Electronic supplementary information

Nanoscale mapping of edge-state conductivity and charge-trap activity in topological insulators

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I. Current and noise mapping by a conducting-AFM integrated with scanning noise set-up

For the electrical current and noise measurements, a platinum (Pt) tip (25-Pt300B, Park-Systems) installed on a conducting AFM (XE-70, Park-Systems) made a contact with the surface of the Bi_2Se_3. While the tip was scanning the surface of the Bi_2Se_3 film, a small DC bias (20 mV) was applied between the Au substrate and the grounded Pt tip by a function generator (DS345, Stanford Research Systems). Importantly, the adhesion of the Bi_2Se_3 multilayer film on the Au substrate was strong, allowing us to reliably measure an image in contact mode with a 300 nN contact force. We typically scanned an area of 5×5 μm^2 with a scan speed of 0.2 Hz. The electrical currents through the Pt tip were measured and converted to amplified voltage signals by a low-noise preamplifier (SR570, Stanford Research Systems). The amplified signals were filtered by a band-pass filter (6 dB) of the SR570 preamplifier to obtain the electrical noise signal which was the fluctuating component of the current signals. The root mean square power of the noise signal was obtained by the homemade custom-designed spectrum analyzer and the RMS-to-DC converter based on an AD737 chip. Note that, the RMS power was measured over the entire frequency range of the pass-band of the filter. Hence, we obtained the absolute noise PSD value at the central frequency of the band, by dividing the total RMS power to the bandwidth of the filter. Using this system, we could obtain the maps of the topography, the current and the noise PSD with a specific frequency on the Bi_2Se_3 multilayer film, simultaneously. Finally, the measured maps were analyzed using a vertical transport model to obtain the maps of conductivities and charge-trap densities in the Bi_2Se_3 multilayer film.

II. Preparation of Bi_2Se_3 multilayer sample

Bi_2Se_3 flakes (purity 99.999%) were purchased from Alfa Aesar (Product Id 13126, 1-6 mm in sizes) and preserved inside a vacuum desiccator in the dark condition. First, a Bi_2Se_3 flake was placed on a Cu tape, and a few top layers of the Bi_2Se_3 were cleaved by a scotch tape to get the clean surfaces of Bi_2Se_3 on the Cu tape. This step also made top layers brittle and detached slightly from the bulk piece. Then, the exfoliated Bi_2Se_3 multilayer was transferred on an Au substrate by a dry transfer method with a polydimethylsiloxane (PDMS) stamp, providing a clean surface free from organic impurities.

III. Calculation of conductivity and charge-trap density

Since the conductivity of the Bi_2Se_3 film was rather low, we could assume that charge carriers mainly flowed in a short vertical current path from an underlying Au substrate to a Pt probe through the film layer in a sandwich structure. We also assumed that parasitic currents in a lateral direction inside the layer were limited. Assuming a vertical charge transport, a conductivity σ can be calculated like $\sigma = Id\,(VA)^{-1}$, where *I*, *d*, *V*, and *A* represent a *measured current*, the *thickness of the film*, an *applied voltage*, and the *contact area of a conducting probe*, respectively. In our experiment, the thickness of the film was ~25 nm. The contact area *A* of our conducting probe was estimated as ~2000 nm^2 from the effective contact radius.[1] The measured conductivity values were comparable to the previously-reported values of the conductivity of Bi_2Se_3 film, showing the reliability of our method. Then, the noise PSD values of the mean-square fluctuation in the number of occupied charge-traps in the small segment of the Bi_2Se_3 film within the contact area *A* of the tip can be written as[2,3]

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$$S_{N_{\mathrm{T}}}(f,x,y) = A\cdot\int_{-\infty}^{\infty}\int \frac{4\tau(E,x,y,z)}{1+[2\pi f\cdot\tau(E,x,y,z)]^2}\cdot f_{\mathrm{t}}(1-f_{\mathrm{t}})\cdot N_{\mathrm{T}}(E,x,y,z)\cdot dz\cdot dE \qquad (1)$$

where the N_{T}, τ, and f are the *density of charge-traps over the space and energy*, a *trapping time constant*, and a *frequency*, respectively. The integral over z ranges from 0 to the film thickness *d*. The trap occupancy function can be written as $f_t(E) = [1 + \exp\{(E-E_f)/kT\}]^{-1}$ where E_f is Fermi level. At a rather low temperature condition including a room temperature, $f_t(1-f_t)$ behaves like a delta function around the Fermi level E_f, and the eqn (1) after the integral over *E* can be simplified as[2,3]

$$S_{N_{\mathrm{T}}}(f,x,y) = A\cdot kT\cdot\int \frac{4\tau(E_{\mathrm{f}},x,y,z)}{1+[2\pi f\cdot\tau(E_{\mathrm{f}},x,y,z)]^2}\cdot N_{\mathrm{T}}(E_{\mathrm{f}},x,y,z)\cdot dz \qquad (2)$$

Assuming that charge-traps are distributed uniformly over the *z* direction, the eqn (2) can be approximated as

$$S_{N_{\mathrm{T}}}(f,x,y) = A\cdot d\cdot kT\cdot N_{\mathrm{T}}(x,y)\frac{4\tau(x,y)}{1+[2\pi f\cdot\tau\,(x,y)]^2} \qquad (3)$$

The noise PSD ΔS_{I} can be written as

$$\Delta S_{\mathrm{I}}(f,x,y) = \frac{(I)^2}{(\Delta C)^2}S_{N_{\mathrm{T}}}(f,x,y) \qquad (4)$$

where ΔC is the carrier number in the segment of the Bi_2Se_3 film. Then, the charge-trap density N_{T} can be written like,

$$N_{\mathrm{T}}(x,y) = \Delta S_{\mathrm{I}}(f,x,y)\frac{(\Delta C)^2}{(I)^2}\cdot\frac{1}{A\cdot d\cdot kT}\cdot\frac{1+[2\pi f\cdot\tau(x,y)]^2}{4\tau(x,y)} \qquad (5)$$

The average *trapping time* τ and the *carrier density* in the Bi_2Se_3 were reported as *~10^{-5} seconds* and *~10^{21} cm^{-3}*, respectively.[4]

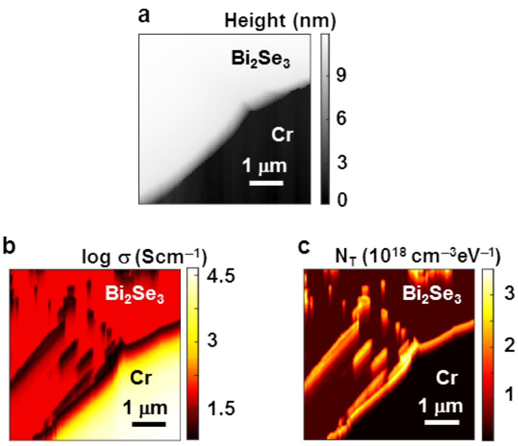

Fig. S1 Scanning noise microscopy mapping of Bi_2Se_3 on magnetic Cr samples. (a) Topography image showing the height of Bi_2Se_3 on Cr substrate. (b) Conductivity map of Bi_2Se_3 on Cr substrate. Edge regions showed lower conductivity than that of surface regions. (c) Charge trap density map of Bi_2Se_3 on Cr substrate. Edge regions showed higher trap density in accordance with non-topological edges.

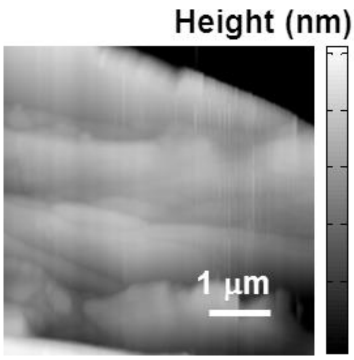

Fig. S2 Topography image of Bi_2Se_3 multilayer film. Contact mode AFM was utilized for imaging. The height of the Bi_2Se_3 film was ~40 nm corresponding to 40 van der Waal planes.

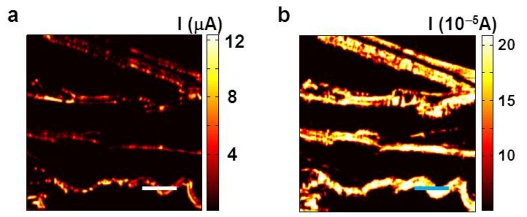

Fig. S3 Current maps of Bi_2Se_3 multilayer film at various bias voltages. (a) Current map of Bi_2Se_3 at the low bias of 0.02 V. (b) Current map of Bi_2Se_3 at the high bias of 0.2 V. At the high bias, edges showed rapid increase in the current. Also, the edge-currents became broader due to stronger spin orbit coupling. Scale bars are 1 μm.

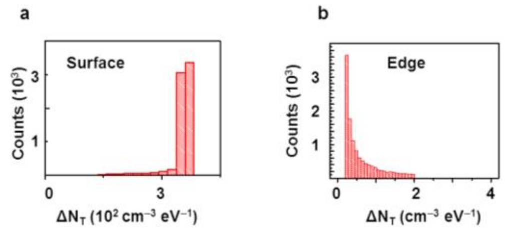

Fig. S4 Change in trap density (ΔN_T) with increasing bias voltage from 0.02 V to 0.2 V. (a) Histogram showing distribution of ΔN_T in flat surface when bias voltage was increased from 0.02 V to 0.2 V. (b) Histogram showing distribution of ΔN_T in edges when bias voltage was increased from 0.02 V to 0.2 V. ΔN_T was nearly homogeneous in surface or edge.

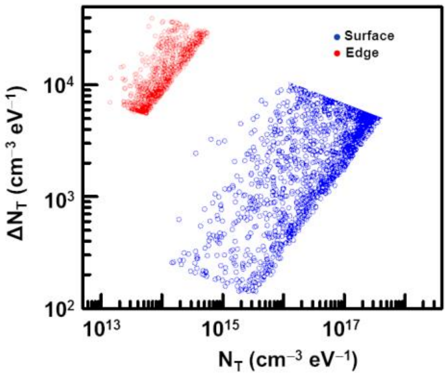

Fig. S5 Effect of white light illumination on the trap density (N_T) of Bi_2Se_3. Scatter plot showing ΔN_T dependence on N_T when the Bi_2Se_3 was illuminated with white light. ΔN_T showed linear dependences on N_T in both edges and the surface.

Notes and references

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