Edge-mode superconductivity in a two-dimensional topological insulator

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Topological superconductivity is an exotic state of matter that supports Majorana zero-modes, which have been predicted to occur in the surface states of three-dimensional systems, in the edge states of two-dimensional systems, and in one-dimensional wires5,6. Localized Majorana zero-modes obey non-Abelian exchange statistics, making them interesting building blocks for topological quantum computing3,4. Here, we report superconductivity induced in the edge modes of semiconducting InAs/GaSb quantum wells, a two-dimensional topological insulator6–8. Using superconducting quantum interference we demonstrate gate-tuning between edge-dominated and bulk-dominated regimes of superconducting transport. The edge-dominated regime arises only under conditions of high-bulk resistivity, which we associate with the two-dimensional topological phase. These experiments establish InAs/GaSb as a promising platform for the confinement of Majoranas into localized states, enabling future investigations of non-Abelian statistics.

Several studies have reported on topological superconductivity in three-dimensional (3D)11 and 1D12–15 materials. In 2D semiconductor quantum wells a topological insulator (TI) is identified by the observation of a quantum spin Hall effect5,6. In this phase the 2D bulk is a gapped insulator and transport only occurs in gapless edge states. These edge modes are spin-polarized and counter-propagating channels, known as helical modes, which are protected against elastic backscattering in the presence of time-reversal symmetry. To date, only two 2D TI systems have been identified experimentally—HgTe/HgCdTe quantum wells4 and InAs/GaSb double quantum wells10,16. In each of these, the origin of the TI phase is different: relativistic band-bending for HgTe/HgCdTe7 and type-II broken band alignment for InAs/GaSb8. Recent scanning microscopy experiments have confirmed the presence of edge currents in both 2D TIs17–19. The two different material classes are considered to be interesting complementary alternatives for topological studies.

Effects arising from proximitizing TIs with superconductors have been investigated, including excess currents due to Andreev reflection19 and Josephson effects in superconductor–normal–superconductor (SNS) junctions20. To demonstrate topological superconductivity (TS), however, it needs to be shown explicitly that superconducting transport takes place along the helical edges. Here, we demonstrate edge-mode superconductivity in InAs/GaSb. A similar experiment was reported recently by Hart et al. in the HgTe material21.

A straightforward consequence of the conventional SNS junction configuration (Fig. 1a), in contrast to an edge-mode superconducting junction (Fig. 1b), can be observed in a superconducting quantum interference (SQI) measurement, where a perpendicular magnetic field induces oscillations in the amplitude of the superconducting current. A wide conventional SNS junction yields the Fraunhofer pattern, as shown in the bottom panel of Fig. 1a. In the case of edge-mode superconductivity the junction effectively acts as a superconducting quantum interference device (SQUID) with a well-known \( \Phi_0 \)-periodic interference pattern (bottom panel of Fig. 1b). A \( \Phi_0 \)-periodic SQI is expected for the helical edge modes in the absence of quasiparticle poisoning (two phases are possible, as shown by the dashed lines in the bottom panel of Fig. 1b, depending on whether or not the two edges have the same fermion parity)22. Quasiparticle poisoning can induce fermion parity switches that restore the \( \Phi_0 \) periodicity, even for helical modes.

To specify this further, we consider a short Josephson junction (defined as \( L \ll \xi \), where \( L \) is the contact separation and \( \xi = ℏ v / Δ_{\text{sd}} \) is the superconducting coherence length in the junction material with Fermi velocity \( v \) and induced gap \( Δ_{\text{sd}} \)), which has a sinusoidal current-phase relation. In this case, the Josephson supercurrent \( I_{\text{J}}(B_J) \) is given by the Fourier transform of the density profile of the critical current \( I_{\text{c}}(x) \) taken at a perpendicular magnetic field \( B_J = 0 \). \( I_{\text{J}}(B_J) = \text{Im} \left[ \int_{-\infty}^{\infty} I_{\text{c}}(x) e^{i k_{\text{B}} s x} \right] \), with \( k_{\text{B}} s \) the magnetic field included in the superconducting coherence length in the junction material.

In contrast, for edge-mode superconductivity, the SQI is simply \( \Phi_0 \)-periodic (Fig. 1b). Note that this analysis does not include effects with a topological origin, such as when the edge modes have helical character. In that case the SQI can become \( 2\Phi_0 \)-periodic1, as illustrated in Fig. 1b and discussed later in this Letter.

Before investigating the superconducting regime we first describe the normal state transport in our Ti/Al–InAs/GaSb–Ti/Al junctions (for details of the device geometry see Fig. 2a,b). We focus on one device (device A) and map out the normal state resistance \( R_N \) when superconductivity is suppressed by \( B_J = 0.1 \) T (Fig. 2a). The junction has width \( W = 3.9 \) µm and contact separation \( L = 400 \) nm, significantly shorter than the edge mode decoherence length of \( \sim 2–4 \) µm (refs 10,16). Transport is gate-tuned using the n GaAs substrate as a back gate, and a Ti/Au top gate. As the top-gate voltage \( V_{\text{tg}} \) is tuned from positive to negative, a resistance peak develops, indicating a charge neutrality point (CNP)16,24 when the Fermi energy is located in the topological gap (upper panel in Fig. 1b). For more positive \( V_{\text{tg}} \), the Fermi level is moved up into the conduction band and the dominant charge carriers are...
electrons, while for more negative $V_{tg}$ the Fermi level is moved down into the valence band and charge transport is dominated by holes. This interpretation is confirmed by measurements in the quantum Hall regime performed on material from the same growth batch. The position of the CNP shifts to more positive $V_{tg}$ as the backgate voltage $V_{bg}$ is tuned more negative, as shown in the line cuts in Fig. 2b, in qualitative agreement with band structure calculations. The maximum resistance at the CNP is $\sim 7 \text{k}\Omega$. This value is smaller than the ideal quantized value of $h/2e^2$ (~13 kΩ) expected for transport only via helical edge modes, indicating a residual bulk conductivity of ~5 kΩ.

For $B_z < 11 \text{ mT}$ we observe a supercurrent, a direct consequence of the d.c. Josephson effect. We define the switching current, $I_{SW}$, as the value of the applied bias current when the developed voltage jumps from virtually zero to a finite value (Fig. 3b). $I_{SW}$ is tuned by means of gate voltages: as $V_{tg}$ becomes less positive $I_{SW}$ first decreases, then saturates at a minimum value for $V_{tg}$ near the CNP, and then increases again for more negative $V_{tg}$ due to hole-mediated transport through the bulk (Fig. 3a). To unambiguously establish the Josephson nature of our junctions, we irradiated the device with microwaves of frequency $f_{RF}$. The familiar Shapiro ladder is observed, with steps at $V = n hf_{RF}/2e$ ($n = 1, 2, \ldots$). Figure 3b shows a comparison of $I-V$ curves measured without and with microwaves, the latter showing characteristic Shapiro steps, which are a consequence of the a.c. Josephson effect. The step heights exhibit the expected linear dependence when $f_{RF}$ is varied (inset of Fig. 3b). Figure 3c shows the characteristic modulation of the widths of the Shapiro steps by the magnitude of the applied microwave field. Similar data near the CNP are presented in Supplementary Fig. 8.

Having established the d.c. and a.c. Josephson effect in our InAs/GaSb junctions, we next analyse the spatial distribution of the supercurrent by performing SQI measurements at different gate values (Fig. 4). As shown by Dynes and Fulton, the current density profile $J_b(x)$ can be determined from the measured SQI provided the phase of the complex Fourier transform can be reliably estimated. We first comment on the validity of the Dynes and Fulton approach for our devices. The superconducting coherence length for an edge mode velocity $v \approx 4.6 \times 10^7 \text{ m s}^{-1}$ in InAs/GaSb is $\xi \geq 240 \text{ nm}$ (using $\Delta_{ind} \leq \Delta \approx 125 \mu\text{eV}$, where $\Delta$ is the superconducting gap of the electrodes, Supplementary Fig. 9). We have verified that in our limit (where $L$ is of order $\xi$) the SQI pattern is only weakly sensitive to deviations from a perfect sinusoidal $I-\Phi$ relation (Supplementary Fig. 15), so the Dynes and Fulton short junction approach is indeed justified for obtaining qualitative supercurrent distributions. Recently, Hui et al. performed independent numerical calculations based on our data and support our results.

Figure 4 summarizes our main result: gate-tuning from bulk to edge-mode superconductivity. The figure shows SQI data at the

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**Figure 1** | Band structure and SQI patterns. (a, b) Top panels: Schematic band diagrams for InAs/GaSb quantum wells. Owing to the type-II broken band alignment within the heterostructure, the electron (red) and hole (blue) 2D bulk bands cross. Coupling between these bands opens up a topological gap, which is crossed by gapless, linearly dispersive helical edge states. These states are shown by the pink and green lines. Arrows indicate the spins of the states. When the Fermi level is in one of the bulk bands (a, orange rectangles) the critical current density profile is spatially uniform (middle panel) and the corresponding SQI has a Fraunhofer-like shape with a central lobe of width $2\Phi_0$ and side lobes of width $\Phi_0$ (bottom panel). When the Fermi level is in the topological gap and crosses the helical edge modes (b, orange rectangle), the critical current density profile is localized at the edges (middle panel) and the corresponding SQI has a SQUID-like shape (bottom panel). For a conventional SQUID, the SQI has $\Phi_0$ periodicity (bottom panel, solid line). A $2\Phi_0$-periodic SQI is expected for the helical edge modes in the absence of quasiparticle poisoning. The dashed lines in the bottom panel show the two possible phases, which depend on whether or not the two edges have the same fermion parity.

**Figure 2** | Device layout and normal state transport. (a) False-colour scanning electron microscope image of a typical S-InAs/GaSb junction, where S represents the superconducting material, which is composed of Ti(5 nm)/Al(150 nm) (see Supplementary Fig. 12 for devices with NbTiN contacts). (b) Cross-sectional view of device layout. Phase diagram measured on InAs/GaSb (device A, cooldown 1). $R_{bg}$ is measured using d.c. excitation current $I_{exc} = 5 \text{nA}$. The Ti/Al contacts are driven into the normal state by an applied field $B_z = 100 \text{ mT}$. The dashed rectangle refers to the data discussed in Fig. 5. (d) Line cuts showing $R_{bg}$ as a function of $V_{bg}$ for three different values of $V_{tg}$ (corresponding to the dashed lines in (c)).
representative points in gate space indicated in Fig. 2c, together with the current density profiles extracted using the Dynes and Fulton approach\(^{21,23}\) with \(L_{\text{eff}} = 640\) nm. We observe three regimes: (I) a distinct Fraunhofer-like pattern when the Fermi energy is in the conduction band. The corresponding current density profile indicates that most of the current is carried by the bulk (Fig. 4a,b); (II) a SQUID-like interference when the Fermi energy is near the CNP. In this regime, the supercurrent density is clearly edge-
mode dominated (Fig. 4c,d); (III) a return to a Fraunhofer-like pattern as the Fermi energy enters the valence band. Here, the current distribution acquires a large bulk contribution, but edge modes also contribute over the range of accessible gate voltage values (Fig. 4e,f). Supplementary Fig. 3 presents additional SQI patterns measured at other points within gate space. Taken together, these data clearly demonstrate gate tuning between bulk and edge-mode superconductivity in InAs/GaSb and provide upper bounds on the edge mode widths (Supplementary Fig. 5). As a further check, we studied a non-topological InAs-only junction (device B), where, as expected, a SQUID-like SQI was not observed (Supplementary Fig. 11).

The edge-mode SQI data typically show conventional $\Phi_0$-periodicity (for example, as in Fig. 4c). However, over a certain gate range (dashed rectangle in Fig. 2c) we observe a striking even–odd pattern in the interference lobes. An example is shown in Fig. 5a. This $2\Phi_0$-periodic effect is also seen in another device with different contact material (Supplementary Fig. 12). In the conventional Dynes and Fulton analysis this would require a current density profile containing three peaks, two at the edges and one in the middle (Fig. 5b). Simulations of such $2\Phi_0$-SQI (Supplementary Fig. 13) indicate that this conventional analysis would require the middle channel to be within 10% of the device centre. It is improbable that such an effect would occur in two separate devices from different growth batches and different superconductors, although we cannot exclude this possibility.

The scenario above considers the possibility that interference paths enclose half the junction area. Alternatively, one could consider interference around the full junction area by particles of charge $e$ instead of Cooper pairs with charge $2e$. The occurrence of $e$-interference is rare because supercurrent probes the coherence between superconductors by exchange of Cooper pairs. Nevertheless, several scenarios have been proposed involving processes with an electron travelling along one edge being Andreev-reflected as a hole into the other edge. Such processes require phase coherence in excess of the sample circumference, $\sim 9 \mu m$, which seems large given previous transport data for InAs/GaSb quantum wells. Another mechanism involves the fractional Josephson effect. In this interpretation the edge modes need to have a helical structure and therefore contain Majorana zero-modes. Josephson-coupled Majoranas transport a charge $e$, indeed resulting in a doubling of the SQI periodicity. This interpretation, however, requires a quasiparticle poisoning time that is in excess of the measurement time (tens of seconds), which also seems improbable. Using existing techniques, future experiments should directly measure the rate of quasiparticle poisoning to further investigate the origin of this $2\Phi_0$-periodic effect.

In conclusion, using superconducting quantum interference, we demonstrate tuning between edge-dominated and bulk-dominated superconducting transport regimes as a function of electrostatic gating in InAs/GaSb quantum wells. This work establishes InAs/GaSb quantum wells as a platform for topological superconductivity and Majorana physics.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions
V.S.P., A.J.A.B. and F.Q. fabricated the devices and performed the measurements. C.C. and W.W. provided the InAs/GaSb heterostructures. V.S.P., A.J.A.B., F.Q., M.C.C. and L.P.K. contributed to the experiments and all authors discussed the results and edited the manuscript.

Additional information
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Competing financial interests
The authors declare no competing financial interests.
Methods
The InAs/GaSb quantum wells were grown using molecular beam epitaxy on n" (001) GaAs substrates. Two different material batches were used: a batch grown using high-mobility Ga (HM) and a batch using lower-mobility Ga (LM). The LM batch has lower residual bulk conductance near the CNP. Measurements were performed in a dilution refrigerator with a mixing chamber temperature of 16 mK equipped with a three-axis vector magnet. SQI patterns corresponding to an edge-mode current density profile were observed in three devices: device A from the main text (HM heterostructures and Al contacts) and devices C and D (based on LM heterostructures and with NbTiN contacts, Supplementary Fig. 12). Device A was measured in two separate cooldowns. No significant changes in the device properties were observed between cooldowns. Offsets in $B_z$ of up to a few mT due to trapped flux in the superconducting magnets or leads were subtracted in the plotted SQI data. The spatial resolution of the current density profiles extracted from SQI patterns is $\sim W\Phi_0/\Delta\Phi$, where $\Delta\Phi$ is the magnetic flux range of the SQI measurement. In each of the plots, the full-width at half-maximum of the InAs/GaSb edge modes is near the Fourier resolution limit and represents an upper bound on the actual width of the edge mode. The maximum $\Delta\Phi$ is limited by reduced visibility of the oscillations for $B_z \geq 11$ mT in the case of Al contacts and by switches along the $B_z$ axis in the case of NbTiN contacts (presumably due to flux depinning in the leads, Supplementary Fig. 12). We attribute the non-zero values of $J_c(x)$ outside the device width to finite resolution and Fourier windowing effects (we used a standard rectangular window).