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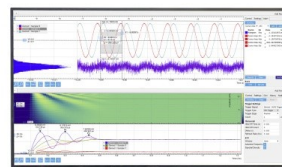
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ABSTRACT

We have used Bi₂Se₃ nanoribbons, grown by catalyst-free physical vapor deposition to fabricate high quality Josephson junctions with Al superconducting electrodes. In our devices, we observe a pronounced reduction of the Josephson critical current density J_c by reducing the width of the junction, which in our case corresponds to the width of the nanoribbon. Because the topological surface states extend over the entire circumference of the nanoribbon, the superconducting transport associated with them is carried by modes on both the top and bottom surfaces of the nanoribbon. We show that the J_c reduction as a function of the nanoribbon width can be accounted for by assuming that only the modes traveling on the top surface contribute to the Josephson transport as we derive by geometrical consideration. This finding is of great relevance for topological quantum circuitry schemes since it indicates that the Josephson current is mainly carried by the topological surface states.

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I. INTRODUCTION

The study of the proximity effect between a superconductor and a semiconductor or an unconventional metal has lately received a dramatic boost due to the increasing possibilities to manufacture a larger variety of interfaces and materials. Novel phenomenology of the proximity effect is currently coming from the integration of semiconducting nanowires, with strong spin-orbit coupling, as barriers, as well as the edge and surface states of two-dimensional (2D) and three-dimensional (3D) Topological Insulators (TIs)^{1–5} and Dirac semimetals.^{6,7} In these cases, the Josephson transport properties of the hybrid devices will manifest neat fingerprints related to the formation of Majorana bound

states, which is of great interest for topological quantum computation.^{8–10} Lately, superconductor–TI–superconductor Josephson junctions with 2D and 3D TIs have shown a 4π periodic Josephson current phase relations,^{11–14} which could be associated with the presence of Majorana modes¹⁵ and gate-tunable Josephson effects^{2,16–19} when the TI is tuned through the TI's Dirac point. Still several aspects of the physics of the Josephson effect related to the topological protected edge/surface states and the contribution of the unavoidable bulk remain to be clarified. In this respect, the use of 3D TI nanoribbons could be advantageous because of the reduced number of transport channels involved in the transport. Here, the transport is ruled by the quantization of

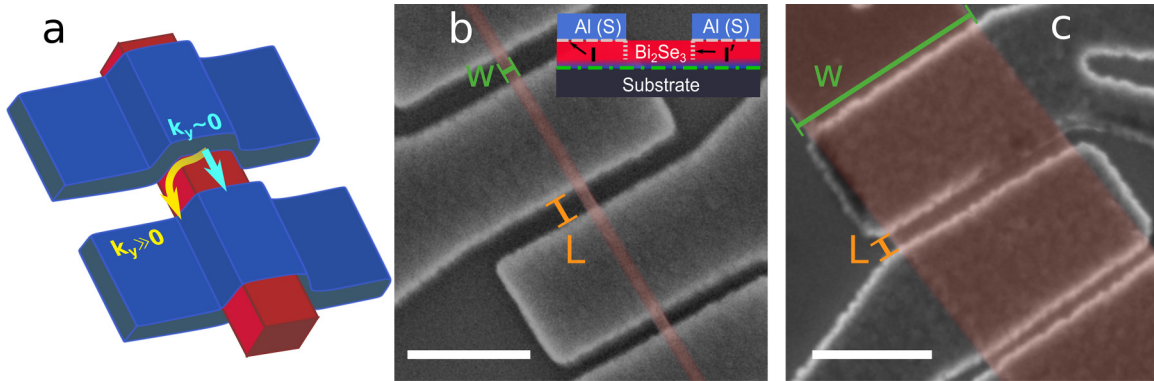


FIG. 1. (a) Schematics of a Bi_2Se_3 nanoribbon Josephson junction. Arrows indicate transport modes carrying supercurrent by the topological surface states at the nanoribbon top surface ($k_y \sim 0$) and around the perimeter ($k_y \gg 0$). (b) and (c) Partly colored SEM images of the fabricated Josephson junctions of Bi_2Se_3 nanoribbons with different widths W . L indicates the length of a junction. The scale bar is 500 nm. The inset in panel (b) is a schematic cross section of a junction, and the dotted-dashed green line highlights the location of a trivial 2DEG.²⁰

the nanoribbon's propagation modes, which could give new hints about the Josephson phenomenology associated with the Topological Surface States (TSSs).

In this work, we have fabricated Josephson junctions by using Bi_2Se_3 Topological Insulator Nanoribbons (TINRs) with widths spanning from 50 nm to almost a micron. Because the TSSs extend over the entire circumference of the TINR, the superconducting transport associated with them is carried by modes on both the top and bottom surface of the nanoribbon. As shown in Fig. 1(a), in our TINR Josephson junction, the current flows between the superconducting contacts fabricated on the top surface of the nanoribbon. For the TINR with a circumference of $C = 2W + 2t$ (where W is the width and t the thickness of the nanoribbon), the transverse momentum k_y , perpendicular to the current (see Fig. 1), is quantized as

$$k_y = 2\pi(n + 1/2)/C, \quad (1)$$

where n is an integer.²¹ Therefore, the modes with $k_y \sim 0$ remain on the top surface, while the modes with $k_y \gg 0$ are winding around the perimeter of the TINR [see Fig. 1(a)]. Here, we show that the value of the Josephson current density strongly depends on the junction width, which in our case corresponds to the width of the nanoribbons [Fig. 1(a)]. We discuss the possible origin of this phenomenology also in connection with the fact that only small k_y value modes are involved in the Josephson transport, which are the ones that travel on the top surface of the nanoribbon. This number reduces by reducing the nanoribbon width [see Eq. (1)]. This finding is of great relevance since it indicates that (a) the Josephson current is mainly carried by the surface states and (b) because of the selectivity in k_y , the number of modes involved in the transport scales much faster compared to the width. This is of great relevance for topological quantum circuitry schemes.

II. EXPERIMENTAL DETAILS AND RESULTS

Nanoribbons of Bi_2Se_3 with a variation of widths from ~ 50 nm to about $1 \mu\text{m}$ were grown as reported in Ref. 22. For the fabrication of Josephson junctions, nanoribbons were transferred to pre-patterned substrates of Si/300 nm SiO_2 and SrTiO_3 (STO). We used two different TINR growth batches for the two substrates, respectively. For the two batches, the carrier densities of the topological surface states measured through Shubnikov-de Haas oscillations varied by a factor of 2.²² A standard process of electron beam lithography was used, followed by the evaporation of 3 and 80 nm thick layers of Pt and Al, respectively. Before the evaporation of the metals, the samples were etched for 30 s by Ar ion milling to remove the native oxide layer of the nanoribbons. SEM images of the fabricated Al/ Bi_2Se_3 /Al Josephson junctions for different nanoribbon widths are shown in Figs. 1(b) and 1(c). The Pt interlayer between the Bi_2Se_3 and Al has an important role in the formation of a transparent interface, as it was shown in our previous works.^{3,23,24}

Junctions were measured at a base temperature of 19 mK in an *rf*-filtered dilution refrigerator. The planar Josephson junction can be described as $\text{SIS}'\text{I}'\text{N} - \text{I}'\text{S}'\text{IS}$. Here, S' is the proximized TINR that lies underneath the superconductor (S)—Al, and N represents the not-covered TINR part between the two Al electrodes [see schematics in the inset of Fig. 1(b)]. I is the interface of the barrier between the Al and the Bi_2Se_3 nanoribbon, while I' represents the barrier interface formed between the Bi_2Se_3 under the Al and the Bi_2Se_3 of the normal metal region N (nanogap). We have previously demonstrated that both I and I' are highly transparent^{3,23} and that we have full control of the strength and phenomenology of the proximity effect. When the voltage drop across the Al/ Bi_2Se_3 interface is negligible, compared to that across the TI in the nanogap, as in our case,²⁵ the physics of the planar junction is effectively that of a $\text{S}'\text{I}'\text{N} - \text{I}'\text{S}'$.

A typical current-voltage characteristic (IVC) of one of the TINR based Josephson junctions is shown in Fig. 2(a). The IVCs of

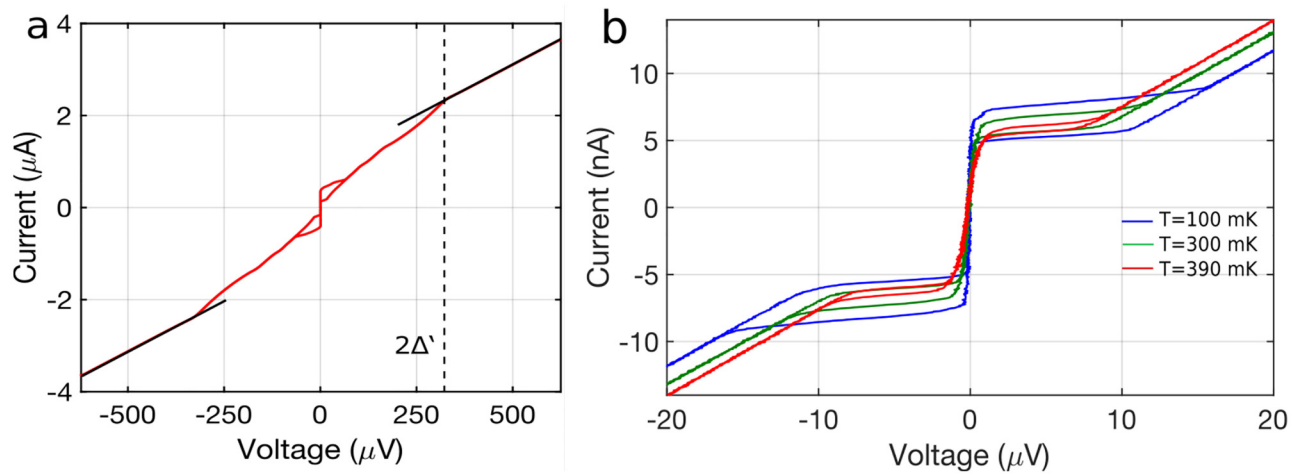


FIG. 2. (a) Current-voltage characteristic of a Bi_2Se_3 nanoribbon junction ($I_c = 0.36 \mu\text{A}$, $L = 70 \text{ nm}$, $t = 16 \text{ nm}$, $W = 430 \text{ nm}$) measured at $T = 20 \text{ mK}$. The solid black lines are linear fits of the IVC at high bias voltages. The departure from linearity observed at $V = 340 \mu\text{V}$ corresponds to twice the induced gap, with gap $\Delta' = 170 \mu\text{V}$ (see the dashed line). (b) Low bias current-voltage characteristics at various temperatures $T = 100, 300$, and 390 mK of a Bi_2Se_3 nanoribbon junction ($I_c = 10 \text{ nA}$, $L = 70 \text{ nm}$, $t = 13 \text{ nm}$, $W = 60 \text{ nm}$). The hysteretic current-voltage characteristics develop a finite resistance in the superconducting branch for increasing temperature.

our junctions have a hysteresis that points to an increased electron temperature as the junction is switched to the resistive state.²⁶ A clear gap structure is seen at $2\Delta'$ (where Δ' is the induced gap of the order of $170 \mu\text{V}$); several bumps in the IVC at $2\Delta'/n$ are also visible: as we have previously demonstrated they are connected to multiple Andreev reflections that are made possible by the high transparency of the I and I' barriers.²³ The IVCs measured at various temperatures are shown in Fig. 2(b). At higher temperatures, we observe a finite resistance in the supercurrent branch. This could be attributed to premature switching and consecutive retrapping of the superconducting phase difference.^{27–30} The so-called phase diffusion regime is characteristic for a moderate to low quality factor Josephson junction. The quality factor can be estimated using $Q = \omega_p RC$, with the plasma frequency $\omega_p = \sqrt{2\pi I_c / \Phi_0 C}$, where $\Phi_0 = h/2e$ is the superconductive flux quantum, and $R \approx 100 \Omega$ is the real part of the shunting admittance of a dc biased Josephson junction.^{31,32} Here, the capacitance is dominated by the shunting capacitance through the substrate. For STO with a relative dielectric constant of 25 000 at low temperatures, we approximate $C \approx 1 \text{ pF}$ resulting in a quality factor smaller than one for junctions having a critical current lower than 50 nA. Alternatively, for the Si/SiO₂ substrate, it is more difficult to estimate the shunting capacitance due to the conducting substrate. However, we expect a much smaller capacitance value resulting in quality factors smaller than one for critical currents already below 500 nA.

The value of the critical current of the junction I_c is obtained from the forward scan, and the critical current density J_c is calculated accordingly by dividing I_c by the width of the nanoribbon (W). The normal state resistance R_N is determined by the inverse of the slope, calculated from the IVC region at voltages above $2\Delta'$ in S' (represented by the area of Bi_2Se_3 underneath the Al).

Figures 3(a) and 3(b) show the dependence of the J_c as a function of the W for devices with different lengths L fabricated on Si/SiO₂ and STO substrates, respectively. In Fig. 3(b), we have included a $10 \mu\text{m}$ wide junction where the Al electrodes are patterned along the length of TINR; for this device, no winding modes are expected to contribute to the Josephson transport. One

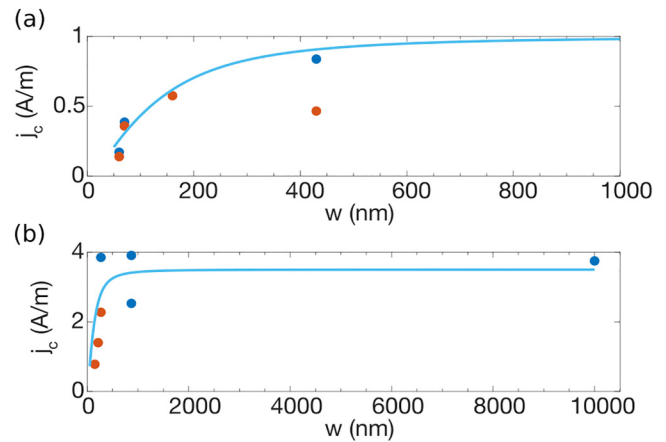


FIG. 3. (a) Critical current density as a function of TINR width for Josephson junction devices realized from the same growth batch on a Si/SiO₂ substrate. (b) Critical current density as a function of TINR width for Josephson junctions realized from a second growth batch [different from those shown in panel (a)] on a SrTiO₃ substrate. All measurements were performed at $T = 20 \text{ mK}$. The blue and red dots are for junction lengths of 50–80 nm and 100–110 nm, respectively.

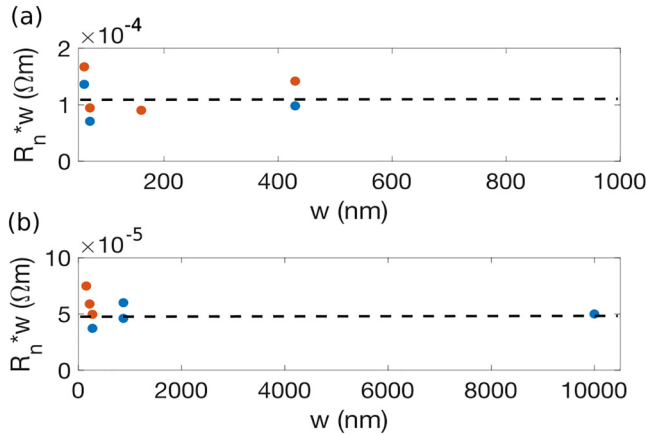


FIG. 4. (a) Specific resistance as a function of TINR width for Josephson junction devices realized from the same growth batch on a Si/SiO₂ substrate. (b) Specific resistance as a function of TINR width for Josephson junctions realized from a second growth batch [different from those shown in panel (a)] on a SrTiO₃ substrate. All measurements were performed at $T = 20$ mK. The blue and red dots are for junction lengths of 50–80 nm and 100–110 nm, respectively.

clearly sees that if the length is fixed, the J_c sharply decreases as a function of the width W of the nanoribbon. We note that the value of J_c can change by a factor of 5–6 by going from the narrowest nanoribbons of 60 nm to the widest ones. In contrast, as shown in Figs. 4(a) and 4(b), the specific resistance, obtained by considering the product $R_N \times (W)$ for the devices on the Si/SiO₂ and STO substrate, respectively, is almost independent of W . This fact allows one to exclude that the reduction of the J_c at small widths W has its origin in strong modifications/deterioration of the junction specific resistance for narrow TINR.

III. DISCUSSION AND CONCLUSIONS

What is the origin of this peculiar $J_c(W)$ phenomenology? As we have discussed earlier, the explanation of the phenomenon can have its ground in the quantization of the nanoribbon's propagation modes. One can derive that the relative number of modes n_{top}/n_{tot} traveling only on the top surface reduces with the junction width for a fixed junction length L . Here, n_{tot} is the total number of modes,

$$n_{tot} = k_F C / 2\pi - 1/2, \quad (2)$$

and n_{top} is the number of modes traveling only on the top surface of the nanoribbon,

$$n_{top} = k_F C W / 4\pi L ((W/2L)^2 + 1)^{-1/2} - 1/2. \quad (3)$$

The relations above can be obtained from geometric considerations; see Fig. 5(a). Here, k_F is the Fermi vector.

In Fig. 5(b), we show the width dependence of the relative number of modes n_{top}/n_{tot} for three different junction lengths.

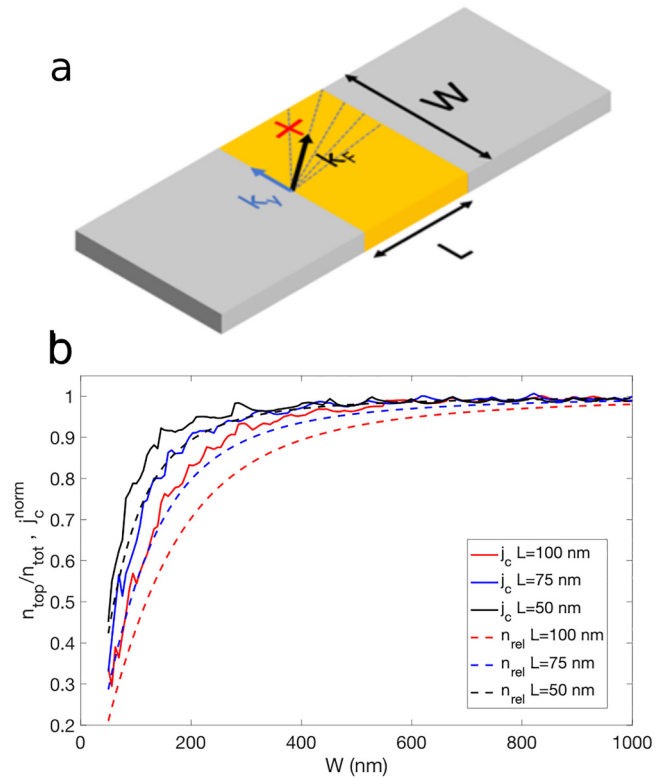


FIG. 5. (a) Sketch of a planar TI junction with electrode separation L and width W . The dashed lines indicate quasiparticle trajectories. The maximum transversal momentum for which the transport mode still propagates only on the top surface is indicated by k_y . For larger transversal momentum, the quasiparticle trajectory has to wind around the TINR and does not contribute to the critical current (red cross). (b) Relative number of transport modes $n_{rel} = n_{top}/n_{tot}$ propagating only on the top surface (dashed lines) and the corresponding normalized critical current density (solid lines) as a function of junction width for three different junction lengths.

The curves of Fig. 5(b) have been obtained by considering $k_F = 0.55 \text{ nm}^{-1}$, a value that is typical for our nanoribbons.²⁰ For $L = 100$ nm, we obtain a reduction of the relative number of modes traveling only on the top surface by a factor of 5 when reducing the junction width from 900 nm to 50 nm.

For comparison in Fig. 5, we also show the full calculation of the supercurrent density following Ref. 7 taking into consideration also the angle dependence of the transmission coefficients of each transport mode traveling only on the top surface. We see that the full calculation of J_c and the relative number of transport modes using Eqs. (2) and (3) give the same qualitative behavior.

This dependency qualitatively reproduces the measured J_c vs width dependence shown in Figs. 3(a) and 3(b). Indeed, the solid lines represent the relative number of transport modes for $L = 100$ nm. This suggests that only the modes traveling on the top surface contribute to the Josephson current. We note that the critical current density of the $10 \mu\text{m}$ wide device is in agreement with

the saturation value of the expected current density, where the contribution of winding modes to the total Josephson current is negligible.

A possible explanation for this finding could be related to the lower mobility of the Dirac states at the interface between the TINR and the substrate. Indeed, our magnetotransport measurements have shown the formation of a trivial 2D gas at the interface with the substrate overlapping with the Dirac states at the nanoribbon bottom [see the inset of Fig. 1(b)].²⁰ This interaction, which leads to a lower mobility (diffusive transport regime) of the Dirac states, might be responsible for the transport modes winding around the nanoribbon (high k_y modes) contributing less to the Josephson transport. Although we cannot exclude that the transport through the trivial 2D gas contributes to the Josephson current, it would only cause a constant offset of the J_C values without affecting the overall width dependence. We observe that the overall values of J_C for the devices on the STO substrate are higher than those on Si/SiO₂. This can be partially attributed to the larger values of the top surface Dirac carrier density of the batch used to realize the devices on the STO substrate. The larger value of the trivial 2D carrier density we typically observe in devices fabricated on STO substrates³³ could be further responsible for the difference observed in the critical current densities between devices on STO and Si/SiO₂ substrates.

To conclude, we have fabricated high transparency 3D TINR Josephson junctions showing a peculiar phenomenology that can be associated with the transport through the topological surface states. This is a step forward toward the study of topological superconductivity in a few mode devices instrumental for topological quantum computation.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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