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Gate-Controlled Semimetal-Topological Insulator Transition in an InAs/GaSb Heterostructure

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Abstract

We demonstrate a gate-controlled transition of an originally semimetallic InAs/GaSb heterostructure to a topological insulator. The transition is induced by applying a positive gate voltage on the GaSb side. Non-local resistance measurements using a dual lock-in technique confirm edge channel transport that signifies the formation of a two-dimensional topological insulator.

1. Introduction

Topological insulators (TIs) have attracted strong interest as a new quantum state of matter categorized neither as a metal nor an insulator [1]. Particularly, counterpropagating dissipationless spin transport through the edge channels of two-dimensional (2D) TIs are promising for low power consumption or spintronic devices. Recently, a topological insulating phase has been realized in InAs/GaSb heterostructures sandwiched by AlGaSb barriers, which are composed of conventional III-V semiconductors [2]. This result encourages device application of TIs based on highly developed III-V semiconductor technology.

In InAs/GaSb heterostructures, the InAs conduction band and GaSb valence band overlap in energy [Fig. 1(a)]. Due to the spin-orbit interaction, a gap opens at the crossing points of these bands in the 2D bulk region [Fig. 1(b)].

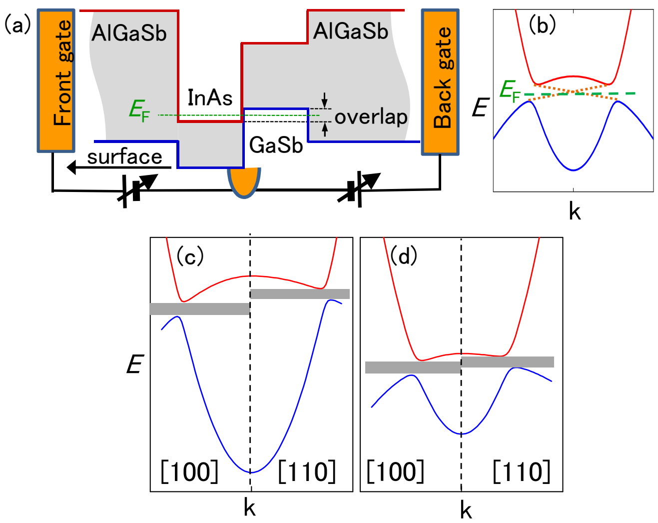

Fig. 1 (a) Energy band profile of the InAs/GaSb heterostructure sandwiched by AlGaSb barriers. (b) Dispersion relation of a typical topological insulator. (c)-(d) Dispersion relations of the InAs/GaSb heterostructure with large band overlap and small band overlap, respectively.

When the Fermi level is in the gap, the system becomes a 2D-TI. Linearly dispersing bands connecting the conduction and valence bands corresponding to the edge channels appear and the conductivity in the bulk region vanishes.

However, in general, the gap opening is very small (~ 4 meV) and the anisotropy of the GaSb valence band is large. As a result, the system tends to be semimetallic [Fig. 1 (c)] [2]. Even when the sample has such a semimetallic band structure, the TI phase is expected to be induced by applying a positive gate voltage on the GaSb side (back gate) [3]. Here, the back gate enhances the confinement in the GaSb layer and reduces the band overlap. As a result, the anisotropy effect is weakened [Fig. 1(d)]. In this presentation, we will present experimental evidence of semimetal-TI transition in an InAs/GaSb heterostructure controlled by a back gate voltage.

2. Experimental Procedures

Sample

The 12-nm InAs (surface side)/10-nm GaSb (substrate side) heterostructure sandwiched by $Al_{0.7}Ga_{0.3}Sb$ barriers is grown by molecular beam epitaxy on an n^+-GaAs substrate which serves as a back gate, following GaAs/AlAs and GaSb/AlSb superlattice gate-insulating buffer layers [Fig. 2(a)]. To bring the Fermi level close to the energy gap region, the upper AlGaSb barrier layer is δ-doped with Be at a setback of 5 nm. A small Hall bar pattern is formed using deep ultraviolet lithography and wet etching [Fig. 2(b)]. Six AuGe Ohmic contacts are evaporated. The distance between the adjacent contacts is 2 µm. A Ti/Au front gate is evaporated on a 20-nm-thick Al_2O_3 gate insulating layer deposited by atomic layer deposition.

Measurement setup

Longitudinal and nonlocal resistances were measured at 0.3 K using a lock-in technique. The suffixes of the re-

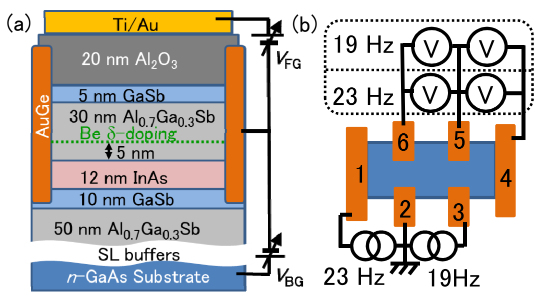

Fig. 2 (a) Schematic sample structure. (b) Hall bar pattern with a dual lock-in nonlocal measurement setup.

sistance $R_{ij,kl}$ (= V_{kl}/I_{ij}) indicate the contacts used for driving the current (i, j) and measuring the resultant voltage (k, l). For nonlocal resistance measurements, currents with different frequencies (19 and 23 Hz) are injected from different contacts [Fig. 2(b)]. This allows us to measure nonlocal resistances for different current injection paths simultaneously.

3. Results and Discussion

Longitudinal resistances

The longitudinal resistances $R_{14,23}$ at different back gate voltages (V_{BG}) are plotted as a function of the front gate voltage (V_{FG}) in Fig. 3(a). On the low V_{FG} side, the Fermi level is in the valence band due to the Be doping. With increasing V_{FG} the Fermi level goes up to the conduction band. When the Fermi level passes through the gap region, the resistance curve shows a peak. At V_{BG} = 0 V, the peak resistance is low (< 1 kΩ), suggesting that this sample has a semimetallic band structure in the unbiased condition. As a positive bias is applied to V_{BG}, the peak resistance increases, indicating that the reduction of the band overlap and the resultant enhancement of the effective gap width. Note that small spike-like features around the peak are reproducible.

The average peak value of $R_{14,23}$ obtained from Gaussian fitting are plotted as a function of V_{BG} in Fig. 3(b). On the high V_{BG} side, the peak value increases, but tends to saturate at a value not far from $h/2e^2$, which is the expected value from the conductance quantization of the edge channels in 2D-TI. This contrasts with the behavior of a system with a semiconductor band structure, for which the resistance increases to ~MΩ [2]. This suggests that the large V_{BG} has turned the system into a TI.

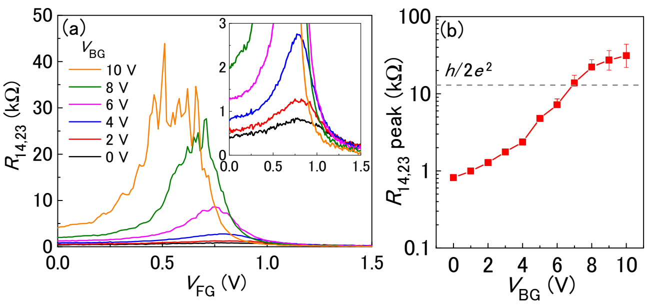

Fig. 3 (a) Longitudinal resistances measured at different V_{BG}. (b) Longitudinal resistance peaks as a function of V_{BG}.

Nonlocal resistances

Typical nonlocal resistances $R_{23,65}$, $R_{12,65}$, $R_{23,54}$ and $R_{12,54}$ at V_{BG} = 0 and 8 V are plotted in Fig. 4(a)-(d), respectively. Similar to the longitudinal resistances, the peak in the nonlocal resistance grows with increasing V_{BG} from 0 to 8 V. Moreover, the peak resistance at V_{BG} = 8V is not far from $h/6e^2$ expected from the conductance quantization.

To confirm the realization of 2D-TI and formation of the edge channels at V_{BG} = 8 V, nonlocal resistances (nonlocal voltages) for different current paths between the adjacent contact pairs are compared in Fig. 4 (e). Around the resistance peak, the ratios between the nonlocal resistances completely agree with each other independent of the cur-

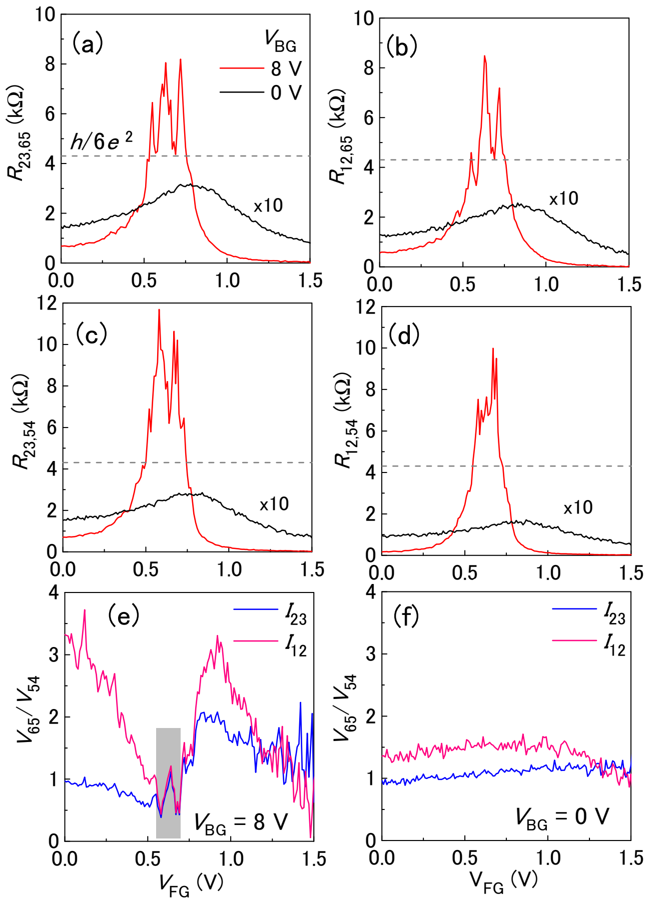

FIg. 4 (a)-(d) Nonlocal resistances measured at V_{BG} = 0 and 8 V. (e)-(f) Nonlocal resistance ratios at V_{BG} = 8 and 0 V.

rent path. Such an agreement has been confirmed for all combinations of the contact geometries. This indicates that the transport is governed by only edge channels and the central bulk region is completely insulating. At V_{BG}= 0 V such an agreement of the nonlocal resistance ratios is not observed [Fig. 4(f)].

4. Conclusions

We induced a topological insulating phase in an originally semimetallic InAs/GaSb heterostructure by applying a back gate voltage. Using a dual lock-in technique, complete agreement of the nonlocal resistance ratios between the adjacent contact pairs has been confirmed.

Acknowledgements

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