Supplementary Information

Ordered Growth of Topological Insulator Bi_2Se_3 Thin Films on Dielectric amorphous SiO_2 by MBE

Sahng-Kyoon Jerng, Yong Seung Kim, Kisu Joo, Youngwook Kim, Sang-Moon Yoon, Jae Hong Lee, Miyoung Kim, Jun Sung Kim, Euijoon Yoon, and Seung-Hyun Chun

1. The influence of Se passivation

Fig. S1a and b show AFM images of Bi_2Se_3 films grown on unpassivated SiO_2 surface and Se passivatied SiO_2 surface, respectively. Surface morphology is obtained by commercial AFM (NanoFocus Inc). Both of samples were not annealed after growth of 2 hours. The morphology of as-grown films without passivation is exhibited small grains (Fig. S1a) and RHEED pattern was indicated a formation of other phase as shown in inset of Fig. S1a (marked by white arrow). On the other hand, as-grown films on Se passivated SiO_2 presents forming of large grains (Fig. S1b) and RHEED pattern of well-crystallized Bi_2Se_3 (the inset of Fig. S1b). The surface roughness is 0.54 nm and 0.66 nm for Bi_2Se_3 films grown on the unpassivated surface and the passivated surface, respectively.

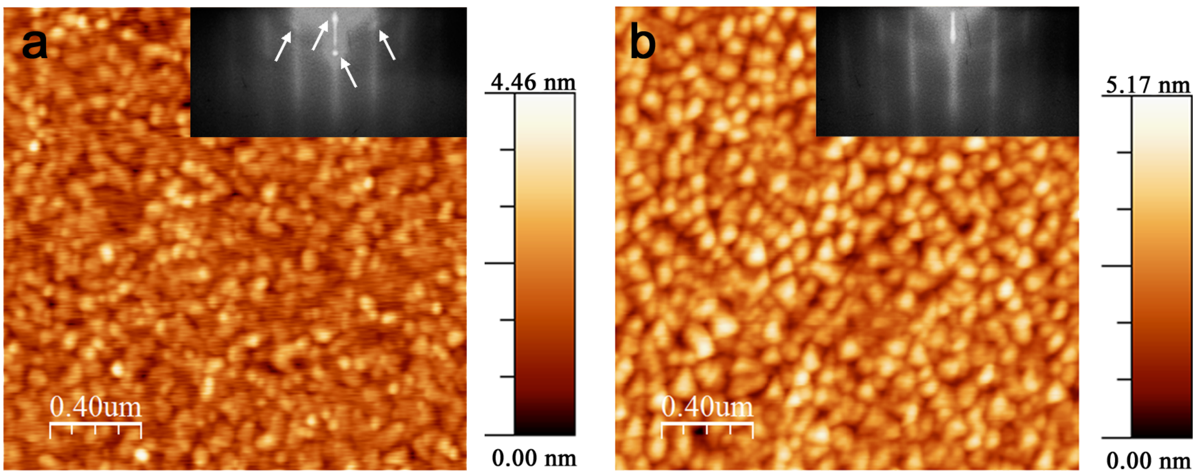

Fig. S1 AFM images of Bi_2Se_3 films for (a) grown on unpassivated SiO_2 surface and (b)

Se passivated SiO_2 surface. The insets are RHEED patterns recorded during the growth.

2. RHEED patterns for Bi_2Se_3 growth procedures

Prior to the growth, samples were heated at 120 °C to remove residual contamination. Fig. S2a shows RHEED pattern of SiO2 substrate at 120 °C, which is typical RHEED pattern for amorphous substrate. After 30 minutes, Se was deposited on SiO_2 surface. RHEED pattern was not changed from that of amorphous (Fig. S2b). Then, temperature increased to 250 °C for growth of Bi_2Se_3 films. During the growth, RHEED pattern is developed to streaky diffraction pattern as shown in Fig. S2c and S2d. After the growth, samples were annealed at 450 °C (Fig. S2e). RHEED patterns are not shown the formation of other phase in the annealing to cool down (Fig. S2f).

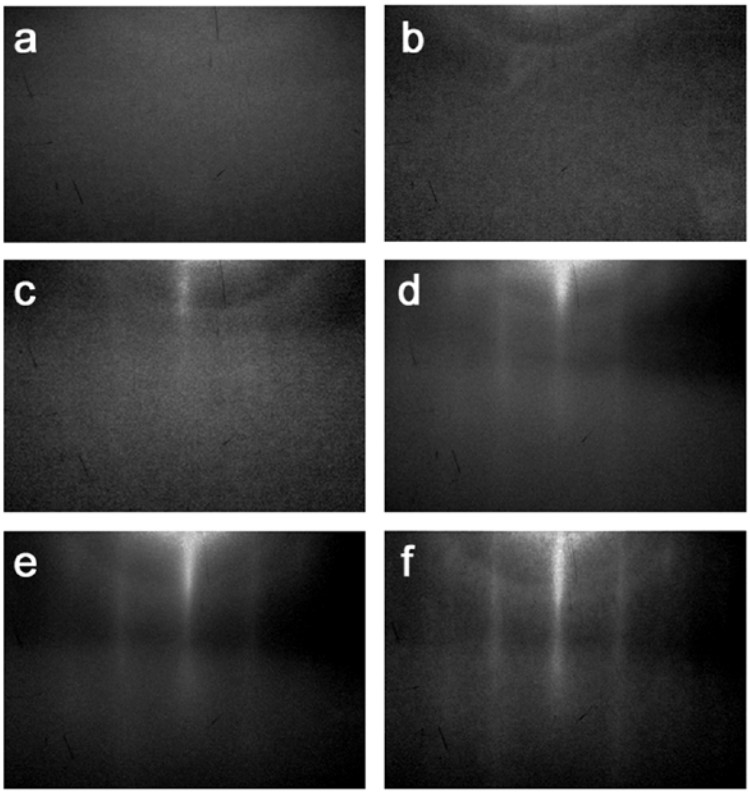

Fig. S2 RHEED patterns for Bi_2Se_3 growth procedures: (a) SiO_2 substrate at 120 °C, (b) Se exposure for passivation, (c)-(d) Bi_2Se_3 growth (RHEED recorded at 30 min and 90 min, respectively), (e) annealing at 450 °C for 30 min, and (f) cool down. The large dark features on the screen are shadows of the substrate holders.

3. RHEED pattern and XRD profile of epitaxially grown Bi_2Se_3 films on $Al_2O_3(0001)$ substrate

Fig. S3 provides RHEED patterns and XRD profile of MBE-grown epitaxial Bi_2Se_3 films on $Al_2O_3(0001)$, known as sapphire, substrate. As shown in Figure S3a, RHEED pattern indicates crystalline sapphire substrate. During the growth of Bi_2Se_3 at 250 °C, RHEED pattern changes to the crystalline Bi_2Se_3. XRD profile, obtained by Shimadzu XRD-6100, reveals the (003) family of diffraction peak of c-axis oriented Bi_2Se_3 films as shown in Fig. S3c.

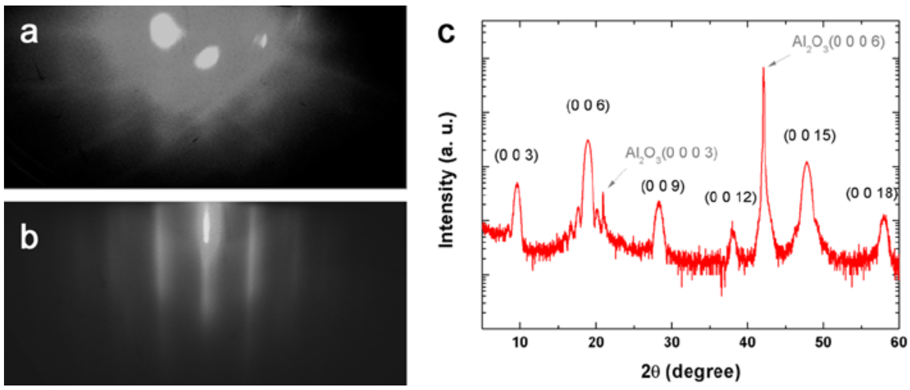

Fig. S3 RHEED pattern of (a) crystalline sapphire substrate and (b) epitaxially grown Bi_2Se_3 films. (c) XRD profile of MBE-grown Bi_2Se_3 films on sapphire substrate.

4. Additional HRTEM images of interface between Bi_2Se_3 films and flat SiO_2

Fig. S4 shows the HRTEM images for different Bi_2Se_3 thin film samples grown on SiO_2. Additional HRTEM measurement was carried out using JEM-2100F instrument operated at

200 kV. Well-stacked Bi_2Se_3 quintuple layers are clearly observed.

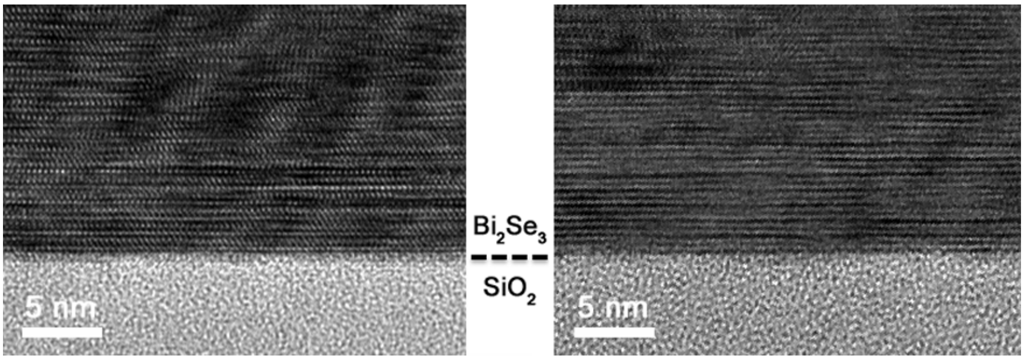

Fig. S4 HRTEM images for Bi_2Se_3 thin films grown on flat SiO_2 surface area.

5. Surface morphology of Bi_2Se_3 films grown on SiO_2

Fig. S5 shows the AFM image of a 20 nm thick Bi_2Se_3 thin film grown on SiO_2. Terraces and/or steps (with triangular and hexagonal shapes) represent the 3-fold symmetry of Bi_2Se_3. The cross-sectional height of triangular feature is ~0.96 nm. The disordered feature of triangular Bi_2Se_3 terraces along the in-plane directions can be attributed to the 300 nm thick amorphous SiO_2 surface which does not provide a lattice constraint for atom stacking during the deposition.

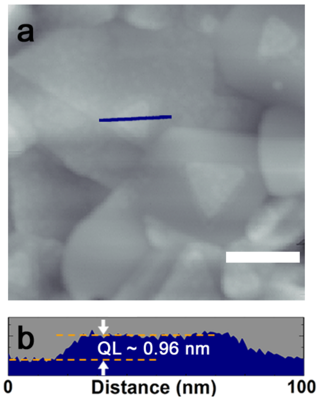

Fig. S5 (a) AFM image of a 20 nm thick film. Scale bar = 100 nm. (b) Cross-sectional profile along the line in (a) showing the QL of Bi_2Se_3.

6. Hall measurement for 20 nm thick films

Fig. S6 shows Hall resistance of 20 nm thick films in the perpendicular magnetic field. The standard six-probe method is used for Hall measurement (I = 100 μA, T = 2 K). Sample is indicated as n-type semiconductor with a carrier concentration of 4.2 x 10^{13} cm^{-2} at V_g = 0 V. The carrier density decreased down to 3.4 x 10^{13} cm^{-2} at V_g = -50 V.

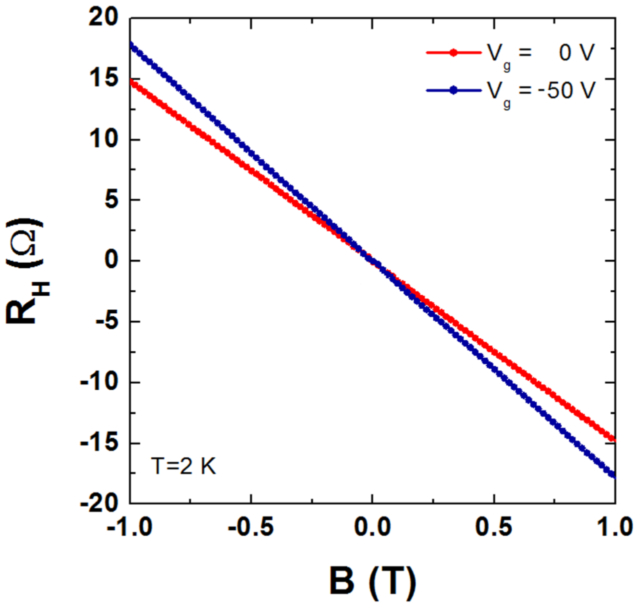

Fig. S6 Hall resistance of 20 nm thick films for applying gate voltage in the magnetic field of ±1 T.