Andreev Reflection of Helical Edge Modes in InAs/GaSb Quantum Spin Hall Insulator

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We present an experimental study of $S$-$N$-$S$ junctions, with $N$ being a quantum spin Hall insulator made of InAs/GaSb. A front gate is used to vary the Fermi level into the minigap, where helical edge modes exist [Phys. Rev. Lett. 107, 136603 (2011)]. In this regime we observe a $\sim 2e^2/h$ Andreev conductance peak, consistent with a perfect Andreev reflection on the helical edge modes predicted by theories. The peak diminishes under a small applied magnetic field due to the breaking of time-reversal symmetry. This work thus demonstrates the helical property of the edge modes in a quantum spin Hall insulator.

A quantum spin Hall insulator (QSHI) is a two-dimensional version 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 [1,2]. Most notably, topological properties of these systems hold great promise in mitigating the difficult problem of decoherence in implementations of quantum computers [3]. Although QSHI has been theoretically predicted in a few different materials [4–7], thus far only the semiconductor systems of HgTe/CdTe [8] and, more recently, inverted InAs/GaSb [9] have shown experimental evidence for the existence of this phase. While 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 are protected from backscattering by time-reversal symmetry. Much of the transport phenomenology of QSHI has been established in a set of remarkable experiments in the 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 bound states [3,11–14]. Recently it has been theoretically suggested that Andreev reflection (AR) can be used as a powerful method to probe helical edge modes, where a perfect Andreev reflection should be observed even in the presence of a finite potential barrier resulting hybridization gap, indicating a strong sensitivity to time-reversal symmetry breaking.

The experiments were performed on high quality 12.5 nm InAs/5 nm GaSb QWs, patterned in a superconductor-normal metal-superconductor ($S$-$N$-$S$) junction geometry. A sample structure is shown in Fig. 1, inset (a). Electron and hole two-dimensional gases are situated in InAs and GaSb layers, respectively, and are confined by AlSb barriers. In the inverted regime, the electron subband is lower than the hole subband leading to band anticrossing and minigap opening [20–22]. Energy spectrum with the resulting hybridization gap is shown in Fig. 1, inset (b). Because of the band inversion, helical edge modes appear in the minigap [7]. In order to probe the helical character of the edge modes, superconducting niobium electrodes with a critical temperature of $T_c = 8.27$ K (BCS gap of $\Delta_c = 1.24$ meV) are deposited directly on InAs layers via magnetron sputtering. The top layers of the contact region are selectively removed by etching, and plasma cleaning in an argon atmosphere is used in situ prior to niobium deposition [17–19]. The width and length of the junctions are $W \sim 1$ $\mu$m and $L \sim 0.5$ $\mu$m. The front gate is fabricated by depositing Si$_3$N$_4$ using a plasma enhanced chemical vapor deposition system, followed by evaporating Ti/Au metal gate. Additional sample and processing...
because of the perfect Andreev reflection at $S$-N interface, allowing for normal reflection and hence reducing the probability for Andreev reflection. The interface barrier is characterized by the scattering parameter $Z$, which is related to the normal transmission of the barrier as $T = \frac{1}{1+Z^2}$. For $Z < 1$, Andreev reflection dominates over normal reflection resulting in zero-bias peaks in differential conductance $dI/dV$. In this case, current enhancement due to Andreev reflection manifests as an excess current $I_{\text{excess}}$, which is obtained by extrapolating a linear $I-V$ curve at high biases, i.e., for $V \gg \Delta_S/e$, to zero bias [25].

Figure 1 shows $dV/dI$ versus bias voltage $V$ across the S-InAs/GaSb-S junction, at different front gate bias $V_{\text{front}}$. The regime of interest to the current work, i.e., the center of the minigap, is reached at $V_{\text{front}} = -2.1$ V. At a positive gate potential (e.g., $V_{\text{front}} = 5$ V), the Fermi level $E_F$ of InAs/GaSb is on the electron side. As the $E_F$ is tuned into the minigap, $dV/dI$ exhibits strong peaks 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. Because of the perfect Andreev reflection at S-QSH interfaces, voltage drop at each contact is halved, leading to a doubling of differential conductance compared to N-QSH case.

Details are given elsewhere [9,22]. Unless specified, data were taken at temperature $T = 300$ mK.

Andreev reflection [23] is a process unique to the 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 [24]:

$$I = \frac{N e}{\hbar} \int [f(E+eV) - f(E)] [1 + A(E) - B(E)] dE,$$

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 ($V < \Delta_S/e$), quasiparticles are only Andreev reflected. This is because transmission is prohibited within the superconducting gap, and there is no potential barrier which would absorb momentum difference necessary for NR. 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.

**Figure 1.** (color). Differential resistance $dV/dI$ versus bias voltage $V$ across the S-InAs/GaSb-S junction as a function of gate bias $V_{\text{front}}$. Inset (a) shows device cross section with Ti/Au front gate on top while inset (b) shows energy spectrum of inverted InAs/GaSb QWs with linearly dispersing helical edge modes in the minigap. As the Fermi level $E_F$ is tuned into the minigap via $V_{\text{front}}$, $dV/dI$ exhibits strong peaks 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. Because of the perfect Andreev reflection at S-QSH interfaces, voltage drop at each contact is halved, leading to a doubling of differential conductance compared to N-QSH case.

**Figure 2.** (color). (a) Normal resistance $R_N$ (blue curve) and excess current due to Andreev reflection $I_{\text{excess}}$ (red curve) versus $V_{\text{front}}$. As $V_{\text{front}}$ is decreased, $E_F$ is tuned towards the minigap and $R_N$ increases towards the peak value of $\sim 2 \text{ k}\Omega$ while concurrently $I_{\text{excess}}$ decreases from the maximal value of $\sim 2.6 \mu\text{A}$ ($V_{\text{front}} = 5$ V) to minigap value $I_{\text{excess}} \sim 150$ nA ($V_{\text{front}} = -2.1$ V). (b) Conductance difference $\Delta G = G(V = 0) - G(V \gg \Delta_S/e)$ versus $V_{\text{front}}$ on a log scale. For $E_F$ in the minigap $\Delta G$ fluctuates around $-2.2 e^2/h$. (c),(d) Zero-bias conductance peak (ZBCP) and $I$ versus $V$ for $V_{\text{front}} = 5$ V and $V_{\text{front}} = -2.1$ V, respectively. The $\Delta V$ marks FWHM of the respective ZBCP. (e) ZBCP is shown on the background of differential conductance in expanded bias range.
$\Delta_s/e$) and plot $\Delta G$ versus $V_{\text{front}}$ on a log scale, in Fig. 2(b). We note that such a subtraction procedure entails an error estimated to be $\pm 20\%$. For $E_F$ in the minigap, $\Delta G$ fluctuates around $-2e^2/h$, a value that is close to $2e^2/h$ predicted for helical edge channels.

We now analyze the nonlinear conductance observed in the usual metallic and the QSH regime, respectively. In Fig. 2(c) we plot $I$-V and $dI/dV$-$V$ curves for $V_{\text{front}} = 5$ V. In this case $E_F$ is high above the hybridization gap, and a ZBCP is observed indicating strong AR. Extrapolating current from high biases gives $I_{\text{excess}} = 10\%$.

In spite of a high transmissivity, the absence of supercurrent suppression at zero bias. Because we actually see conductance enhancement, this must be due to edge states and their topological protection. Also, note that the ZBCP is in fact broadened [see Fig. 2(d), HWHM $\sim 1.9$ meV] in the hybridization regime as compared to outside of the gap [Fig. 2(c), HWHM $\sim 0.62$ meV]. A broader than usual ZBCP is in agreement with the theoretical prediction of perfect AR on the QSH-S interface [15]. The observation of a $-2e^2/h$ AR conductance peak thus renders strong support for the helical nature of the edge modes.

The $I_{\text{excess}}$ deduced in the minigap shows a large range of fluctuations between 100 and 200 nA; this value is consistent with, but somewhat smaller than, the value obtained from BTK analysis. According to BTK theory, the maximal value of $\Delta G_{\text{excess}}/\Delta_s = 3/4$ at $T = 0$, for perfectly transmissive interfaces, i.e., when $A = 1$ [27,28]. In the case of $S$-QSH-$S$ structures, normal resistance is $h/2e^2$, so the maximal excess current that can be obtained for perfectly transmissive helical edge modes with zero backscattering

is $I_{\text{excess}} = 16 \Delta_s/3h \sim 250$ nA.

In the case of $S$-QSH single helical edge interface, the absence of backscattering channels in the helical edge suppresses the NR probability $B(E)$ to 0. Within the superconducting gap $E < \Delta_s$, electron transmission is excluded, requiring a perfect AR with probability $A(E) = 1$ [15]. Evaluating Eq. (1) in the zero temperature limit for this case gives a contact resistance of $h/4e^2$ for a single helical edge channel when $V < \Delta_s/e$. In two-terminal $S$-QSH-$S$ geometry, used in our experiments, this gives a resistance of each helical edge mode to be $h/4e^2 + h/4e^2 = h/2e^2$, giving a total two-terminal resistance of $h/2e^2 \parallel h/2e^2 = h/4e^2$. On the other hand, for $E > \Delta_s$ electron transmission into the superconducting lead is possible and the AR probability scales as $A(E) = (\Delta_s^2/E^2) \rightarrow 0$ for $V \gg \Delta_s/e$ [24], reducing Eq. (1) to the familiar case of $N$-QSH single interface with contact resistance of $h/2e^2$. A simple resistance combination now gives a total two-terminal resistance of $h/2e^2$.

In the present InAs/GaSb QWs this analysis may be somewhat complicated by the presence of residual minigap bulk carriers [22,26] with an estimated carrier density $< 5 \times 10^{10}$ cm$^{-2}$. Such carriers give a background conductance of $G_{\text{bulk}} \sim 10e^2/h$, as can be estimated from $g_{\text{bulk}} \times (W/L)$, with bulk conductivity $g_{\text{bulk}} \sim 5e^2/h$ [9]. At such low densities, however, apart from significant wave vector mismatch [27,28], disorder generally dominates and hence a substantial AR contribution from the bulk can be excluded. As a result, AR can be thought of as essentially from the edge channels, leading to $\Delta G = G(V = 0) - G(V \gg \Delta_s/e) = 2e^2/h$ [Fig. 1, inset (c)]. This has indeed been observed [Fig. 2(d), $V_{\text{front}} = -2.1$ V] as a ZBCP of an amplitude $\sim 2e^2/h$, for $E_F$ in the minigap. We note that regardless of a high transmissivity of $T = 0.7$ above the minigap, in the hybridization regime the $I$-$V$ curve is tunnelinglike [see Fig. 2(e)] [29], which indicates interface transparency of less than 0.5. According to BTK this would give conductance suppression at zero bias. Because we actually see conductance enhancement, this must be due to edge states and their topological protection. Also, note that the ZBCP is in fact broadened [see Fig. 2(d), HWHM $\sim 1.9$ meV] in the hybridization gap as compared to outside of the gap [Fig. 2(c), HWHM $\sim 0.62$ meV]. A broader than usual ZBCP is in agreement with the theoretical prediction of perfect AR on the QSH-S interface [15]. The observation of a $-2e^2/h$ AR conductance peak thus renders strong support for the helical nature of the edge modes.

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FIG. 3 (color). (a) $R_S$ and $I_{\text{excess}}$ versus $V_{\text{front}}$ for temperature $T = 0.5$ K, and $T$ from 5 K to 8 K varied in 0.5 K increments. Note that $I_{\text{excess}}$ drops slowly until $T$ is close to $T_c = 8.27$ K. (b) Color map of $dV/dI$ versus $V$ and $T$ ($V_{\text{front}} = 0$ V). Full and dashed lines show BCS dependence of the superconducting gap $\Delta_s$ and $2\Delta_s$, respectively. Dips in $dV/dI$ closely follow the BCS gap $\Delta_s$. (c) Normalized $I_{\text{excess}}$, i.e., $I_{\text{excess}}/(300 \text{ mK})$, versus $\Delta_s/T$ for $E_F$ above the minigap (in red) and $E_F$ in the minigap (in blue). In both cases, normalized $I_{\text{excess}}$ shows equal decrease as the $\Delta_s$ is reduced with $T$. 
The temperature dependence of $I_{\text{excess}}$ in Fig. 3(a) shows only a weak dependence for temperatures up to 6.5 K, and $I_{\text{excess}}$ is quickly suppressed as the temperature is further increased towards the critical temperature of niobium leads. Furthermore, a color map of the temperature evolution of $dV/dI$ is shown in Fig. 3(b), with dips in $dV/dI$ closely following the BCS temperature dependence of the superconducting gap $\Delta_S$. We note here that for both cases, i.e., $E_F$ inside and outside of the minigap, $I_{\text{excess}}$ shows 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., $I_{\text{excess}}(T)/I_{\text{excess}}(300 \text{ mK})$, plotted in Fig. 3(c) 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 minigap is suppressed much faster than in the case when $E_F$ is outside of the minigap. In fact, a perpendicular magnetic field of less than 50 mT is sufficient to fully suppress AR processes in the minigap, while above the minigap AR processes survive in fields up to at least 500 mT. Similar disparity is also observed for the in-plane magnetic fields, albeit in this case minigap $I_{\text{excess}}$ survives for fields up to 100 mT while above the minigap AR processes are still observable at 500 mT. Such fragility of the observed minigap excess current under small magnetic fields is indicative of its origin, namely, due to protection of helical edge channels under time-reversal symmetry. Applying small magnetic fields breaks this symmetry, destroying the perfect destructive interference of backscattering paths [2], and opening the backscattering channels in our structures. In this case, maximal AR probability is no longer guaranteed and $I_{\text{excess}}$ quickly vanishes. The ZBCP as a function of perpendicular magnetic field in the two cases are shown in Fig. 4(c) (above the minigap) and in Fig. 4(d) (in the gap), respectively.

In conclusion, we probe the recently discovered helical edge modes in InAs/GaSb QWs via Andreev reflection. A zero-bias conductance peak of $\sim 2e^2/h$ is observed as the Fermi level is tuned into the minigap, which is in good agreement with the prediction of perfect Andreev reflection of the helical edge modes, guaranteed by the absence of backscattering channels. The perfect AR occurs in spite of a finite barrier at the interface and shows strong sensitivity to time-reversal symmetry breaking—hallmarks of the helical nature of the QSH edges. With further optimization in fabrication, the superconductor-contacted InAs/GaSb system readily arises as a viable platform where theoretical predictions of Majorana fermion bound states [11–14] can be experimentally explored.

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We take excess current as a semiquantitative measure for AR in this experiment. AR probability scales as the ratio of superconducting gap to voltage bias squared. Because the superconducting gap is ~1 meV, a bias of ~3 mV will significantly suppress AR processes, and hence the linear portion is fitted from 3 mV to 5 mV. This procedure may generally underestimate excess current, but with an error estimated to be less than 10%.

Note that the hybridization gap here is 3–4 meV in magnitude. Hence by applying several mV we will probe states slightly above and below the center of the hybridization gap.