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

Morteza Kayyalha,1,∗ Mehdi Kargarian,2 Aleksandr Kazakov,3 Ireneusz Miotkowski,3 Victor M. Galitski,2 Victor M. Yakovenko,2 Leonid P. Rokhinson,3,1 and Yong P. Chen3,1,4,

1School of Electrical and Computer Engineering and Birck Nanotechnology Center, Purdue University, West Lafayette, IN 47907, USA
2Department of Physics, Condensed Matter Theory Center and Joint Quantum Institute, University of Maryland, College Park, MD 20742, USA
3Department of Physics and Astronomy, Purdue University, West Lafayette, IN 47907, USA
4Purdue Quantum Center, Purdue University, West Lafayette, IN 47907, USA

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 $I_c \propto \exp\left(-k_B T/\delta\right)$, where $k_B$ is the Boltzmann constant. The extracted characteristic energy-scale $\delta$ 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 $\delta$ to low-energy Andreev bound states (ABS) arising from winding of the electronic wavefunction around the circumference of the topological insulator nanoribbon (TINR). Our TINR-based 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 \( \pi \), 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 BiSbTeSe\(_2\) 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 BiSbTeSe\(_2\) using the exfoliation technique and fabricate superconductor-(TI nanoribbon)-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 \( \pi \)-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 \( \sim 20\% \) of the junction critical temperature \( T_c \). Interestingly, this upturn temperature (\( \sim 0.2T_c \)) 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 BiSbTeSe$_2$ were grown by the Bridgman technique [30]. Flakes exfoliated out of our BiSbTeSe$_2$ crystals exhibit the ambipolar field effect, half-integer quantum Hall effect, and $\pi$ Berry’s phase characteristic of the spin-helical Dirac fermion topological surface states (TSS) [30, 31]. We obtain BiSbTeSe$_2$ nanoribbons [29] using the scotch-tape exfoliation technique and transfer them onto 300-nm-thick SiO$_2$/500-μm-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 $I_cR_N$ 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 \((T_c \sim 0.5 - 2.2 \text{ K})\), the temperature below which the junction resistance vanishes, is much lower than the critical temperature of Nb \((T^{\text{Nb}}_c \sim 7.5 \text{ K})\) 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 \(T = 20 \text{ mK}\) 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 \(V_g = -20 \text{ V}\) 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 \(T = 20 \text{ mK}\). 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 \(\sim 120 \text{ nA}\) near \(V_{CNP} \sim -15 \text{ V}\), 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 \((T_* \sim 0.36 \text{ K}\) marked for the \(V_g = 45 \text{ V}\) dataset with \(T_c \sim 2.2 \text{ K}\) as an example), below which \(I_c\) increases sharply and eventually reaches its largest value \(I^{\text{max}}_c\) at the lowest accessible temperature \((T \sim 20 \text{ mK})\). The normalized critical current \(I_c/I^{\text{max}}_c\) 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 \(I_c/I^{\text{max}}_c\) 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 \(\sim 0.2\) 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 temperature-dependent supercurrent calculated for a ballistic short junction [6, 10, 39], given by:

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

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, $\phi$ 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 $\Delta(T = 0) = \Delta_0 = 1.76 k_B T_c$ [46]. We obtain the critical current $I_{c1}(T)$ by maximizing $I_1(\phi, T)$ over $\phi$ as:

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

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 $d$ ($d \geq C \gg L$). We assume such modes are in the ballistic long-junction limit with $d \geq \xi$, where $\xi = h v_F/\Delta \sim 640$ 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 \( T_{\text{sat}} < T < T_\ast \), where \( T_{\text{sat}} \ll \delta/k_B \) 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 \( \delta \), we perform an exponential fit to \( I_c \) for \( T_{\text{sat}} < T < T_\ast \) (where we take \( T_{\text{sat}} \sim 0.04 T_c \)) 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 larger than \( C \sim 700 \text{ nm} \). 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 \( k_F = \sqrt{4\pi C_g / e (V_g - V_{CNP})} \) 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 SiO\(_2\). 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 \( \delta \) 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 $\phi$) in our TINR junction at $T = 20$ mK using an asymmetric SQUID \cite{50, 51}, as discussed in SI \cite{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 $T < T_{\text{sat}}$ but transitions to a sinusoidal form for $T \gg T_{\text{sat}}$ \cite{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 $\sim 10$ µA flowing through the reference junction. Observation of a higher electron temperature has been previously reported in similar experiments \cite{50, 52}. Therefore, the measured sinusoidal CPR may reflect a high electron temperature ($T > T_{\text{sat}}$) in 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 BiSbTeSe$_2$ 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 ($\sim 0.2T_c$), 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 \cite{4}.

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* mkayyalh@purdue.edu
† yongchen@purdue.edu

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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 (BiSbTeSe$_2$) 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 $\Phi_0 = \hbar/2e$ 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.