Bulk cyclotron resonance in the topological insulator Bi_2Te_3

Supplemental material

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The film used in the magneto-optical measurements was characterized by a number of experimental probes as described below.

A. Structural and morphological characterization

For X-ray diffraction (XRD) measurements we used a Panalytical MRD Extended diffractometer (PANalytical, Almelo, the Netherlands). In Figure S1, the results of these studies are shown. In panel (a), a series of (*0 0 l*) reflections from the film is seen together with the intensive *(hhh)* peaks from the BaF_2 substrate. Thus, the growth of a highly oriented single-phase layer with the basal plane (0 0 1) parallel to the BaF_2 substrate (1 1 1) cleavage plane is evidenced. The high crystalline quality is supported by the absence of any noticeable broadening when going from the (0 0 3) to the (0 0 36) reflection peaks. As one can see from panel (b), the full width at the half maximum of the (0 0 15) rocking curve is $\Delta\omega$=0.082°. The somewhat asymmetric shape of the curve indicates the presence of the anti-site defects, responsible for impurity scattering.

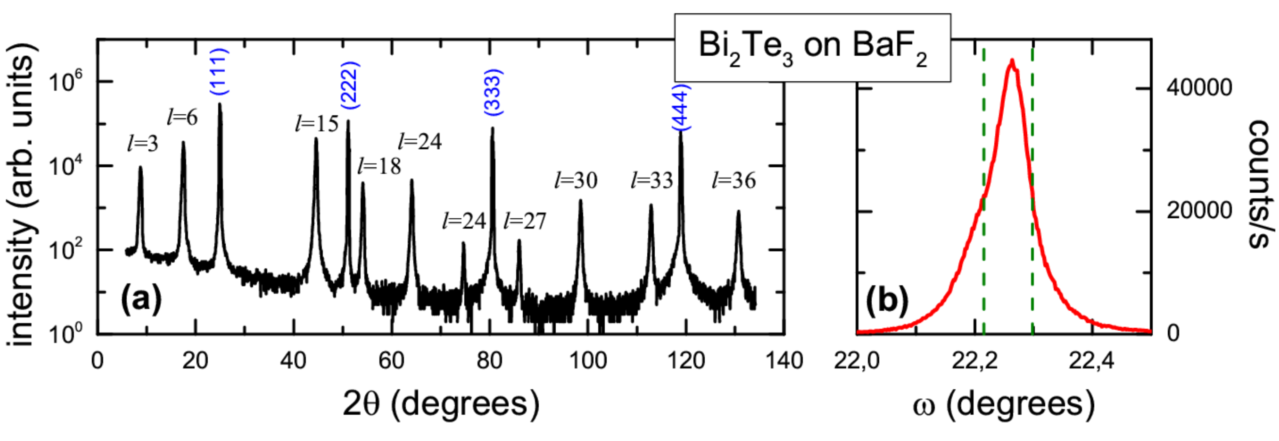

Figure S1. Panel (a): X-ray diffraction scan of the Bi_2Te_3 epitaxial film used in this study. A series of the (*hhh*) peaks belongs to the substrate, while all the (00*l*) reflections are from the Bi_2Te_3 layer. Panel (b): Rocking curve for the (0 0 15) reflection peak.

We used a JSM-7001F (JEOL, Tokyo, Japan) scanning electron microscope (SEM) to obtain the cleaved cross-section images of the film. One of such images is shown in Figure S2 (panel (a)). From this picture, the thicknesses of the Bi_2Te_3 film and of BaF_2 cap layer were evaluated to be 115 and 49 nm, respectively.

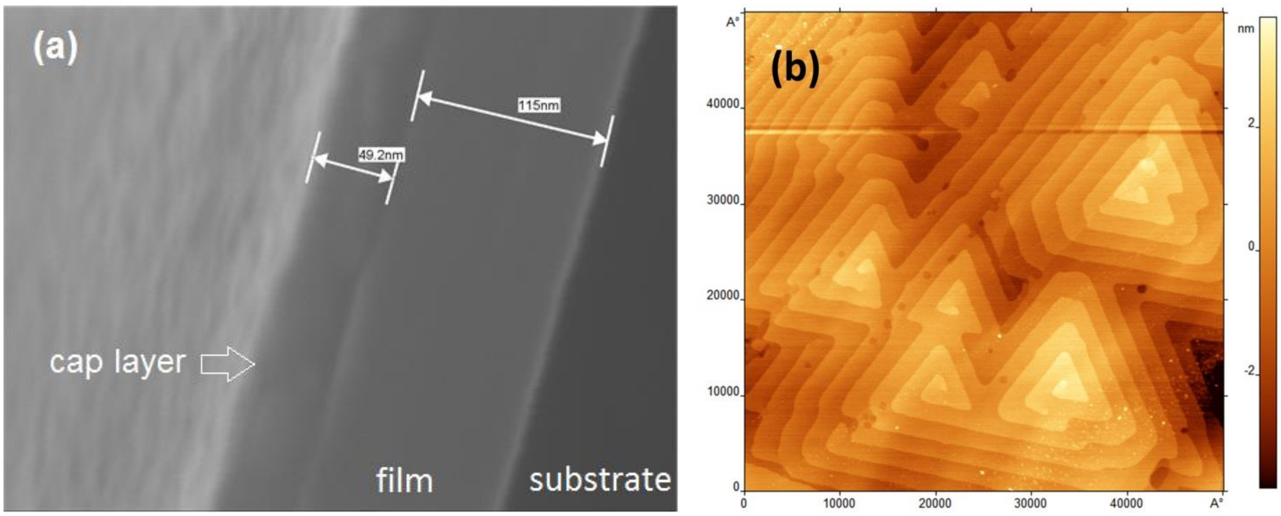

Figure S2. Panel (a): Cross-section SEM image of the Bi_2Te_3 film with a BaF_2 cap layer obtained with the 300000-times magnification. Panel (b): Surface characterization of the Bi_2Te_3 film by AFM. The scanned area is 50 000 Å × 50 000 Å. The vertical scale is color-coded as shown in the bar on the right-hand side.

The morphology of the studied film was explored by means of the atomic force microscopy (AFM) in the tapping mode using the NT-MDT Solver 47 Pro system (NT-MDT, Zelenograd, Moscow, Russia). For these measurements, the barium fluoride capping layer was removed by the procedure described in Ref. [S1]. A representative (5 × 5 μm) AFM scan of the investigated Bi_2Te_3 film is shown in panel (b) of Figure S2. Regular triangular pyramids with large domain terraces and 1 nm high steps indicate high crystal quality. Observed spiral-like growth was reported previously [S2, S3] and is believed to promote formation of twin-free films. All triangular domains are oriented in the same direction evidencing single domain sample with trigonal symmetry.

B. Photoemission characterization

The ARPES measurements were performed with a hemispherical SPECS HSA3500 electron analyzer, characterized by an energy resolution of about 10 meV. Monochromatized He I (21.2 eV) radiation was used as photon source. During the measurements, the sample was cooled with the aid of liquid nitrogen to 100 K. Prior the measurements, the surface of the samples was cleaned by several sputter-anneal cycles (Argon sputtering: 500 eV/30 min; Annealing: 260 ℃/15 min). The results of the measurements are shown in Fig. S3.

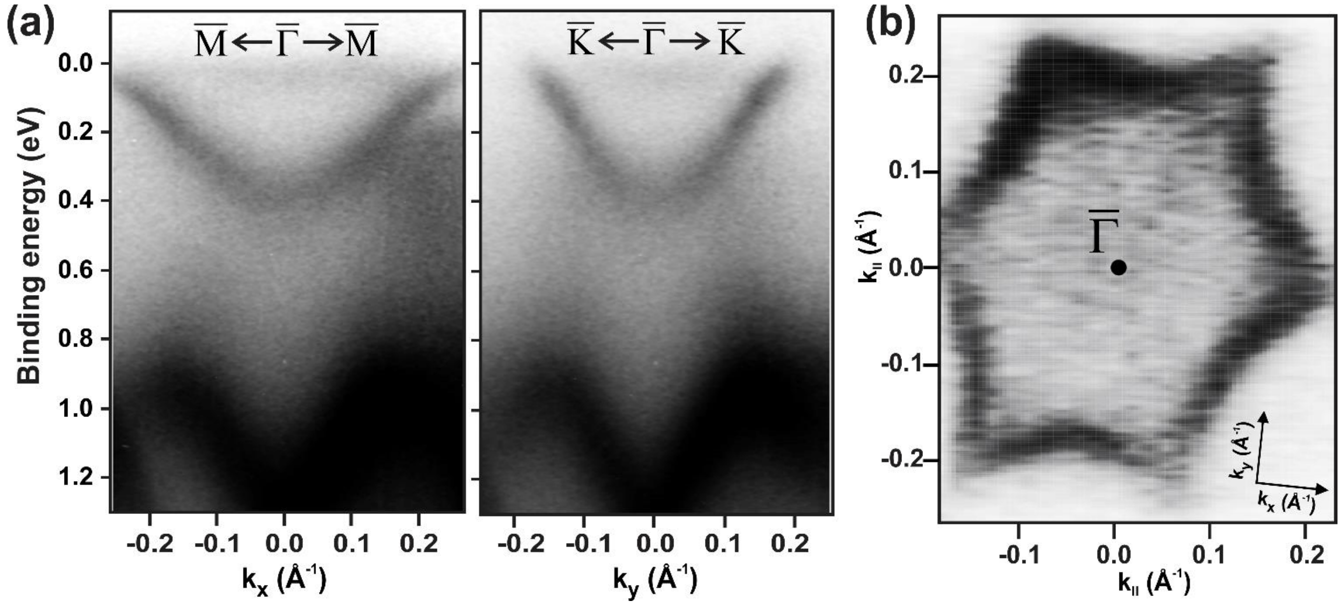

Figure S3. (a) Experimental band structure of Bi_2Te_3 film along $\overline{M}$ - $\overline{\Gamma}$ - $\overline{M}$ and $\overline{K}$ - $\overline{\Gamma}$ - $\overline{K}$ directions of the Brillouin zone, and, (b) the corresponding Fermi surface recorded at 100 K. The surface state cone clearly appears in the measurements. Very near the Γ point, the linearity of the surface bands is not perfect due to an admixture of the bulk states (cf. the ARPES data from Ref. [S4]). Note that the surface states provide a much sharper ARPES images, than the bulk states. The bulk states near the Fermi level around the Γ point could be identified in Ref. [S4], where photon energy of 48 eV was employed. At this high energy, the cross-sections for both, surface and bulk, bands are strong. We believe these very bulk states are responsible for the observed cyclotron resonance.

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[S2] Liu, Y.; Weinert, M.; Li L. Spiral growth without dislocations: Molecular beam epitaxy of the topological insulator Bi_2Se_3 on epitaxial graphene/SiC (0001). *Phys. Rev. Lett.* **2012**, *108*, 115501.

[S3] Bonell, F.; Cuxart, M. G.; Song, K.; Robles, R.; Ordejón, P.; Roche, S.; Mugarza, A.; Valenzuela, S. O. Growth of twin-free and low-doped topological insulators on BaF_2(111). *Cryst. Growth Des.* **2017**, *17*, 4655–4660.

[S4] Chen, Y. L.; Analytis, J. G.; Chu, J.-H.; Liu, Z. K.; Mo, S.-K.; Qi, X. L.; Zhang, H. J.; Lu, D. H.; Dai, X.; Fang, Z.; Zhang, S. C.; Fisher, I. R.; Hussain, Z.; Shen Z.-X. Experimental realization of a three-dimensional topological insulator, Bi_2Te_3. *Science* **2009**, *325*, 178–181.