Anomalous low-temperature enhancement of supercurrent in topological-insulator nanoribbon Josephson junctions: evidence for low-energy Andreev bound states

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Abstract

We report anomalous enhancement of the critical current at low temperatures in gate-tunable Josephson junctions made from topological insulator BiSbTeSe₂ nanoribbons with superconducting Nb electrodes. In contrast to conventional junctions, as a function of the decreasing temperature T, the increasing critical current I_c exhibits a sharp upturn at a temperature T_* around 20% of the junction critical temperatures for several different samples and various gate voltages. The I_c vs. T demonstrates a short junction behavior for $T > T_*$, but crosses over to a long junction behavior for $T < T_*$ with an exponential T-dependence $I_c \propto \exp(-k_B T/\delta)$, where k_B is the Boltzmann constant. The extracted characteristic energy-scale δ is found to be an order of magnitude smaller than the induced superconducting gap of the junction. We attribute the long-junction behavior with such a small δ to low-energy Andreev bound states (ABS) arising from winding of the electronic wavefunction around the circumference of the topological insulator nanoribbon (TINR). Our TINRbased Josephson junctions with low-energy ABS are promising for future topologically protected devices that may host exotic phenomena such as Majorana fermions. Three-dimensional (3D) topological insulators (TI) are characterized by insulating bulk and non-trivial conducting surface states, where the spin is helically locked perpendicular to the momentum, and the carriers are massless Dirac fermions with linear energy-momentum dispersion [1–3]. Theoretical work by Fu and Kane [4] has predicted that, once coupled to an s-wave superconductor, the surface states of TI's undergo unconventional superconducting pairing, which can provide a useful platform to study exotic phenomena such as topological superconductivity and Majorana fermions [2, 4]. In contrast to the conventional spin-singlet superconductivity, the induced superconductivity in the surface states of a 3D TI [4] is a mixture of singlet and triplet pairings due to the lifted spin degeneracy [5–7]. Furthermore, Andreev bound states (ABS) formed within a superconductor-TI-superconductor (S-TI-S) Josephson junction (JJ) can exhibit a robust zero-energy crossing when the phase difference between the two superconductors is π , giving rise to Majorana modes [4, 6]. Possible probes of topological superconductors/junctions may include the tunneling spectroscopy, the current-phase relation (CPR), and temperature dependence of the critical current [8–13].

In recent years, S-TI-S Josephson junctions with two- and three-dimensional TI's have been extensively studied. Gate-tunable supercurrent and Josephson effects, such as Fraunhofer patterns and Shapiro steps, have also been observed [14–29]. However, in many of the devices studied so far, the bulk of the TI can have notable contributions to the transport properties of the junction and make it difficult to separate the contribution of the surface states.

In this work, we use the topological insulator BiSbTeSe₂ with a distinct advantage that at low temperatures the bulk is insulating and only the surface states contribute to electrical transport [29–31]. We obtain nanoribons of BiSbTeSe₂ using the exfoliation technique and fabricate superconductor-(TI nanoribon)-superconductor (S-TINR-S) JJ's. Due to the enhanced surface to volume ratio, uniform cross-sectional area, and relatively small size, TINR-based devices have shown to be an excellent platform to study topological transport, exhibiting ballistic conduction and π -Berry-phase Aharonov-Bohm effects [32–34], and are also predicted to be promising for the study of topological superconductivity [35, 36]. In our TINR-based JJ's, in contrast to conventional junctions, we observe a sharp upturn of the critical current I_c for temperatures T below ~ 20% of the junction critical temperature T_c . Interestingly, this upturn temperature (~ 0.2 T_c) is observed in a variety of JJ's with different gate voltages V_g 's. We interpret the experimental results using a phenomenological model for junctions based on TINR's. This model relates the enhancement of I_c at low temperatures to the ABS whose energy scale is around an order of magnitude smaller than the induced superconducting gap. The reduced energy scale of the ABS is attributed to the winding of their wavefunction around the circumference of the TINR. Such ABS are in the long junction limit and give rise to an exponential enhancement of I_c with decreasing T. Furthermore, we observe a sinusoidal current-phase relation (CPR) measured using an asymmetric superconducting quantum interference device technique, consistent with the expectation for these samples at our measurement temperature.

High-quality single crystals of BiSbTeSe₂ were grown by the Bridgman technique [30]. Flakes exfoliated out of our BiSbTeSe₂ crystals exhibit the ambipolar field effect, half-integer quantum Hall effect, and π Berry's phase characteristic of the spin-helical Dirac fermion topological surface states (TSS) |30, 31|. We obtain BiSbTeSe₂ nanoribbons |29| using the scotch-tape exfoliation technique and transfer them onto 300-nm-thick $SiO_2/500-\mu$ m-thick highly-doped Si substrates, which are used as back gates. Nanoribbons of various width W and thickness t are then located using an optical microscope. Subsequently, electron beam lithography is performed to define two closely separated electrodes with a separation L < 100 nm. Finally, a thin layer of Niobium (Nb) as a superconductor, 50-nm thick, is deposited in a DC sputtering system. Prior to Nb deposition, brief (~ 3 seconds) Ar ion milling is performed to improve the quality of Nb contacts to TINR's. We have previously observed large $I_c R_N$ product (where R_N is the normal-state resistance) and multiple Andreev reflections in such TINR JJ's [29], demonstrating the high quality of the junctions including the Nb-TINR interface. Inset of Fig. 1b depicts an atomic force microscope (AFM) image of a representative S-TINR-S junction (sample 1). We have studied a variety of TINR JJ's with electrode separation $L\sim 40-70$ nm, width $W\sim 250-400$ nm, and thickness $t\sim 38-50$ nm. These dimensions are measured by an AFM. Detailed parameters for all the samples studied are listed in Table S1 in the supplemental information (SI) [37].

Fig. 1a shows the ambipolar field effect in the two-terminal resistance R vs. V_g measured in sample 1 at T = 14.5 K, above the superconducting critical temperature of Nb. By varying V_g , the carrier type in the TINR can be changed from n-type to p-type, and the chemical potential can be tuned into the bulk bandgap to be in the TSS. The gate voltage where the maximum of R vs. V_g occurs represents the charge neutrality point (CNP) which is $V_{CNP} \sim -15$ V for this sample. The junction critical temperature ($T_c \sim 0.5 - 2.2$ K), the temperature below which the junction resistance vanishes, is much lower than the critical temperature of Nb ($T_c^{Nb} \sim 7.5$ K) in our S-TINR-S junctions. The DC voltage V_{dc} vs. the DC current I_{dc} , measured in sample 1 when sweeping I_{dc} from -300 nA to 300 nA at T = 20 mK for a few different V_g 's is plotted in Fig. 1b. When the applied DC current I_{dc} is small, the voltage across the junction is zero, indicating that the junction is in its superconducting state and supports a supercurrent (I_{dc}). However, once the current is increased above some critical current (defined as I_c , marked by the arrow for the $V_g = -20$ V curve), the junction leaves the superconducting state and transitions to the normal state with a finite voltage drop. Fig. 1c shows the color map of the two-terminal differential resistance dV/dI vs. V_g and I_{dc} (swept from 0 to 300 nA) at T = 20 mK. The solid white line in this figure marks the critical current I_c of the junction. Notably, we observe that I_c exhibits an ambipolar field effect (which has not been realized in previous devices [22, 23, 29]) and reaches a minimum of ~ 120 nA near $V_{CNP} \sim -15$ V, consistent with that measured in the normal-state ambipolar field effect (Fig. 1a).

Fig. 2a shows the *T*-dependence of I_c for three different V_g 's in sample 1. Starting from T_c , I_c increases with decreasing *T*. Notably, we observe an anomaly in I_c vs. *T* at an upturn temperature ($T_* \sim 0.36$ K marked for the $V_g = 45$ V dataset with $T_c \sim 2.2$ K as an example), below which I_c increases sharply and eventually reaches its largest value I_c^{max} at the lowest accessible temperature ($T \sim 20$ mK). The normalized critical current I_c/I_c^{max} vs. the normalized temperature T/T_c for this sample is depicted in Fig. 2b. Interestingly, T_* is always $\sim 0.2T_c$ for this sample regardless of the applied V_g . Fig. 2c plots I_c/I_c^{max} vs. T/T_c for five different samples, with each sample measured at a few V_g 's. We observe that T_*/T_c remains ~ 0.2 for all our TINR-based JJ's, regardless of their T_c and V_g (see Table S1 in the SI [37]). Noteworthy, we observe an exponential enhancement of I_c with decreasing *T* for $T < T_*$ as highlighted by the solid red lines in Fig. 2b and c.

The anomalous temperature dependence of I_c observed in our samples is radically different from that of conventional JJ's. In conventional *short* junctions, depending on the junction transparency, I_c is expected to saturate at low temperatures without exhibiting any exponential behavior [38, 39]. In contrast, for *long* junctions, it has been demonstrated that I_c increases exponentially with decreasing temperature [39–43]. Therefore, the increase in I_c vs. decreasing T for $T_* < T < T_c$ followed by an exponential enhancement of I_c for $T < T_*$ as observed in Fig. 2b suggests that I_c in our samples may be dominated by a short junction behavior for $T > T_*$ and a long junction behavior for $T < T_*$. Such a transition from short to long junction behaviors may be related to the nature of the TSS in the TINR. Because, the TSS extend over the entire circumference of the TINR, the superconducting transport is carried by modes on both the top (corresponding to I_1 depicted in the inset of Fig. 2b) and bottom (corresponding to I_2 depicted in the inset of Fig. 2b) surfaces of the TINR, i.e., the total supercurrent $I = I_1 + I_2$.

For the TINR with a circumference C = 2W + 2t, the transverse momentum k_y , perpendicular to the current, is quantized as $k_y = \frac{2\pi}{C}(n+1/2)$, where *n* is an integer [44, 45]. Therefore, the modes with k_y near zero remain on the top surface and contribute to I_1 , while the modes with $|k_y| \gg 0$ extent around the perimeter of the TINR and contribute to I_2 . We note that the $k_y = 0$ mode is prohibited in the TINR.

The modes (corresponding to I_1) on the top surface travel a short distance L, the separation between the two Nb contacts, and are supposedly in the short-junction limit. We found our experimental data of I_c vs. T for $T > T_*$ can be described using the temperaturedependent supercurrent calculated for a ballistic short junction [6, 10, 39], given by:

$$I_1(\phi, T) = N_1 \frac{e\pi\Delta(T)}{h} \sin(\frac{\phi}{2}) \tanh\left(\frac{\Delta(T)\cos\left(\frac{\phi}{2}\right)}{2k_B T}\right),\tag{1}$$

where h is the Plank constant, k_B is the Boltzmann constant, e is the electron charge, N_1 is the number of modes in the top surface, ϕ is the phase difference between the two superconductors, and $\Delta(T)$ is the induced superconducting gap. We assume a BCS temperature dependence for $\Delta(T)$ with $\Delta(T = 0) = \Delta_0 = 1.76k_BT_c$ [46]. We obtain the critical current $I_{c1}(T)$ by maximizing $I_1(\phi, T)$ over ϕ as:

$$I_{c1}(T) = \max_{\phi} \left(I_1(\phi, T) \right). \tag{2}$$

We have plotted $I_{c1}(T)$ obtained from Eq. (2) with the solid blue curve in Fig. 2b. The computed $I_{c1}(T)/I_{c1}^{max}$, where $I_{c1}^{max} = I_{c1}(T = 0)$, is divided by 2.2 in order to show its agreement with experimental results for $T > T_*$.

In contrast, the modes (corresponding to I_2) flowing through the bottom surface extend over the entire circumference ($C \sim 700$ nm for sample 1 shown in Fig. 2a and b) of the TINR (through the side surface) and hence travel a longer distance d ($d \ge C \gg L$). We assume such modes are in the ballistic long-junction limit with $d \ge \xi$, where $\xi = \hbar v_F / \Delta \sim 640$ nm is the superconducting coherent length of the junction and v_F is the Fermi velocity. As a result, we observe a reduced energy gap $\delta = \hbar v_F/2\pi d$ for these modes [39, 43, 47–49]. In the limit of $T_{sat} < T < T_*$, where $T_{sat} \ll \delta/k_B$ is the temperature below which I_c saturates, the critical current of these modes exhibits an exponential dependence on T, i.e. $I_c \propto \exp(-k_B T/\delta)$ [39, 43, 47–49]. This exponential dependence is clearly seen in the experimental data in Fig. 2b. To extract δ , we perform an exponential fit to I_c for $T_{sat} < T < T_*$ (where we take $T_{sat} \sim 0.04T_c$) as depicted by the solid red line in Fig. 2b. The fit gives $\delta \sim 0.08\Delta$, corresponding to $d \sim 1.2 \ \mu m$ ($\sim 2\xi$, and moderately lager than $C \sim 700 \ nm$). We have found similar trends in other samples shown in Fig. 2c (see Table S1 [37]). We note that the effect of impurity in TI's can lead to an effective length that is longer than the physical length of the junction [12]. This impurity effect may also be a contributing factor in the increased effective length d experienced by the modes flowing around the circumference and through the bottom surface.

We can extract $N_1 \sim 1-5$ for different samples from the fit of I_{c1} as determined by Eq. (2) to the experimental results. The extracted value of N_1 is much smaller than the estimated total number of modes $N = k_F C/2\pi \sim 24$ -114, where $k_F = \sqrt{4\pi \frac{C_g}{e}(V_g - V_{CNP})}$ is the Fermi wave vector and $C_g = 12 \text{ nm/cm}^2$ is the parallel plate capacitance per unit area of a 300-nm SiO₂. Furthermore, we can estimate the number of modes N_2 corresponding to I_2 as $N_2 = N - N_1 \sim (10 - 20)N_1$. This suggests that the majority of the modes in our TINRs are going around the circumference and through the bottom surface to contribute to I_2 , consistent with the expectation that only modes with k_y near zero contribute to I_1 . We note that I_c at the lowest T is proportional to the number of modes and the energy scale of the ABS in both the long and short junction limits (i.e. the low- $T I_1$ and I_2 are proportional to $N_1\Delta_0$ and $N_2\delta$, respectively). The extracted large $N_2 \sim (10 - 20)N_1$ and the small $\delta \sim 0.1\Delta_0$ imply that the contribution of I_1 and I_2 to the total critical current at low T should be comparable, which is consistent with our experimental observations in Fig. 2b and c. For instance, I_{c1} represented by the solid blue line in Fig. 2b approaches $\sim 50\%$ of the total I_c when extrapolated to the lowest T.

In the above phenomenological model, we have used one effective reduced gap δ to describe all the modes flowing around the circumference and through the bottom surface. However, in reality these modes can have different gaps depending on how far they travel between the two superconductors. Currently there is no theory for the temperature dependence of I_c specific to TINR (considering the wrapping of the electronic wavefunction around the circumference). Further studies are required to fully understand the nature of the induced superconductivity in this system.

We have measured a CPR (supercurrent I vs. phase ϕ) in our TINR junction at T = 20 mK using an asymmetric SQUID [50, 51], as discussed in SI [37], and found the CPR to be sinusoidal. Fig. 3a depicts a scanning electron microscope (SEM) image of the SQUID. The measured CPR (symbols) is shown in Fig. 3b alongside a sinusoidal function (black curve), which describes well the measured CPR. We note that the CPR in long ballistic junctions is predicted to have a saw-toothed form for $T < T_{sat}$ but transitions to a sinusoidal form for $T \gg T_{sat}$ [39]. We suspect that the electron temperature in our SQUID device may be higher than the sample $T \sim 20$ mK possibly due to a large critical current $\sim 10 \ \mu$ A flowing through the reference junction. Observation of a higher electron temperature has been previously reported in similar experiments [50, 52]. Therefore, the measured sinusoidal CPR may reflect a high electron temperature $(T > T_{sat})$ in the the SQUID device used in the experiment.

In this paper, we present transport measurements of the JJ's based on nanoribbons of the bulk-insulating topological insulators BiSbTeSe₂ with superconducting Nb contacts. We experimentally find an anomalous behavior in the T-dependence of I_c in a variety of junctions with different T_c and V_g 's. For all samples, I_c increases with decreasing temperature from T_c to an upturn temperature (~ $0.2T_c$), followed by an exponential increase with further decrease of the temperature. To understand our results, we introduce a phenomenological model based on winding of the ABS around the circumference of the TINR. Our model relates the enhancement of I_c at low temperatures to the anomalously small energy scale of ABS in the long-junction limit. Furthermore, our measured CPR shows a sinusoidal behavior, consistent with the expectation for such long Josephson junctions under our experimental conditions. Our experimental observations indicate that our TINR junctions can be promising platforms for further exploration of topological superconductivity and Majorana fermions predicted in such systems [4].

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FIG. 1. (a) Two-terminal R vs. V_g measured at T = 14.5 K, above the critical temperature $T_c^{Nb} = 7.5$ K of the Nb electrodes. (b) The DC voltage V_{dc} vs. the DC current I_{dc} of the junction for different V_g 's at T = 20 mK (sample 1). Inset: Atomic force microscope (AFM) image of a typical topological insulator (BiSbTeSe₂) nanoribbon (TINR)-based Josephson device with superconducting Nb electrodes. Scale bar is 0.5 μm . (c) Color map of the two-terminal dV/dI vs. V_g and I_{dc} at T = 20 mK. An AC excitation current $I_{ac} = 1$ nA was used for the dV/dI measurement. Solid white line marks the junction critical current I_c vs. V_g .



FIG. 2. (a) Temperature dependence of I_c for different V_g 's for sample 1. (b) Normalized I_c/I_c^{max} vs. normalized T/T_c in log-linear scale. The solid blue line is the normalized I_{c1}/I_{c1}^{max} (Eq. 2) divided by factor 2.2 and the solid red line is a fit to $\exp(-\frac{k_B T}{\delta})$ with $\delta \sim 0.08\Delta$. The symbols have the same legends as in (a). Inset: cartoons of the TINR JJ depicting the current I_1 corresponding to the modes on the top surface and the current I_2 corresponding to the modes that extend around the circumference and flow through the bottom surface. Due to the exponential decay of I_2 with increasing T, only I_1 contributes to the critical current at high temperatures. (c) I_c/I_c^{max} vs. T/T_c in a log-linear scale for five different TINR-based Josephson devices measured at a few (1-3) V_g 's for each device. The exponential fit and the experimental data in (b) are also included in this plot as the solid red line and black symbols, respectively.



FIG. 3. (a) False-colored scanning electron microscope image of an asymmetric SQUID used to measure the current-phase relations (CPR) in our TINR-based JJ's. (b) Normalized current I/I_c vs. normalized flux $\Delta \Phi/\Phi_0$, where $\Phi_0 = h/2e$ is the flux quanta, at $V_g = 20$ V and T = 20 mK. As the absolute value of the flux inside the superconducting SQUID is unknown, the experimental curve is shifted along the horizontal axis for comparison with a sinusoidal function.