Local and Nonlocal Fraunhofer-like Pattern from an Edge-Stepped Topological Surface Josephson Current Distribution

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Supporting Information

ABSTRACT: We report a surface-dominant Josephson effect in superconductor–topological insulator–superconductor (S–TI–S) devices, where a Bi$_{1.5}$Sb$_{0.5}$Te$_{1.7}$Se$_{1.3}$ (BSTS) crystal flake was adopted as an intervening TI between Al superconducting electrodes. We observed a Fraunhofer-type critical current modulation in a perpendicular magnetic field in an Al–TI–Al junction for both local and nonlocal current biasing. Fraunhofer-type modulation of the differential resistance was also observed in a neighboring Au–TI–Au normal junction when it was nonlocally biased by the Al–TI–Al junction. In all cases, the Fraunhofer-like signal was highly robust to the magnetic field perpendicular to the top and bottom surfaces of the Al electrodes, corresponding to the edge-stepped nonuniform supercurrent density arising from the top and rough side surfaces of the BSTS flake, which strongly suggests that the Josephson coupling in a TI is established through the surface conducting channels that are topologically protected.

KEYWORDS: Topological insulators, Josephson coupling Fraunhofer interference pattern, surface pair current

Strong spin–orbit (SO) interaction of carriers in combination with time-reversal symmetry leads to a new quantum state of matter known as topologically insulating electronic phases.\textsuperscript{1–12} A three-dimensional (3D) topological insulator (TI) is characterized by the presence of an insulating state with an inverted band gap in its bulk and a topologically protected ungapped Dirac-band state on its surface. On a TI surface, the spin polarization of a carrier is tightly linked to its momentum direction\textsuperscript{13} and the Majorana Fermionic state\textsuperscript{14} is predicted to be excited at the interface of an s-wave-superconductor–TI hybrid structure.\textsuperscript{15,16}

Superconductor–topological insulator–superconductor (S–TI–S)-type Josephson coupling has recently been experimentally confirmed, based on Bi$_2$Se$_3$\textsuperscript{17–20} Bi$_2$Te$_3$\textsuperscript{21,22} strained HgTe\textsuperscript{23} and Bi$_2$Sb$_2$Te$_3$\textsuperscript{24} with a dissipationless supercurrent, which is revealed as the superconducting order of the two closely separated S electrodes spatially overlaps across the intervening TI layer. An S–TI hybrid structure is a key element for searching for the Majorana Fermionic state and realizing topologically robust conductive devices. Thus, it is essential to confirm the proximity coupling via the surface channels of a TI, which is separated from the bulk channels, as a step toward inducing a superconducting state in an S–TI hybrid structure. In previous studies of the Josephson effect in TIs, superconducting electrodes were often arranged on the top surface of a TI. The magnetic field modulation of the junction critical current (Fraunhofer diffraction pattern) exhibited features corresponding to a uniform Josephson current distribution along the width of a junction. In this case, the Fraunhofer pattern did not include the information on the Josephson coupling via the side surfaces of a TI, which depended most critically on the topological protection.

In our study, the side surfaces of a TI were also in contact with the S electrodes, which led to a highly persistent Fraunhofer-like pattern, with respect to increasing the magnetic field perpendicular to the top and bottom surfaces. The persistent character of the Fraunhofer-like modulations, corresponding to a Josephson current distribution that was uniform along the top surface and nonuniformly edge-stepped in the Al–TI–Al junction, indicated the existence of the Josephson current on the rough side surfaces as well as the top surface of the TI flake between two Al electrodes. This confirms that the Josephson coupling was confined in all the surface conducting channels, which have topologically protected robust characters. We also obtained Fraunhofer-like diffraction modulations of Josephson critical current across the Al–TI–Al junction and differential resistance across the Au–TI–Au junction in a nonlocal measurement configuration, where the bias current and potential were measured between the different sets of junctions. This “mirage” Fraunhofer signal in the nonlocal configurations provided additional confirmation of the robust surface Josephson coupling.

We first explain the scheme of monitoring the surface conduction separated from the bulk conduction in terms of the current flow in a hypothetical device shown in Figure 1. We assume that the device consists of a normal (N) conductor and...
four electrodes labeled A, B, C, and D shown with cross-sectional view, along with the probable current profile via the surface and the bulk. The cross-section is drawn through the middle of the N conductor along the x-axis, which corresponds to the dotted x1−x2 line in Figure 2a. Electrodes A and B are used as the source and drain, respectively, for biasing current $I_{AB}$ and the potential difference $V_{CD}$ is monitored between electrodes C and D. Figure 1a depicts the case in which the N material consists of conducting bulk, (b,c) insulating bulk, and conducting surface. The conducting surface in (c) is superconducting between the electrodes A and B. The arrows denote the current directions in the normal conductors. The cross-section between $x_1$ and $x_2$ corresponds to the dotted $x_1−x_2$ line in Figure 2a.

Figure 1. A false-colored schematic diagram of devices with nonlocal measurement configurations, where the electrodes A and B are used as a source and a drain, respectively, for the bias current $I_{AB}$ and the voltage difference $V_{CD}$ are monitored between electrodes C and D. The normal conductor of the device consists of (a) conducting bulk, (b,c) insulating bulk, and conducting surface. The conducting surface in (c) is superconducting between the electrodes A and B. The arrows denote the current directions in the normal conductors. The cross-section between $x_1$ and $x_2$ corresponds to the dotted $x_1−x_2$ line in Figure 2a.

The Josephson coupling occurs dominantly via the surface-conducting layer. One would not expect this nonlocal mirage to be the case of N, sandwiched between the two S electrodes A and B with finite bulk conduction because in this case the current $I_{AB}$ ($>I_{c}$) would mostly be confined between A and B as in Figure 1a. Only when the conductance in a TI is predominated by the surface conducting layer, the situation depicted in Figure 1c is expected.

A scanning electron micrograph of the actual device and its measurement configuration is shown in Figure 2a. The setup consisted of a 115 nm-thick BSTS crystal flake, overlaid with Al and Au electrodes. The BSTS flake, grown using the self-flux method, was mechanically exfoliated onto a Si substrate capped with a 300 nm thick SiO$_2$ layer. Details of the BSTS crystal growing are described elsewhere. The Au electrodes were deposited on the BSTS flake by combining electron*(e)-beam patterning, sequential e-gun evaporation of a Ti/Au (5 nm/350 nm thick and 400 nm wide) bilayer, and lift-off. Immediately prior to the Ti/Au deposition, the surface of the BSTS flake was Ar ion-beam cleaned for 20 s with a beam power of 4 W ($= 400$ V × 10 mA). The superconducting Al electrodes were prepared in a similar fashion as the Au electrodes, using a Ti/Al (5 nm/350 nm thick and 400 nm wide) bilayer in place of the Ti/Au bilayer. The thin Ti layers were added to create a good ohmic contact at the BSTS/Al and BSTS/Au interfaces. The electrical leads A, B, C, and D were the source and drain for current biasing the Al−BSTS−Al (Au-BSTS-Au) junction, obtained by numerically differentiating the $I_{AB}$ characteristics at different values of perpendicular magnetic field $B$, as a function of $B$ and $I_{AB}$, normalized by $I_{c}(0)$.

The differential resistance $dV_{AB}/dI_{AB}$ of the Al−BSTS−Al junction, measured using a scanning electron microscope.
the leads A1 and B1 (C1 and D1), which were equipotential with
the leads A2 and B2 (C2 and D2), respectively. The nonlocal
potential difference \( V_{D,C} \) was also measured to probe
the spatial distribution of \( I_{A,B} \) via the surface-conducting
channels of the BSTS flake. Josephson coupling was established
across the Al–BSTS–Al junction (between the leads A1 and B1), with a spacing of \( L_1 \approx 190 \text{ nm} \), at temperatures below the
critical temperature of Al electrodes. However, with a spacing of
\( \sim 1700 \text{ nm} \) between the leads B1 and C1, the proximity effect at
the Al–BSTS–Al junction did not induce Josephson coupling
at the Au–BSTS–Au junction between the leads C1 and D1,
with a spacing of \( \sim 1500 \text{ nm} \).

Electrical transport properties of the device were examined
by measuring dc (I–V characteristics) or ac (differential
resistance) values at bath temperatures between 10 mK and
300 K. The ac measurements were carried out using the
conventional lock-in technique at a frequency of 13.3 Hz and a
bias current of 10 nA root-mean-square (rms). Figure 2b shows
the current–voltage \( (I_{A,B}, V_{A,B}) \) characteristics of the Al–
BSTS–Al junction at a bath temperature of 10 mK, where the
arrows indicate the sweeping directions of the bias current \( I_{A,B} \).

At temperatures significantly below the critical temperature \( T_c \)
(\( \approx 750 \text{ mK} \)) of the Al electrodes, penetration of the
superconducting order into the BSTS surface conducting
layer was manifested by the presence of a clear supercurrent
branch for \( I_{A,B} \) up to \( I_{A,B}^{\ast} \) (\( \approx 110 \text{ nA} \)) in Figure 2b, above
which an abrupt switching occurred to a finite voltage
corresponding to the normal-state resistance of approximately
80 \( \Omega \). The superconducting phase coherence length \( \xi \) was
estimated to be 150 nm using the relation of \( (R_N - R_S)/R_N \sim
\xi/L_{B,C_1} \). Here, \( L_{B,C_1} (= 1.7 \mu \text{ m}) \) is the spacing between
centers of \( B_1 \) and \( C_1 \), and \( R_N/(R_S) \) is the resistance of \( L_{B,C_1} \) in the normal
(superconducting) state of Al electrodes. The hysteretic reverse
switching from the resistive to supercurrent state occurred at
\( I_{A,B}^{\ast} \) (\( < I_{A,B}^{\ast} \)), which is usually found in capacitively shunted
Josephson junctions.39,40 The geometrical estimate of the capacitance \( C_{geo} \),
in the Al–BSTS–Al junction was approximately \( \sim 100 \text{ fF} \) between the Al electrodes, and \( C_{geo} \) approximately \( \sim 370 \text{ fF} \) between the BSTS flake and the
electron-doped Si substrate. This indicates that the Al–BSTS–
Al junction was an overdamped Josephson junction with
sufficiently small shunting capacitance39 (see Supporting
Information 2). Thus, the observed hysteresis may have been
caused by the reduction of the retraction current associated
with the Joule heating of the carriers for the bias above the
junction critical current.41

Figure 2c shows the differential resistance \( dV_{A,B}/dI_{A,B} \) of the
Al–BSTS–Al junction, obtained by numerically differentiating
the \( I_{A,B}, V_{A,B} \) characteristics at different values of perpendicular
magnetic field \( B \), as a function of \( B \) and \( I_{A,B} \), normalized by
\( I_{A,B}^{\ast} \). The \( I_{A,B}, V_{A,B} \) characteristics were obtained while
swEEPing up the bias. The pattern is not symmetric between
the opposite bias polarities because of the hysteresis in the
\( I_{A,B}, V_{A,B} \) characteristics. In the magnetic field perpendicular
to the plane of the BSTS flake, the junction supercurrent shows
Fraunhofer-diffraction-type quasi-periodic variation with a
magnetic field period of \( \Delta B \approx 6.42 \text{ G} \). This resulted from the
superconducting proximity coupling across the Al–BSTS–
Al junction via the surface conducting channels of the BSTS
flake. Here, the effective penetration depth of the Al electrodes
\( \lambda \) was estimated to be about 210 nm, from the relation \( \Phi_0 = (L_1 + 2\lambda)W \Delta B \). \( \Phi_0 \approx 5.3 \mu \text{ m} \) is the width of the junction and \( \Phi_0 = h/(2e) \) is the magnetic flux quantum. This value of \( \lambda \) agreed with
the value in our previous report with Al–graphene–Al
Josephson junctions.42 In Figure 2c, the modulation of the
junction supercurrent is not reduced rapidly with \( B \) but persists
over many field periods of the envelope modulation almost up
to the superconducting critical field of the Al electrodes, \( B_c \) (\( \approx 130 \text{ G} \)). Notably, \( \lambda_{R,B} \) at the ninth lobe in the Fraunhofer-type
oscillations is strongly suppressed, the cause of which is not
well understood. The differential resistance \( dV_{A,B}/dI_{A,B} \) of the
Al–BSTS–Al junction, obtained alternatively by the lock-in
technique is shown in Supporting Information 3. The data,
having much lower fluctuations, show the behavior very similar
to those obtained by dc measurements in Figure 2c, but with
smeread boundary of the critical current. It resulted as
\( \Delta I_{A,B} \) \( (I_{A,B} = 0) \) reached a value less than the
lock-in modulation current \( I_{A,B} = 10 \text{ nA} \) (see Supporting
Information 3).

Figure 3. Fits of the observed junction critical current \( I_{A,B} \),
denoted by symbols, to Fraunhofer diffraction relation. Black symbols were extracted from the boundary of the pattern in Figure 2c. Critical currents with highly smeared boundary in Figure 2c, which are denoted by orange symbols, were determined by fitting the corresponding \( I_{A,B}, V_{A,B} \) curves to Ambegaokar-Halperin model.

Red and green curves are best fits using Josephson junction models with edge-stepped nonuniform and uniform supercurrent distributions, respectively. Upper panel of the inset: schematic cross-sectional view of superconducting Al electrodes overlaid on a BSTS flake. Lower panel of the inset: distribution of the supercurrent density \( J_{A,B} \) along the y axis. \( s_1 \) and \( s_2 \) are the thicknesses of the side and top layers of the BSTS surface, respectively. \( t \) (\( \approx 115 \text{ nm} \)) and \( W \) (\( \approx 5300 \text{ nm} \)) are the thickness and the width of the BSTS flake, respectively. Here, it is assumed that the bottom (light green) of the BSTS surface is in the normal state, the top and two sides of the BSTS surface (cyan) are superconducting, and the BSTS bulk (dark green) is insulating.

Figure 3 shows the normalized critical current \( I_{A,B}^{\ast} \), curve. Black symbols denote the reduced critical current, which were obtained from the boundary of the Fraunhofer pattern in Figure 2c, corresponding to a local maximum of a \( dV_{A,B}/dI_{A,B} \) curve. Critical currents with highly smeared boundary in Figure 2c, which are denoted by orange symbols, were determined by fitting the corresponding \( I_{A,B}^{\ast} \), curve.
$V_{A,B_i}$ curves to Ambegaokar–Halperin model.  The green (red) curve is the best fit to a Josephson-junction model of the Fraunhofer-type magnetic field dependence of the maximum Josephson current with uniform (edge-stepped nonuniform) supercurrent density distribution, where the variation of the critical current in proportion to the $B$-field-dependent superconducting gap, $\Delta(B)/\Delta(0) = [1 - (B/B_c)^2]^{1/2}$, is taken into account. A model of the nonuniform supercurrent density provides a far better fit to the observed data than that of a uniform supercurrent density. The equation $I_{A,B_i}(\Phi/\Phi_0) = I_{A,B_i}(0)[1 - (\Phi/\Phi_c)^2]^{1/2}[(\pi/\Phi_0)/(\pi/\Phi_c)]$ was used to calculate the fit of the uniform supercurrent density, where $\Phi$ is the magnetic flux threading the Al–BSTS–Al junction and $\Phi_c$ is the value corresponding to the critical field $B_c$. For the fits in Figure 3, $\Phi_0$ was set to be 6.42 G (5.95 G) for the red (green) curve.

With the Al electrodes taking on a superconducting state for $T < T_c$ all of the conducting surfaces of the BSTS flake were sandwiched between the two Al electrodes in the Al–BSTS–Al junction; that is, the top and two side surfaces of the BSTS flake, became superconducting as a result of proximity coupling, while the bulk and the bottom surface remained insulating and normal-conducting, respectively (see the upper panel of the inset). This produced an edge-stepped nonuniform supercurrent density $J_{A,B_i}$ along the $x$-direction, as schematically shown in the lower panel of the inset. The magnetic flux dependence of $I_{A,B_i}$ for the Josephson junction model with the edge-stepped $J_{A,B_i}(y)$ is given as (see Supporting Information 4)

\[
\frac{I_{A,B_i}(\Phi/\Phi_0)}{I_{A,B_i}(0)} \approx \left[1 - \frac{\Phi}{\Phi_c}\right]^2 \left(\frac{\pi}{\Phi_0} - \frac{2}{\sqrt{\pi}}\right) + \frac{1}{2} \left(\frac{\pi}{\Phi_0} - \frac{2}{\sqrt{\pi}}\right) \cos \left[\left(1 - \frac{s_1}{W}\right)\frac{\pi}{\Phi_0}\right]
\]

(1)

Here, $s_1$ and $s_2$ are the thickness of the side and top layers of the BSTS surface, respectively, and $t$ is the thickness of the BSTS flake.

In eq 1, for $s_1$, $s_2 \ll W$ as in this study, the $B$-field dependence of $I_{A,B_i}$ for an edge-stepped current distribution is mainly governed by the factor $(t/s_2) \times \left(s_1/W\right)$. For the fixed values of $t$ and $W$, it implies that the overall shape of the Fraunhofer pattern mainly depends on the ratio of $s_1/s_2$. Because of the factor $(1 - s_1/W)$ in the second cosinusoidal term, however, the detailed behavior of eq 1 in the high-$B$-field region close to $B_c$ is sensitive to the value of $s_1$ (or, equivalently $s_2$ for a fixed ratio of $s_1/s_2$) in comparison with $W$ as well (see Supporting Information Figures S5–S7). The fit of eq 1 to the observed $I_{A,B_i}(\Phi/\Phi_0)$ in Figure 3 is obtained for $s_1 = s_2 \approx 5.5$ and $s_2 = 1$ nm. The quality of the fit is retained as long as $s_2 < 5$ nm but noticeable degradation appears for $s_2 > 7$ nm or beyond as $B$ approaches $B_c$. This upper-limit value of 5 nm for $s_2$ is in good agreement with the previous report of 6 nm. The difference between $s_1$ and $s_2$ in our device may have resulted from the enhanced roughness of the side surfaces of the BSTS flake (see Supporting Information Figure S4). Because of the geometrical factor $2(\pi/s_2)(s_1/W) \approx 1/4$ in eq 1, the first sinusoidal term predominate for small $\Phi/\Phi_0$ ($\sim 1$), giving rise to the typical Fraunhofer-type variation of $I_{A,B_i}$. However, as the value of $\Phi/\Phi_0$ increases sufficiently beyond 1, the second cosinusoidal term predominate, which represents the typical $\cos(\pi\Phi/\Phi_0)$-type $B$-field modulation of the junction critical current similar to that of a superconducting quantum interference device (SQUID). The second term produces highly persistent field-modulation amplitude of $I_{A,B_i}$ for $B$ up to $B_c$ as seen in Figure 3. It is easy to deduce that the uniform supercurrent distribution inside the edge (inset of Figure 3) corresponds to the Fraunhofer-diffraction-type $I_{A,B_i}$ field modulation while the enhanced edge-stepped nonuniform supercurrent density corresponds to the SQUID-like behavior in eq 1.

The $B$-field modulation of the extracted junction critical current shown in Figure 3 agrees well with eq 1, both in its magnitude and field periodicity. In fact, the period of field modulation of the observed $I_{A,B_i}$ in Figure 3 is in the low field range is slightly smaller than that in the high field range, which agrees reasonably well with the combined variation with $B$ of the first and second terms in eq 1. By contrast, the observed field modulation of $I_{A,B_i}$ is not in phase with the ordinary Fraunhofer behavior with a fixed field periodicity for a uniform current distribution (see Supporting Information 5 for more discussion). The good fit of both the magnitude and the periodicity of $I_{A,B_i}$ to eq 1 up to $B_c$ strongly indicates the edge-stepped nonuniform current distribution. This provides clear confirmation of a supercurrent through topologically robust conducting channels of the BSTS TI surface, including the side surfaces.

The existence of the topologically protected conducting surface of the BSTS flake was also evidenced by the nonlocal measurements corresponding to the illustrations in Figures 1b and 1c. Figure 4a shows $V_{D,C_i}$ as a function of $I_{A,B_i}$ and $B$, which is the rms modulation voltage corresponding to $i_{A,B_i,D,C_i}$. Here, $i_{A,B_i,D,C_i} = \frac{\Phi_0}{2\pi} \frac{B_c}{B_B} \frac{\Phi_0}{\Phi_c} \frac{\Phi}{\Phi_0}$ is the fraction of the modulation current $i_{A,B_i}$ ($\approx 10$ nA) flowing between $D_1$ and $C_1$, when $i_{A,B_i}$ is applied between $A_1$ and $B_1$ in combination with the dc bias current $I_{A,B_i}$. Figure 4a mimics Figure 2c as $V_{D,C_i}$ is sensitive to changes in the spatial distribution of $I_{A,B_i}$ via the BSTS TI surface. $V_{D,C_i}$ vanished for a supercurrent flow ($I_{A,B_i} < I_{A,B_i,D,C_i}$) through the Al–BSTS–Al junction. For $I_{A,B_i} > I_{A,B_i,D,C_i}$, however, $V_{D,C_i}$ gave a finite value corresponding to $i_{A,B_i,D,C_i} \times R_{D,C,j} = R_{D,C,j}$ ($= 660 \Omega$) is the resistance across the region. We obtained the result $i_{A,B_i,D,C_i} = 0.003 \times i_{A,B_i}$ (see Supporting Information 6). The reverse process was also valid with the relation $i_{C_i,D,C_i,A_i} = 0.023 \times i_{C_i,D,C_i}$, where $i_{C_i,D,C_i,A_i}$ is the fraction of $i_{C_i,D_i} (=100$ nA) flowing between $B_1$ and $A_1$ (see Supporting Information 6). $V_{R,A_i}$ was also sensitive to change in the
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(Figure 4a) Nonlocal modulation voltage $v_{D,C}$ corresponding to $i_{A,B,D,C}$ as a function of the bias current $I_{A,B}$ applied between $A_1$ and $B_1$, and magnetic field $B$. $i_{A,B,D,C}$ is the fraction of the modulation current $I_{A,B}$ flowing between $D_1$ and $C_1$; $v_{D,C}$ exhibits Fraunhofer-type variations. The blue-colored (red-colored) inside (outside) region of the pattern denotes the pair-conducting (resistive) state of the Al–BSTS–Al junction. (b) Nonlocal modulation voltage $v_{B,A}$ corresponding to $i_{C,D,B,A}$ as a function of the bias current $I_{C,D}$ applied between $C_1$ and $D_1$ and magnetic field $B$. $i_{C,D,B,A}$ is the fraction of $I_{C,D}$ ($= 100 \text{nA}$) flowing between $B_1$ and $A_1$. $v_{B,A}$ also exhibits Fraunhofer-type variations. Temperature increase due to Joule heating altered the shape of the primary peak of $v_{B,A}$ around $B = 0$.

distribution of the bias current $I_{C,D}$ via the BSTS TI surface.
$v_{B,A}$ vanished if $I_{C,D,B,A} < I_{B,A}^{*}$. For $I_{C,D,B,A} < I_{B,A}^{*}$, $v_{B,A}$ became $I_{C,D,B,A} \times R_{B,A}$ as shown in Figure 4b, where $R_{B,A} = 80 \Omega$ was the normal-state resistance between $B_1$ and $A_1$. The appearance of this nonlocal feature indicates the existence of a topologically protected conducting surface on our BSTS flake$^{25}$ with Josephson coupling across it.

The primary lobe of $v_{B,A}$ in Figure 4b exhibits a typical Fraunhofer-type modulation but differs from that of $v_{D,C}$, as shown in Figure 4a; the differential resistance is highly enhanced along the edge of the critical current. This difference resulted from the temperature increase due to Joule heating generated by the bias current $I_{C,D}$ ($\simeq 43 I_{B,A}$). $I_{C,D}$ is $\simeq 3 \mu \text{A}$ in Figure 4b, which corresponds to $I_{B,A} \simeq 70 \text{nA}$. The Joule heating due to $I_{C,D}$ was transferred to the BSTS flake between $B_1$ and $A_1$ with the carrier temperature in the BSTS flake reaching a temperature of $\sim 115 \text{mK}$ (see Supporting Information 7). The value of $I_{B,A}$ ($\simeq 70 \text{nA}$) was suppressed below $110 \text{nA}$ at $T = 10 \text{mK}$ (without Joule heating) as the carrier temperature rose to $115 \text{mK}$ due to Joule heating, which led to the condition $\Delta I_{B,A}(0) < I_{B,A}$, so that enhancement of the differential resistance at the edge of the critical current occurred, as discussed in Supporting Information 3 in association with Supporting Information Figure S3.

Fraunhofer modulation has been reported over an extended volume in Bi$_2$Se$_3$ from the Pb–Bi$_2$Se$_3$ interface by the proximity effect.$^{19}$ The same group has also reported a strong superconducting proximity effect between Pb and Bi$_2$Te$_3$ established along the thickness direction of the Bi$_2$Te$_3$ flake. These observations were interpreted in terms of a widely extended proximity effect, including the bulk of the flakes.$^{22}$ Because the bulk transport can be substantial in these materials, this interpretation is plausible. However, considering that the extremely extended Josephson coupling in these reports is not well understood, the nonlocal effect we report here may have been involved in the observation.

In summary, we demonstrated a surface-dominant Josephson effect in S–TI–S junctions. This constitutes a direct and unequivocal confirmation of the existence of a dominant surface conduction in BSTS TI flakes$^{28}$ and Josephson coupling confined to the surface conducting channels when the TI flake are in proximity to superconductors. The magnetic field modulations of the supercurrent of the Al–BSTS–Al junction remained up to the superconducting critical field of the Al electrodes. A voltage in part of the TI outside the Al–BSTS–Al junction was nonlocally triggered along with modulations of the junction supercurrent. The voltage across the Al–BSTS–Al junction was also modulated by the nonlocal bias current at the Au–BSTS–Au junction. This mirage Fraunhofer effect can be explained only in terms of the existence of robust surface conducting channels, which extend to the sides of the TI. The local and nonlocal Fraunhofer diffraction-type modulation of the junction critical current and differential resistance with persistent field modulation of the envelope shows nice fits to the model of a edge-stepped nonuniform supercurrent density on the rough side surfaces of the BSTS flakes. This strongly suggests that the Josephson coupling in a TI is established through the surface conducting channels that are topologically protected. This study provides a unique method for confirming Josephson coupling via the topological surface conducting channels, which in turn provides a solid basis for exploring Majorana Fermionic excitation states by adopting TI/superconductor heterostructures.

### ASSOCIATED CONTENT

#### Supporting Information

Normal-state properties of the BSTS crystalline flake, overdamped characteristics of the Josephson junction, differential resistance of the Al–BSTS–Al junction by ac measurements, Fraunhofer interference pattern for a nonuniform supercurrent density, fits to the uniform-current Fraunhofer diffraction for different field periodicity, estimation of the nonlocal current, and suppression of $I_c$ due to bias-induced Joule heating. This material is available free of charge via the Internet at http://pubs.acs.org.

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**Notes**

The authors declare no competing financial interest.

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