Observation of the Quantum Hall Effect in Interface-Engineered Bi$_2$Se$_3$ Thin Films with Record Low Sheet Carrier Density and High Mobility

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Introduction
Due to significant material defects, binary chalcogenide TIs (Bi$_2$Se$_3$, Sb$_2$Te$_3$ and Bi$_2$Te$_3$) fabricated to date have high carrier density, significant bulk conduction and low mobilities, which obscure the transport properties of topological surface states (TSS). Recently, with the use of interface engineering, we were able to grow Bi$_2$Se$_3$ on atomically engineered insulating (Bi$_{1-x}$In$_x$)$_2$Se$_3$ buffer layer (BIS buffer), with substantially suppressed interfacial and bulk defects and TSS dominated conduction. This new generation of samples with low-carrier-density $n_{\text{sheet}}$ (1 to 3 × 10$^{12}$ cm$^{-2}$) and high-mobility $\mu$ (up to ~16,000 cm$^2$/V.s) provides a promising platform to observe novel physics phenomena, such as surface-originated quantum Hall effect (QHE). We were able to reduce $n_{\text{sheet}}$ even further to nearly half of the uncapped values, while keeping $\mu$ relatively high (~4000 cm$^2$/V.s) with the use of in-situ deposition of electron-depleting MoO$_3$ capping layer. $n_{\text{sheet}}$ as low as 7 × 10$^{11}$/cm$^2$ was obtained for 8 to 10QL (1QL ≈ 1nm) Bi$_2$Se$_3$ grown on buffer layer with MoO$_3$ capping. By maintaining such low carrier density with the proper capping, first-time observation of surface QHE in pure Bi$_2$Se$_3$ thin film was realized in our first visit of NHMFL without external gating.

Experimental
In our first-time visit (June 2015) of 35T resistive magnet (cell 12), we measured the following samples:
- Bi$_2$Se$_3$ grown on insulating (Bi$_{1-x}$In$_x$)$_2$Se$_3$ buffer layer and on sapphire substrate with MoO$_3$ and Se capping (with no gating). Se capping is an additional protection layer. The samples were hand-patterned hall bars.

Results and Discussion
In these samples, we were able to observe the TSS-originated quantum Hall effect (QHE) for the first time in Bi$_2$Se$_3$. Figs.1(a) and 1(b) show Hall and longitudinal resistance as a function of magnetic field at different temperatures for a hand-patterned hall bar of the 8QL Bi$_2$Se$_3$ sample (inset in Fig. 1(a)), respectively. Perfect quantization of Hall resistance at 25812 $\Omega$ ($\pm$1 $\Omega$) $\approx \hbar/e^2$ above 29 T indicates a well-defined surface QHE at 0.3 K. Accordingly, longitudinal resistance vanishes to 0.0 $\Omega$ ($\pm$0.5 $\Omega$) above 30 T indicating dissipation-less transport due to bulk-insulating, low-carrier-density sample. Further, as shown in Fig.1 the signatures of the QHE persists up to 50K. The results from our buffer-based growth of Bi$_2$Se$_3$ along with the QHE results of the non-gated MoO$_3$ capped sample has been published recently.[1]

In conclusion, achieving low-carrier density and high mobility thin films allowed us to successfully observe TSS-originated QHE in Bi$_2$Se$_3$. It is worth stressing that the novelty of this work lies in first, obtaining bulk-insulating, low-carrier-density TI Bi$_2$Se$_3$ thin films with high carrier mobility via interface engineering and second, first-time observation of TSS-originated QHE with zero longitudinal resistance in Bi$_2$Se$_3$ and with no use of gating.

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References