cr^{3+}$.

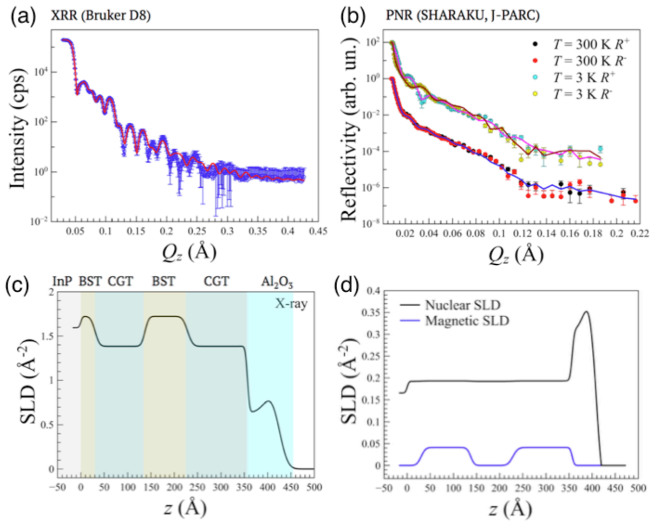


Fig. 2: (a) XRR and (b) PNR data of the CGT/BST heterostructure. SLD profiles obtained from (c) XRR and (d) PNR measurements.

**4. Conclusion**

The present results revealed the long-range ordered ferromagnetism in the CGT layers and presence of the sharp interfaces between CGT and BST layers. We also expected that the proximity effect induced magnetization in the BST layers. However, any additional magnetic SLD in BST layers do not improve the fitting, suggesting that magnetic moments are present only in the CGT layers. This is a sharp contrast to a previous PNR study on a EuS/$Bi_2Se_3$ bilayer [3], in which the proximity-effect induced magnetization was found in the TI ($Bi_2Se_3$) layer. We are still discussing on this issue, and planning further experiments to elucidate the coupling between the surface electrons on the TI layers and the magnetic moments in the MI layer.

References:

[1] M. Z. Hasan and C. L. Kane, Rev. Mod. Phys. **82**, 3045 (2010).

[2] C. Z. Chang *et al.*, Science **340**, 167 (2013).

[3] F. Katmis et al. Nature **533**, 513 (2016).