Perfect Andreev Reflection of Helical Edge Modes in Inverted InAs/GaSb Quantum Wells

Ivan Knez and Rui-Rui Du
Department of Physics and Astronomy, Rice University, Houston, TX 77251-1892

Gerard Sullivan
Teledyne Scientific and Imaging, Thousand Oaks, CA 91360

Quantum Spin Hall Insulator (QSHI) is a two-dimensional variant of a novel class of materials characterized by topological order, whose unique properties have recently triggered much interest and excitement in the condensed matter community.1–3 Most notably, topological properties of these systems hold great promise in mitigating the difficult problem of decoherence in implementations of quantum computers.4–7 Although QSHI has been theoretically predicted in a few different materials,8–10 so far only the semiconductor systems of HgTe/CdTe and, more recently, inverted InAs/GaSb11–13 have shown direct evidence for the existence of this phase. Ideally insulating in the bulk, QSHI is characterized by one-dimensional channels at the sample perimeter, which have helical property, with carrier spin tied to the carrier direction of motion, and protected from back-scattering by time-reversal symmetry. Here we experimentally show that QSH edge channels in InAs/GaSb exhibit perfect Andreev reflection (AR), validating their helical property and topological protection from back-scattering.

Much of the transport phenomenology of QSHI has been established in a set of remarkable experiments in HgTe material system,8–10 including the quantized conductance and the non-local character of the QSH edge modes. Combining QSHI with superconductors is the next experimental challenge, posing fundamental questions regarding the nature of topological superconductors and the possible realizations of Majorana fermion excitations.11–13 Recently it has been theoretically suggested that Andreev reflection can be used as a powerful method to probe helical edge modes.14 InAs/GaSb material system is well suited for the task, due to its low Schottky barrier and good interface to superconductors.15–17

In this Letter, we study inverted InAs/GaSb quantum wells (QWs) contacted by superconducting electrodes. We observe strong zero-bias dips in the differential resistance as the Fermi level is tuned across the hybridization gap via a front gate. Analysis of the relative size of the dips and corresponding gap excess current is in agreement with expectations of perfect Andreev reflection of the helical edge modes. The perfect AR occurs in spite of a finite barrier at the interface, with the interface transmissivity estimated to be 0.7. Excess current and differential resistance dips show only a weak temperature dependence for temperatures lower than the critical temperature of the superconducting electrodes. On the other hand, weak magnetic fields of less than 50 mT are sufficient to completely suppress excess current in the hybridization gap, indicating strong sensitivity to time-reversal breaking.

InAs/GaSb QWs contain both electron and hole two-dimensional states situated in InAs and GaSb layers respectively, and enclosed with AlSb barriers. Sample structure is shown in Fig. 1 inset a. In the inverted regime, the electron subband is lower than the hole subband leading to band anti-crossing and miniband gap opening.18–20 Energy spectrum with the resulting hybridization gap is shown in Fig. 1 inset b. Due to the band inversion, helical edge modes appear in the mini gap.21 In order to probe the helical character of the edge modes, superconducting niobium electrodes with critical temperature of $T_c = 8.27$ K (BCS gap of $\Delta_S = 1.24$ meV) are deposited directly on the InAs layers, while the electrostatic front gate is used to tune the Fermi energy $E_F$ into the hybridization regime.

Andreev reflection is a process unique to the superconductor-normal metal (S-N) interface, where impinging normal quasiparticle retroreflects, having thus not only opposite velocity but also opposite charge, and resulting in the enhancement of the total current across the interface. The electrical current through a single S-N interface can be calculated using the Blonder-Tinkham-Klapwijk (BTK) model:

$$I = \frac{N \cdot e}{h} \int \left[ f(E + eV) - f(E) \right] \left[ 1 + A(E) - B(E) \right] dE$$

(1)

where $N$ is the number of modes in the normal conductor, $f(E)$ is the equilibrium Fermi distribution function, $V$ is the voltage drop at the interface, and $A(E)$ and $B(E)$ are probabilities for Andreev and normal reflection (NR) of the electron at the interface. In the case of ideal interface, and for biases within the superconducting gap ($V < \Delta_S$), quasi-particles are only Andreev reflected. This is because within the superconducting gap transmission is prohibited, and there is no potential barrier which would absorb the momentum difference necessary for normal reflection. In practice, due to native oxides or Schottky barriers, a potential step always exists at the S-N interface, allowing for normal reflection and hence reducing the probability for Andreev reflection. The interface barrier is characterized by the scat-
by Andreev reflection processes. Inset c exhibits strong dips, suggesting transport dominated $dV/dI$ helical edge modes in the mini-gap. As the Fermi level $E_F$ is tuned across the mini-gap via $V_{front}$, $dV/dI$ exhibits strong peak at larger $V$. On the other hand, for $V$ close to zero, $dV/dI$ exhibits strong dips, suggesting transport dominated by Andreev reflection processes. Inset c shows two-terminal structure with superconducting and normal leads. Due to the perfect Andreev reflection at S-QSH interfaces, voltage drop at each contact is halved, leading to doubling of differential conductance compared to N-QSH case.

Fig. 1 shows $dV/dI$ vs bias voltage $V$ across the S-InAs/GaSb-S junction and front gate bias $V_{front}$. As $E_F$ is tuned into the mini-gap via $V_{front}$, $dV/dI$ exhibits strong peak at larger biases ($V \approx \frac{\Delta_s}{e}$). On the other hand, for $V < \frac{\Delta_s}{e}$, $dV/dI$ exhibits strong dips, i.e. enhanced conductance due to AR. This transmissivity $T = \frac{1}{1 + Z^2}$. For $Z < 1$, AR dominates over NR resulting in zero bias dips in differential resistance $dV/dI$. In this case, current enhancement due to AR also manifests itself as an excess current $I_{excess}$, which is obtained by extrapolating linear $I-V$ curve at high biases, i.e. for $V \gg \frac{\Delta_s}{e}$, to zero bias.

Fig. 2a shows normal resistance $R_N$ vs $V$ for $V \gg \frac{\Delta_s}{e}$, vs $V_{front}$ (in blue) and $I_{excess}$ vs $V_{front}$ (in red). As $E_F$ is tuned towards the mini-gap, $R_N$ increases towards the peak value of $\sim 2k\Omega$ signaling mini-gap entry, while concurrently $I_{excess}$ decreases from the maximal value of $\sim 2.6\mu A$ ($V_{front} = 5$ V) to mini-gap value $I_{excess} \sim 150\, nA$ ($V_{front} = -2.1$ V). Panel b and c show $dV/dI$ and $I$ vs $V$ for $V_{front} = 5$ V and $V_{front} = -2.1$ V respectively. Excess current is determined as an intercept of the linear fit to the $I-V$ curve for large $V$. Panel d shows conductance difference $\Delta G \equiv G(V=0) - G(V \gg \Delta S/e)$ vs $V_{front}$ on a log scale. For $E_F$ in the mini-gap $\Delta G$ plateaus at $2e^2/h$, indicating perfect AR of helical edge channels.
into the superconducting lead becomes possible and AR probability scales to zero as $A(E) \sim \frac{(\Delta_S/e)^2}{\Delta} \rightarrow 0$ reducing equation (1) to the familiar case of N-QSH interface with a contact resistance of $\frac{\hbar}{4e^2}$. Simple resistance combination now gives a total-two-terminal resistance of $h/4e^2$.

In InAs/GaSb QWs this analysis may be further complicated by the presence of low mobility mini-gap bulk carriers. However, we note here that scattered states, which lead to residual bulk conductivity due to their loss of quantum properties and inability to tunnel, are not expected to participate in AR which is a quantum process. As a result, difference between two-terminal conductances at zero and high bias will be: $\Delta G \equiv G(V = 0) - G(V \gg \Delta_S/e) = \frac{2e^2}{\hbar}$ (Fig. 1 inset c). Note that in Fig. 2c, where $E_F$ is in the hybridization gap, $\frac{dI}{dV}(V = 0) \sim 1.7 \text{k}\Omega$, while $\frac{dI}{dV}(V \gg \Delta_S/e) \sim 2 \Omega$. Inverting these two values gives $\Delta G \sim 2.2 \frac{e^2}{h}$, which is surprisingly close to the expected value of $\frac{2e^2}{h}$. This is better illustrated in Fig. 2d, which shows plateauing of $\Delta G$ to a conductance value of $\frac{2e^2}{h}$, as $E_F$ is pushed into the hybridization gap, validating the picture of perfect AR of helical edge channels.

Furthermore, dissimilar conductance values within and outside of the superconducting gap translate into non-linear $I - V$ curve which can be approximated by $I = \left(\frac{2e^2}{h} + G_{\text{bulk}}\right) V$ for $V < \frac{\Delta_S}{e}$ and $I = \left(\frac{2e^2}{h} + G_{\text{bulk}}\right) V + \frac{2e\Delta_S}{h}$ for $V > \frac{\Delta_S}{e}$. The intercept of the latter equation gives an estimate of the excess current as $I_{\text{excess}} \sim \frac{2e\Delta_S}{h} \sim 100 \text{nA}$. Considering the approximative character of the given analysis, the latter value is in reasonable agreement with the measured value of 150 nA in Fig. 2a and 2c.

The temperature dependence of $I_{\text{excess}}$ in Fig. 3a shows only a weak dependence for temperatures up to 6.5 K and it is quickly suppressed as the temperature is further increased towards the critical temperature of niobium leads. Furthermore, a color map of temperature evolution of $dV/dI$ is shown in Fig. 3b, with dips in $dV/dI$ closely following the BCS temperature dependence of superconducting gap $\Delta_S$. We note here that $I_{\text{excess}}$ for $E_F$, both inside and outside of the mini-gap, show comparative suppression when $\Delta_S$ is reduced with increased temperature. This is most easily seen when $I_{\text{excess}}$ is normalized by the corresponding low temperature values, i.e. $I_{\text{excess}}(T) / I_{\text{excess}}(300 \text{ mK})$ and plotted in Fig. 3c for these two cases.

This is in sharp contrast to the magnetic field dependence of $I_{\text{excess}}$ shown in Fig. 4, where $I_{\text{excess}}$ for $E_F$ in the mini-gap is suppressed much faster than in the case when $E_F$ is outside of the mini-gap. In fact, perpendicular magnetic fields of less than 50 mT are sufficient to fully suppress AR processes in the mini-gap, while above the mini-gap AR processes survive in fields up to at least 500 mT. Similar disproportionality is also observed for the in-plane magnetic fields, albeit in this case mini-gap $I_{\text{excess}}$ survives for fields up to 100 mT while above the mini-gap, AR processes are still observable at 500 mT.

Figure 3: Temperature dependence. Panel a shows $R_N$ and $I_{\text{excess}}$ vs $V_{\text{front}}$ for temperature $T = 0.5 \text{K}$, and $T$ from 5 K to 8 K varied in 0.5 K increments. Dependence is exceptionally weak except when $T$ approaches $T_c = 8.27 \text{K}$. Panel b shows color map of $dV/dI$ vs $V$ and $T$ ($V_{\text{front}} = 0 \text{V}$). Full and dashed lines show BCS dependence of the superconducting gap $\Delta_S/e$ and $2\Delta_S/e$ respectively. Dips in $dV/dI$ follow closely the BCS gap $\Delta_S$. Panel c shows normalized $I_{\text{excess}}$, i.e. $I_{\text{excess}}(T) / I_{\text{excess}}(300 \text{ mK})$, vs $\Delta_S(T)$ for $E_F$ above the mini-gap (in red) and $E_F$ in the mini-gap (in blue). In both cases, normalized $I_{\text{excess}}$ shows equal decrease as the $\Delta_S$ is reduced with $T$.

Figure 4: Magnetic field dependence. Panels show $R_N$ and $I_{\text{excess}}$ vs $V_{\text{front}}$ for perpendicular magnetic fields of $B_\perp = 0 \text{T}$, 0.05 T, 0.1 T, 0.2 T, and 0.5 T in a and in b for in-plane magnetic fields $B_\parallel$ with the same increments. Although for $E_F$ above the hybridization gap, $I_{\text{excess}}$ survives up to 0.5 T, for $E_F$ in the mini-gap $I_{\text{excess}}$ is completely suppressed with $B_\perp = 0.05 \text{T}$ and $B_\parallel = 0.1 \text{T}$. This is in contrast to the equal suppression of $I_{\text{excess}}$ in temperature dependence (Fig. 3c), suggesting different nature of excess current in and outside of the hybridization gap.
Such sensitivity to time-reversal breaking indeed suggests that the observed mini-gap $I_{\text{excess}}$ is due to the perfect AR of helical edge modes. Applying small magnetic fields destroys the perfect destructive interference of back-scattering paths$\textsuperscript{2}$, opening the back-scattering channels in our structures. In this case, the probability of AR decreases, and $I_{\text{excess}}$ vanishes.

In conclusion, we probe the recently discovered helical edge modes in InAs/GaSb QWs via Andreev reflection. Strong zero-bias dips in the differential resistance mark the presence of perfect Andreev reflection of the helical edge modes, necessitated by the absence of back-scattering channels. The perfect AR occurs in spite of a finite barrier at the interface and shows strong sensitivity to time-reversal breaking. Such sensitivity to time-reversal breaking indeed suggests that the observed mini-gap $I_{\text{excess}}$ is due to the perfect AR of helical edge modes.

In conclusion, we probe the recently discovered helical edge modes in InAs/GaSb QWs via Andreev reflection. Strong zero-bias dips in the differential resistance mark the presence of perfect Andreev reflection of the helical edge modes, necessitated by the absence of back-scattering channels. The perfect AR occurs in spite of a finite barrier at the interface and shows strong sensitivity to time-reversal breaking. Such sensitivity to time-reversal breaking indeed suggests that the observed mini-gap $I_{\text{excess}}$ is due to the perfect AR of helical edge modes.

In conclusion, we probe the recently discovered helical edge modes in InAs/GaSb QWs via Andreev reflection. Strong zero-bias dips in the differential resistance mark the presence of perfect Andreev reflection of the helical edge modes, necessitated by the absence of back-scattering channels. The perfect AR occurs in spite of a finite barrier at the interface and shows strong sensitivity to time-reversal breaking. Such sensitivity to time-reversal breaking indeed suggests that the observed mini-gap $I_{\text{excess}}$ is due to the perfect AR of helical edge modes.

In conclusion, we probe the recently discovered helical edge modes in InAs/GaSb QWs via Andreev reflection. Strong zero-bias dips in the differential resistance mark the presence of perfect Andreev reflection of the helical edge modes, necessitated by the absence of back-scattering channels. The perfect AR occurs in spite of a finite barrier at the interface and shows strong sensitivity to time-reversal breaking. Such sensitivity to time-reversal breaking indeed suggests that the observed mini-gap $I_{\text{excess}}$ is due to the perfect AR of helical edge modes.

The perfect AR occurs in spite of a finite barrier at the interface and shows strong sensitivity to time-reversal breaking - hallmarks of helical nature of the QSH edges. Although sufficient coherence is not achieved in the junction, the authors declare no competing financial interests.

### Author contributions
I.K. fabricated the devices, performed the measurements, and analysed the data. G. S. prepared the sample wafer. R.R.D. supervised and provided continuous guidance for the experiments and analysis. Manuscript was prepared by I. K. and R. R. D.

The authors declare no competing financial interests.

---

1. Hasan, M.Z. & Kane, C.L. Topological insulators. Rev. Mod. Phys. 82, 3045 (2010).
2. Qi, X.-L. & Zhang, S.C. Topological insulators and superconductors. arXiv:1008.2026 (2010).
3. Fu, L., & Kane, C. L. Superconducting Proximity Effect and Majorana Fermions at the Surface of a Topological Insulator. Phys. Rev. Lett. 100, 096407 (2008).
4. Knez, I., Du, R.R., & Sullivan, G. Evidence for Helical Edge Modes in Inverted InAs/GaSb Quantum Wells. Science 314, 1757-1761 (2006).
5. Liu, C., Hughes, T.L., Qi, X.-L., Wang, K., & Zhang, S.-C. Quantum Spin Hall Effect in Inverted Type-II Semiconductors. Phys. Rev. Lett. 100, 236601 (2008).
6. Konig, M. et al. Quantum Spin Hall Insulator State in HgTe Quantum Wells. Science 318, 766-770 (2007).
7. Knez, I., Fu, L., & Kane, C. L. Josephson current and noise at a superconductor/quantum-spin-Hall insulator/superconductor junction. Phys. Rev. B 79, 161408 (2009).
8. Benjamin, C. & Pachos, J.K. Detecting Majorana bound states. Phys. Rev. B 81, 085101 (2010).
9. Adrogue, P. et al. Probing the helical edge states of a topological insulator by Cooper-pair injection. Phys. Rev. B 82, 081303(R) (2010).
10. Nguyen, C., Werking, J., Kroemer, H., & Hu, E.L. InAs-AlSb quantum well as superconducting weak link with high critical current density. Appl. Phys. Lett. 57, 87 (1990).
11. Heida, J. P., van Wees, B. J., Klapwijk, T. M. & Borghs, G. Critical currents in ballistic two-dimensional InAs-based superconducting weak links. Phys. Rev. B 60, 13135 (1999).
12. Giazotto, F. et al. Josephson Current in Nb/InAs/Nb Highly Transmissive Ballistic Junctions. J. Sup. 17, 317 (2004).
13. Naveh, Y. & Laikhtman, B. Band-structure tailoring by electric field in a weakly coupled electron-hole system. Appl. Phys. Lett. 66, 1980 (1995).
14. Yang, M. J., Yang, C. H., Bennett, B. R. & Shanabrook, B. V. Evidence of a Hybridization Gap in ”Semimetallic” InAs/GaSb Systems. Phys. Rev. Lett. 78, 4613 (1997).
15. Knez, I., Du, R.R. & Sullivan, G. Finite conductivity in mesoscopic Hall bars of inverted InAs/GaSb quantum wells. Phys. Rev. B 81, 201301(R) (2010).
16. Andreev, A. F. Thermal conductivity of the intermediate state of superconductors. Soviet. Phys. JETP 19, 1228–1231 (1964).
Blonder, G. E., Tinkham, M. & Klapwijk, T. M. Transition from metallic to tunneling regimes in superconducting microconstrictions: Excess current, charge imbalance, and supercurrent conversion. Phys. Rev. B 25, 4515 (1982).

Octavio, M., Tinkham, M., Blonder, G. E. & Klapwijk, T. M. Subharmonic energy-gap structure in superconducting constrictions. Phys. Rev. B 27, 6739 (1983).

Flansberg, K., Bindslev Hansen, J. & Octavio, M. Subharmonic energy-gap structure in superconducting weak links. Phys. Rev. B 38, 8707 (1988).

Naveh, Y. & Laikhtman, B. Magnetotransport of coupled electron-holes. Euro. Phys. Lett. 55, 545 (2001).

Caldeira, A. & Legett, A. J. Influence of Dissipation on Quantum Tunneling in Macroscopic Systems. Phys. Rev. Lett 46, 211 (1981).

Recent experiments show that low bulk conduction has little effect on edge conduction, presumably due to the large disparity in Fermi wave-vectors between bulk and edge states, allowing for simple addition of edge and bulk contributions.