Quantized critical supercurrent in SrTiO₃-based quantum point contacts

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Superconductivity in SrTiO₃ occurs at remarkably low carrier densities and therefore, unlike conventional superconductors, can be controlled by electrostatic gates. Here, we demonstrate nanoscale weak links connecting superconducting leads, all within a single material, SrTiO₃. Ionic liquid gating accumulates carriers in the leads, and local electrostatic gates are tuned to open the weak link. These devices behave as superconducting quantum point contacts with a quantized critical supercurrent. This is a milestone toward establishing SrTiO₃ as a single-material platform for mesoscopic superconducting transport experiments that also intrinsically contains the necessary ingredients to engineer topological superconductivity.

INTRODUCTION

Conductance quantization in ballistic quantum point contacts (QPCs) is a notable example of departure from the classical Drude picture of electrical conductivity set by the rate of charge carrier scattering (J). When a constriction between two electron reservoirs is sufficiently narrow and disorder free, its conductance becomes quantized according to the number of occupied modes: discrete transverse momenta allowed within the constriction’s confinement potential. Each mode contributes a conductance quantum $G = 2e^2/h$ (spin-degenerate case), a value that does not depend on the exact geometry of the device.

A related phenomenon is expected to arise in a constriction between two superconducting reservoirs (2, 3), i.e., a superconducting QPC (SQPC). Again, the transverse momentum spectrum becomes discretized under the constriction confinement potential. The supercurrent carried by each mode is determined by the Andreev bound state (ABS) spectrum, which is typically a function of constriction geometry. SQPCs are thus characterized by quantized critical supercurrent $I_c$ with a nonuniversal step height $\delta I_c$. However, in the limit of a short junction length, only one ABS per ballistic mode remains, and the current carried by each mode can reach a maximum value $\delta I_c = e\Delta/h$. This ideal step height is again geometry independent and scales only with the superconducting gap $\Delta$.

The widespread route for fabricating gate-tunable superconducting weak links has been to combine two optimal components in a hybrid system: a clean semiconductor (typically a III-V semiconductor or Ge) and metallic superconducting leads (e.g., Nb and Al). These hybrid systems have been successfully used to demonstrate quantized critical supercurrent, but with quantization step heights far below $e\Delta/h$ (4–9). The two major challenges for reaching the universal limit for quantized supercurrent are the geometric requirement that the distance between superconducting leads be much less than the superconducting coherence length $\xi$ and the need for near-perfect semiconductor/superconductor contact transparency (3). Achieving the latter in hybrid semiconductor-superconductor systems has been a major materials science challenge that has required deployment of in situ heteroepitaxial growth techniques (10).

An alternate route taken in this work is to form both leads and constriction in a single electrostatically tunable superconducting material, such as SrTiO₃ (STO). Working within a single-material platform is attractive for fabricating SQPCs, as the superconductor/normal metal (SN) boundary can be purely electronic (no structural discontinuity) and thus potentially highly transparent.

One of STO’s remarkable aspects is superconductivity in the extremely dilute charge carrier density limit (11, 12). In two-dimensional (2D) electron systems (2DESs) at the surface of STO, such as LaAlO₃ (LAO)/STO, LaTiO₃/STO, and ionic liquid–gated STO, superconductivity occurs in the range of 0.01 electrons per unit cell (13, 14). Consequently, one can electrostatically control the transition between superconductor, normal metal, and insulator in this material. On the macroscopic scale, this control is well established using back gating through the STO substrate, top gating through a dielectric layer, and ionic liquid gating (13–18).

More recently, several approaches have emerged for nanoscale patterning of conduction in LAO/STO, leading to demonstration of quantization effects in normal state, but, so far, not in superconducting transport. Realization of a conventional split-gate QPC geometry in LAO/STO is challenging as it involves depleting and/or accumulating charge densities of at least $\approx 10^{13}$ cm$^{-2}$, close to the limit of conventional dielectrics. Spatial inhomogeneity and relatively short mean free paths in these 2DESs present another challenge, leading patterned constrictions to often be dominated by tunneling through accidental quantum dots (19–21). A QPC with normal state but not superconducting conductance quantization has recently been demonstrated in underdoped, nonsuperconducting LAO/STO (22). In (21), a constriction defined by split gates with normal state conductance about half of a single spin–degenerate ballistic mode was estimated to have corresponding partially transmitting single-mode supercurrent, although it did not show direct effects of quantization. A different technique is to write conductive channels on LAO/STO with voltage–biased atomic force microscope (AFM) tips. This method enabled demonstration of quantum wires and dots coupled by tunnel barriers to superconducting leads, with quantized normal-state transport and indirect signatures of electron pairing (23–26) but not superconductivity.

In this work, we demonstrate quantized supercurrent in QPCs in a split-gate geometry based on ionic liquid–gated STO. We observe
a discretized step structure in the critical current, with tuning from zero to three ballistic modes. Step height per mode $\delta I_c$ is only three to five times smaller than the canonical value $e^2/h$, as close to ideal as achieved in any hybrid system (6). The fabrication process of our devices is enabled by the fine patterning of local electrostatic gates using liftoff of metal and atomic layer–deposited Hafnia ($\text{HfO}_2$) with a feature size close to 40 nm. This is distinct from the approaches taken in previous works on LAO/STO weak links (20–22, 27–29). Notably, we avoid an epitaxial growth step at high temperature, which complicates the workflow for patterning and potentially introduces disorder [see, e.g., (30, 31)]. We thus consider this fabrication technique an attractive alternative for further development of STO as a platform for mesoscale superconducting devices.

**RESULTS**

Our devices are 20-μm-wide Hall bars covered by ionic liquid, which is polarized to accumulate a 2D carrier density at any exposed STO surface. The coarse contours of the Hall bar are defined by patterning an insulating SiO$_2$ layer, which separates the surface of undoped STO from the ionic liquid (Fig. 1, A and B); underneath the SiO$_2$, the STO surface remains insulating, while the carrier density in the Hall bar region is tuned into the superconducting regime. Split gates with thin, self-aligned HfO$_2$ dielectrics define 40-nm-wide constrictions (Fig. 1C) between neighboring superconducting reservoirs. The design includes five or six ohmic contacts on each side of the split gates (Fig. 1B) to enable four-terminal measurements of both the constriction and the adjacent superconducting leads.

The carrier density profile is electrostatically defined by voltages on four gates, as illustrated in Fig. 1A: a large coplanar gate that controls the polarization of the ionic liquid (V$_{\text{GIL}}$), a back gate (V$_{\text{BG}}$) and two split gates (V$_{\text{G1}}$ and V$_{\text{G2}}$, denoted as V$_{\text{G12}}$ for the case V$_{\text{G1}}$ = V$_{\text{G2}}$). V$_{\text{GIL}}$ and V$_{\text{BG}}$ are “global” gates that tune the carrier density and vertical confinement in both the 2DES leads and the constriction. V$_{\text{G12}}$ is a “local” gate that only tunes carrier density and lateral confinement in the constriction. V$_{\text{GIL}}$ is set when the device is near room temperature and maintained as the sample is cooled below the freezing temperature of the ionic liquid (220 K). V$_{\text{GIL}}$ is used to polarize a drop of ionic liquid that covers both the coplanar gate electrode and the device. At lower temperatures, the polarization of the ionic liquid is frozen in. V$_{\text{GIL}}$ is the primary control knob for the carrier density in the leads, which can be tuned from $\approx 5 \times 10^{12}$ to $10^{14}$ cm$^{-2}$ (32, 33). The superconducting transition temperature as a function of density has a maximum near $3 \times 10^{13}$ cm$^{-2}$ (see section S3). The main results presented here will focus on this nearly optimally doped state obtained by cooling the device under $V_{\text{GIL}} = +3$ V. For additional data on the second constriction on the right side of the Hall bar in Fig. 1B, different devices, and cooldowns with carrier density tuned across a larger range, see sections S2 to S6.

The voltage V$_{\text{BG}}$ on a back gate contacting the bottom of the STO crystal provides additional global tuning of the 2DES at base temperature, primarily by modulating the depth of the 2DES. For

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**Fig. 1. Electrostatically defined constriction in superconducting SrTiO$_3**

(A) Schematic cross section of the device and illustration of the gate voltage definitions. (B) Confocal laser microscope image of the Hall bar region of the device and illustration of the measurement scheme. The dashed arrow indicates the location of the cross section in (A). (C) Scanning electron microscope image of the constriction region on a reference device. (D) Superconducting transition in the constriction and lead resistance. “Right” and “Left” refer to measurement of $V_{\text{ACmax}}$ on both sides of the constriction. (E) Constriction conductance map with temperature and split gate voltage. (F) Constriction conductance map with magnetic field and local gate voltage. Symbols in (F) indicate the selected gate voltage values for which line cuts in field are shown in (G). Lead resistance at extremes of $V_{\text{G12}}$ is also shown in (G) to illustrate the independence of local gate voltage. The top axis shows the mapping from critical field $B_c$ (red circles) to the coherence length. The estimated $\xi$ is shown in (C) for comparison with device dimensions, along with the mean free path from Hall measurements in the leads (see section S4). In (D) to (G), $V_{\text{GIL}} = 3$ V and $V_{\text{BG}} = 50$ V.
most experiments on this device, we set $V_{BG} = +50$ V to pull the electron density farther away from surface disorder [see (34) and section S4].

Figure 1D shows the superconducting transition $T_c$ measured by sourcing a small AC excitation through a constriction at $V_{G12} = +3$ V and $V_{BG} = +50$ V. In the following, constriction resistance and conductance will be denoted as $R = dV_{AC}/dI_{DC}$ and $G = 1/R$ and the resistances of the leads as $R_{lead} = dV_{lead}/dI_{AC}$ (see Fig. 1B and Materials and Methods for more details). On both sides of the constriction, $R_{lead}$ shows a sharp transition near 350 mK. This is near the optimal $T_c$ value for 2D STO (14, 17). The measured Hall density of $3.05 \times 10^{13}$ cm$^{-2}$ and the slight increase of $T_c$ by 20 mK upon removing the back-gate voltage suggest that this device state is slightly on the overdoped side of the superconducting dome (see section S4).

The constriction resistance $R$ also starts decreasing near the lead $T_c$, but its transition to zero resistance (within accuracy of our measurement) is significantly broader than that of the leads. Decreasing $V_{G12}$ suppresses both the zero resistance state and the normal state conductance and eventually pinches off the weak link (Fig. 1, E and F). At base temperature, superconductivity can also be suppressed by a perpendicular magnetic field (Fig. 1F). Using $\xi \approx \Phi_0/(2\pi R_c)$ (35), with $\Phi_0 = h/2e$ being the flux quantum, the critical field $B_c = 130$ to 140 mT in the constriction yields an estimated coherence length of $\xi = 50$ nm (43 nm in the leads). This estimate is consistent with the dirty-limit Bardeen-Cooper-Schrieffer superconductor picture (36, 37) in which the coherence length is set by the mean free path $L_{MF}$. From Hall measurements on the leads, we extract a Hall mobility $\mu = 600$ cm$^2$/Vs and $L_{MF} = 55$ nm.

The shortness of these length scales illustrates the challenge of fabricating QPCs and SQPCs in STO (see Fig. 1C). Observing ballistic transport requires junction length $L < L_{MF}$. Achieving a single-ABS junction with critical current quantization also requires short junction length: $L < \xi$. Although the junction length is not well defined in a split-gate geometry, we fabricated the gates with very narrow lateral spacing (40 nm) and sharp tips to strive for the ballistic (or quasi-ballistic) regime.

The ballistic nature of the SQPC is most apparent in differential resistance at finite DC current. Filling of states in the constriction with $V_{G12}$ results in a staircase shape of the critical supercurrent $I_c(V_{G12})$ (Fig. 2). Adopting a definition of $I_c$ as the current at which the resistance $R$ is halved with respect to the high-$V_{DC}$ normal state, plateaus at both positive and negative integer multiples of $\delta I_c = 2.48$ nA are seen in the $V_{G12}$-$I_{DC}$ map of constriction resistance normalized to its normal state value (Fig. 2B).

In the ballistic SQPC picture, $I_c/\delta I_c$ corresponds to $n$, which is the number of ballistic modes below the Fermi energy in the constriction (Fig. 2C). The first mode plateau is intermittent as a function of gate voltage due to resonant transmission through the weak link, correlated with the charging levels of an accidental Coulomb blockade observed near pinch-off at low $V_{G12}$ (see section S7), whereas the second and third plateaus are more stable. An alternative way to estimate the number of modes is from normal state conductance $G_N$, where each fully transmitting spin-degenerate mode is expected to contribute a conductance $\delta G = 2e^2/h$. The number of modes inferred by dividing $G_N$ by this increment matches that extracted from the sequence of steps in supercurrent. We also see hints of plateaus in normal state conductance at fixed $V_{DC} = 100$ $\mu$V near $n = 1$ and 2 (Fig. 2D). Features suggestive of normal state conductance quantization are more clearly apparent above $T_c$ (Fig. 2E), where one does not need to apply a DC bias to suppress the supercurrent, and disorder-induced fluctuations are reduced. The plateau structure persists as a function of back gate voltage (detailed further in section S5).

Ideally, the magnitude of steps in $I_c$ through a constriction should scale only with the superconducting gap as

$$\delta I_c = \frac{\epsilon \Delta}{h}$$

This scaling is expected to hold for a short junction ($L \ll \xi$) with perfectly transparent SN contacts (2, 3).

Fig. 2. Critical current quantization. (A) DC current dependence of constriction and lead resistances at $V_{G12} = 3$ V. (B) Constriction resistance, normalized to normal state resistance at $V_{DC} = 100$ $\mu$V. The solid red line indicates the critical current $I_c$. The dashed lines indicate 1, 2, and 3 integer multiples of $\delta I_c = 2.48$ nA. (C) $V_{G12}$ dependence of $I_c$, normalized to $I_{DC}$, and (D) normal state conductance $G_N$ at $V_{DC} = 100$ $\mu$V, with a series resistance of 800 $\Omega$ subtracted from the raw data. The shaded region between (C) and (D) emphasizes the numerical correspondence in the observed number of ballistic modes $n$. The dashed line in (C) is a fit to the saddle potential QPC model (see section S1). (E) Split- and back-gate voltage dependence of zero-bias conductance above $T_c$. $G$ has been corrected for a variable series resistance gradually increasing from 1.15 to 2.1 kilohm. Short plateaus can be seen at integer multiples of $2e^2/h$ ($n = 1$, 2, and hints at higher multiples). Unintentional Coulomb blockade levels can be seen near 0.2$e^2/h$, $e^2/h$, and 2.5$e^2/h$. 

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For most experimental realizations of SQPCs in hybrid metal superconductor/semiconductor devices, neither of these requirements is fully satisfied, and $\delta I_c$ is generally suppressed by at least an order of magnitude (4, 5, 7–9). One work on Si/Ge nanowires with Nb contacts reported suppression by only a factor of 2.9 (6). In our case, data in Fig. 2 suggest a comparable factor of 3 to 5. The uncertainty comes from the choice of method to extract $\Delta$ (see section S8): from $T_c$ of the constriction [$\delta I_c/(e\Delta/h) = 2.9$], from $T_c$ of the leads [$\delta I_c/(e\Delta/h) = 4.1$], or from the temperature dependence of the excess current [$\delta I_c/(e\Delta/h) = 4.8$].

Analysis of the excess current $I_{exc}$ allows separating the role of imperfect SN contact transparency $\tau_{SN}$ from that of finite junction length. We define $I_{exc}$ as the zero-bias intercept of the normal-state resistance extrapolated from high $V_{DC}$ (Fig. 3A). Both $I_c$ and $I_{exc}$ are expected to scale with $G_N$ (see section S1) and, thus, approximately track each other with $V_{G12}$. However, these two quantities encode different physics: the shape of the ABS spectrum for $I_c$ (2) and the balance between ordinary and Andreev reflections for $I_{exc}$ (38). The quantity $\epsilon_{exc} R_N/\Delta$ can be nonlinearly mapped onto $\tau_{SN}$ following the treatment of Andreev reflections in a superconductor/normal metal/superconductor (SNS) junction in (39, 40). Over the gate voltage range with a well-defined and quantized supercurrent (1.5 $< V_{G12} < 2.5$), we thereby extract $\tau_{SN} = 0.72^{+0.12}_{-0.08}$. We use $\epsilon_{exc}$ for its good agreement with calculations for the case in (38), where $L = 0.56\xi$. In this work, assuming that $\alpha = 0.7$ yields $L = 0.85\xi = 42$ nm, which is close to the 40-nm lithographic width of our QPC.

**DISCUSSION**

Transparency is likely to be the main driver for the reduction in $\delta I_c$ from its ideal value despite being competitive with the hybrid III-V/superconductor systems, where $\tau_{SN}$ is typically estimated below 0.85 (7–9, 42) except for pristine epitaxial interfaces (10). An advantage of our single-material system is that the SN contact interface is electrostatically defined and presumably does not have a structural discontinuity. In our present realization, transparency is likely limited by the smooth gate-induced density variation, which, in turn, entails a gradually varying order parameter. We anticipate that $\tau_{SN}$ can be further improved by manipulating the SN boundary with additional local gates near the weak link.

Furthermore, we anticipate improvements by increasing the mean free path. In ionic liquid–gated STO and LAO/STO, $L_{MFP}$ is typically less than 100 nm. However, improvements to $\mu > 10^4$ cm$^2$/V at $L_{MFP} > 1$ $\mu$m have been demonstrated by separating the ionic liquid from the channel by an ultrathin spacer layer (16), band engineering with spacer layers in LAO/STO (43), or forming the channel from high-quality molecular beam epitaxy–grown STO in the 3D case (44). These demonstrations have so far only been accomplished in unpatterned or coarsely patterned films, but we anticipate that these approaches can be compatible with the nanopatterning technique developed here. The fabrication route used in this work is relatively simple—based on commercially available STO crystals, avoiding epitaxial growth steps—so complex patterning, device, or heterostructure design refinements could be added without rendering it unwieldy.

Using ionic liquid–gated STO as a platform, we have realized SQPCs with quantized critical supercurrent, tunable between zero and three ballistic modes by split gates. This is a first realization of a quantized gate–tunable SQPC in a single material system, enabling highly transparent SN contacts without structural discontinuity at the boundary. This work establishes spatially patterned screening of ionic liquid from an STO surface as a promising alternative to existing methods for nanoscale patterning of conduction and superconductivity in STO: patterning LAO/STO with pregrowth templates (19, 20, 28, 29), electrostatic depletion by patterned gates (21, 22, 27), or conductive channel writing by voltage-biased AFM tips (23–26, 45). Our method appears particularly suited for realizations of ballistic superconducting transport, which require maintaining high carrier densities within nanopatterned constrictions. Naturally occurring depletion near the edges of an STO-based conducting channel (45, 46) can be counteracted with local gates as we have shown.

Our approach may also be especially attractive for exploring topological superconductivity in several contexts. Combining ballistic transport with superconductivity, strong spin–orbit coupling, and tunable dimensionality offers hope for engineering extrinsic topological superconductivity in 1D nanostructures (47–49). Even an unpatterned STO 2DES may host intrinsic topological superconductivity.
in certain conditions because of interplay between its multiorbital band structure, spin-orbit coupling, and ferroelectricity (50–52). A ballistic point contact similar to the SQPC demonstrated here could serve as the tunnel probe central to many detection schemes for the resulting Majorana bound states (53–55). The single-mode ballistic Josephson junction regime demonstrated here is also a requisite ingredient of theoretical proposals for realizing topological ABS spectra in multiterminal junctions (56, 57). Last, this work is an important step toward realizing controlled negative $U$ quantum dots (20, 23) in the classic geometry of an “island” coupled to two QPCs (58).

MATERIALS AND METHODS

Fabrication is based on commercially (001) oriented STO single-crystal substrates, purchased from MTI. To obtain a Ti-terminated surface with terrace-step morphology, these substrates were soaked in heated deionized water for 20 min and annealed at 1000°C for 2 hours in flowing Ar and O$_2$ in a tube furnace.

All subsequent patterning was performed with liftoff processes using e-beam–patterned poly(methyl methacrylate) (PMMA) 950K, 4% in anisole for the first step and 8% for all subsequent steps. The first step is the local split-gate pattern, written on a 100-kV e-beam write system. Atomic layer deposition was used to deposit 15 nm of HfO$_2$ (100 cycles of HF precursor and water). The deposition stage temperature was 85°C. We note the importance of cleaning the sample and starting the deposition quickly to avoid PMMA pattern collapse. The 5-nm Ti/50-nm Au gate contact was then deposited by liftoff of both HfO$_2$ and Ti/Au layers was then performed by soaking in heated N-Methyl-2-pyrrolidone (NMP), followed by ultrasonication in acetone.

The remaining patterning was performed with a 30-kV e-beam write system. The second step is the gate contact using liftoff of 40-nm Ti/100-nm Au in acetone. The third step is the ohmic contact deposition. It requires exposing the pattern to Ar$^+$ ion milling before e-beam evaporation of 10-nm Ti/80-nm Au followed by liftoff in acetone. The fourth patterning step is the mesa insulation, deposited by magnetron sputtering 70 nm of SiO$_2$, followed by liftoff in acetone. The measured devices were imaged with a conventional optical microscope and with a Keyence VK-X confocal laser microscope. Scanning electron microscope imaging was performed on reference patterns written on the same chips.

Finished devices were annealed for 20 min at 150°C in air. The back gate contact to a gold pad on an alumina ceramic chip carrier was made with silver paste. Immediately after depositing a drop of silver paste, immediately after depositing a drop of silver paste, it was slowly ramped up to desired value at room temperature, followed by several minutes of stabilization and then rapid-cooling the measurement probe below the freezing point of DEEM-TFSI (220 K). Typical measurement 2-terminal resistance per successful ohmic contact was 3 to 10 kohm, which includes a 2- to 3-kilohm contribution from the measurement lines and built-in radio frequency filters in the probe. All measurements presented in the main text and in the Supplementary Materials were performed in a four-probe configuration (with the exception of fig. S9). Measurements were performed by voltage-sourcing nominal AC and DC excitations ($V_{AC}^*$ and $V_{DC}^*$) through an adder circuit and measuring the drained current (I$_{AC}$ and I$_{DC}$). V$_{QPC}$ and V$_{DC}$ refer to the AC and DC components of the voltage drop across the weak link measured at the adjacent voltage probes (as shown in Fig. 1B). The constriction resistance is $R = 1/G = dV_{AC}/dI_{AC}$. $V_{lead}$ is the AC voltage drop between the next adjacent pair of voltage probes. The resistance of the unpatterned 2DES is $R_{lead} = V_{lead}/I_{AC}$.

Measured $R$ contains two contributions: the resistance of the constriction itself (tuned by $V_{G12}$) and a series resistance $R_s$. Unless specified, $R$ and $G$ are shown as measured. In selected plots of $G$ in the normal state, a specified $V_{G12}$-independent value of $R_s$ was subtracted from the measured $R$. As discussed in more detail in section S5, $R_s$ was chosen to match the plateau structure to integer multiples of $e^2/h$, with $R_s/R_{lead} \approx 2 - 3$. On the basis of the device geometry, $R_s$ is expected to be approximately equal or larger than $R_{lead}$.

The Supplementary Materials to this report present extensive additional discussion and characterization of a total of six devices fabricated on three different STO chips. The contents of each supplementary section are briefly summarized below to facilitate their navigation. Section S1: theoretical framework for the ballistic SNS constriction model, $I_C$ dependence on $\Delta$, $L$, and $V_{G12}$, $I_{QPC}$ dependence on $\tau_{NS}$. Section S2: description of additional devices and their fabrication. Section S3: tuning of carrier density and superconductivity with $V_{G12}$. Section S4: $V_{G12}$ and $V_{BG}$ effect on $R$, $R_{lead}$, $L^*$, $C$, $I_C$, and Hall density. Additional characterization of transport through the constriction in the normal state (section S5), in the superconducting state (section S6), and in the tunneling and accidental Coulomb blockade regimes (section S7). Section S8: discussion of the different methods to extract the superconducting gap $\Delta$ and the associated uncertainty.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at https://science.org/doi/10.1126/sciadv.abi6520

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