Gate-tunable superconducting weak link and quantum point contact spectroscopy on a strontium titanate surface

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Two-dimensional electron systems in gallium arsenide and graphene have enabled ground-breaking discoveries in condensed-matter physics, in part because they are easily modulated by voltages on nanopatterned gate electrodes. Electron systems at oxide interfaces hold a similarly large potential for fundamental studies of correlated electrons and novel device technologies^{1–3}, but typically have carrier densities too large to control by conventional gating techniques. Here we present a quantum transport study of a superconducting strontium titanate (STO) interface, enabled by a combination of electrolyte^{4–7} and metal-oxide gating. Our structure consists of two superconducting STO banks flanking a nanoscale STO weak link, which is tunable at low temperatures from insulating to superconducting behaviour by a local metallic gate. At low gate voltages, our device behaves as a quantum point contact that exhibits a minimum conductance plateau of e^2/h in zero applied magnetic field, half the expected value for spin-degenerate electrons, but consistent with predictions^{8–12} and experimental signatures^{13–18} of a magnetically ordered ground state. The quantum point contact mediates tunnelling between normal and superconducting regions, enabling lateral tunnelling spectroscopy of the local superconducting state. Our work provides a generic scheme for quantum transport studies of STO and other surface electron liquids.

Transition metal oxides exhibit electronic ground states not seen in conventional semiconductors^{2,3}. For instance, the interface between lanthanum aluminate and strontium titanate¹⁹—two non-magnetic band insulators—hosts superconductivity²⁰ and magnetism^{13–18}. Rashba spin–orbit coupling at conductive STO interfaces²¹ has led to predictions of unconventional superconducting states¹⁰, and of helical wires and Majorana fermions in nanoscale STO channels¹¹. Furthermore, nanoscale lateral control of carriers could allow fabrication of gate-tunable, single-material Josephson junctions and superconducting quantum interference devices, as well as mesoscopic devices. However, few experiments on nanostructures in STO systems exist: superconductivity has been demonstrated in submicron regions tunable with a global back gate²², and channels sketched by a nanoscale tip show superconducting features²³. In this work, we demonstrate the first realization of an all-STO, gate-tunable superconducting weak link. We tune our device to the ballistic 1D limit and perform superconducting spectroscopy that agrees with BCS weak-coupling expectations and previous work²⁴.

Undoped STO is a band insulator. Inducing a two-dimensional (2D) electron density near 10^{13} cm^{-2} creates a metal, and several times that density creates an optimally doped superconducting

state⁴. To modulate the density on this scale, we use the electric double-layer transistor technique^{4–7}. A schematic of our sample is shown in Fig. 1a. A single crystal of TiO_2 -terminated (100) SrTiO_3 is patterned with ohmic contacts and a narrow metal top gate separated from the STO surface by a 5 nm alumina layer (Fig. 1b and Methods). The sample is covered in ionic liquid, which is polarized by an electrode (not shown) to induce a 2D electron layer at the exposed STO surface; the area below the top gate remains insulating, because the gate screens the ions. The polarized sample is cooled to base temperature in a dilution refrigerator, freezing the ionic liquid and thus fixing the electron density in the exposed STO regions. The voltage on the top gate is then modulated to control transmission across the device, and conductance measurements are carried out with standard lock-in techniques in a four-terminal geometry (see Supplementary Information for filtering details).

The data reported in this Letter originate from a single cooldown of an STO channel 2 μm in width spanned by a top gate of length 50 nm (other devices with similar behaviour are described in the Supplementary Information). The electron density in the STO regions exposed to the liquid was fixed near $5 \times 10^{13} \text{ cm}^{-2}$, corresponding to $T_c \approx 300 \text{ mK}$ (Supplementary Information). At 14 mK and top gate voltage $V_{\text{TG}} = 0$, the device is insulating for source–drain bias voltage V_{SD} up to 1 mV (left inset, Fig. 1c). At intermediate V_{TG} , the IV curve resembles that of an opaque tunnel junction, in which current flows only above a threshold V_{SD} (middle inset, Fig. 1c). This threshold decreases with increasing V_{TG} until a non-zero conductance appears at $V_{\text{SD}} = 0$. At the highest applied voltages $V_{\text{TG}} \approx 3 \text{ V}$, the IV curve resembles that of a superconductor with critical current I_c (right inset, Fig. 1c). We observe a normal-state resistance $R_N > 1 \text{ k}\Omega$ and a non-zero resistance dV/dI below I_c , similar to other weak links with high normal-state resistance²⁵.

Current-biased differential resistance measurements reveal that I_c is a strong function of V_{TG} (Fig. 2a). I_c can first be resolved around $V_{\text{TG}} = 2.1 \text{ V}$, and increases to over 100 nA by $V_{\text{TG}} = 3.2 \text{ V}$ (I_c is defined as the lowest current at which the device reaches its normal-state resistance R_N). V_{TG} is limited to 3.5 V by the breakdown of the alumina dielectric; for all data shown, gate leakage is below experimental sensitivity. The product $I_c R_N$, which is a measure of the superconducting gap Δ in the banks surrounding the weak link²⁶, saturates near $150 \mu\text{V}$ whereas I_c steadily rises with increasing V_{TG} (lower panel, Fig. 2a). For a short superconductor–normal–superconductor (SNS) junction in the dirty limit, Kulik–Omelyanchuk theory (KO-1; ref. 26) predicts that $eI_c R_N / \Delta \sim 2$, giving $\Delta \sim 75 \mu\text{eV}$ in our sample. As described

Figure 1 | Device properties. **a**, Schematic of the device, which is submerged in ionic liquid. Cations are drawn to the sample by a positively charged electrode (not shown) that is also immersed in the liquid, accumulating electrons at the exposed superconducting strontium titanate (STO) surface (lavender shading). The top gate defines a channel of low electron density by spacing and screening the cations. **b**, Scanning electron micrograph of a top gate of nominal length 60 nm (the device described in the text has length 50 nm). The scale bar is 100 nm. The alumina dielectric laterally protrudes 5–10 nm (faint edge around top gate). **c**, Electronic properties versus top gate voltage V_{TG} at 14 mK. Main panel: differential conductance at zero source-drain bias. Insets: I/V curves from the insulating, tunnelling, and superconducting regimes.

below, we measure $\Delta \sim 80$ μeV by tunnelling spectroscopy, in agreement with KO-1. Furthermore, the saturating behaviour of $I_C R_N$ is expected: the top gate modulates the density in the weak link, which is largely independent of Δ in the banks. The above results are qualitatively insensitive to the exact definition of I_C .

I_C decreases smoothly to zero in a magnetic field perpendicular to the plane (Fig. 2b). Were supercurrent flowing uniformly beneath the top gate, we would expect a Fraunhofer diffraction pattern²⁷ for $I_C(H)$, with zeros every 20 mT. Instead, the magnetic field response mirrors the diminishing superconductivity in the bulk. We suggest that only a small fraction of the area under our top gate becomes conductive, even at high V_{TG} .

We next focus on the transition from tunnelling to superconducting behaviour. Figure 3a shows a waterfall plot of differential conductance versus source-drain voltage V_{SD} at intermediate V_{TG} , measured in a voltage-biased configuration with $\mu_0 H = 0.25$ T to suppress superconductivity. The traces cluster slightly below 1 and 2 e^2/h for zero bias, and near 1/2 and 3/2 e^2/h for $V_{SD} \approx 200$ μV . We estimate a series resistance ~ 2 $k\Omega \ll h/e^2$ (Supplementary Information), which would make the 1 and 2 e^2/h quantization quite accurate. This quantization appears as plateaux in dI/dV as a function of V_{TG} for $V_{SD} = 0$ (Fig. 3d), and the plateau features form a crossing structure in V_{SD} – V_{TG} space (Fig. 3b). These data strongly resemble measurements on ballistic quantum point contacts (QPCs) in clean 2D systems, where the zero-bias conductance is quantized to integer multiples of $G_0 = ge^2/h$ for subband degeneracy g . The high-bias plateaux at half-integer multiples of G_0 are well documented²⁸, and arise when the number of subbands below the Fermi level differs by one between the two leads.

The subbands seem to be non-degenerate ($g = 1$) even for $H = 0$ (Fig. 3d). Two spin-degenerate QPCs connected in series without

Figure 2 | Tunable superconducting weak link. **a**, Differential resistance versus top gate voltage and d.c. bias current I_{dc} . A critical current I_C is clearly observed, and grows with increasing V_{TG} . Right panel: $V_{TG} = 3.2$ V (black dashed line in left panel). Lower panel: extracted I_C and $I_C R_N$ product, where R_N is the normal-state resistance measured at high I_{dc} . $I_C R_N$ saturates whereas I_C continues to grow with increasing V_{TG} . **b**, Differential resistance versus applied perpendicular magnetic field and I_{dc} . I_C is suppressed with increasing magnetic field, but without a magnetic diffraction pattern.

phase coherence could mimic broken degeneracy in a single QPC, as their resistances ($h/2ne^2$, integer n) would simply add. But this scenario would require nearly identical Fermi levels and dimensions for both QPCs, as we observe only one set of QPC features (Fig. 3b). The apparent broken degeneracy is more naturally explained by ferromagnetism, which has been observed^{13–18} in $\text{LaAlO}_3/\text{SrTiO}_3$ and is expected by theory: in some models, mobile d -electrons align their spins^{8,9}, whereas in others itinerant electrons move in the Zeeman field of localized, spin-polarized d_{xy} electrons^{10–12}. Models that include a strong spin–orbit coupling²¹ alongside ferromagnetism in a 1D STO system predict a helical wire, again leading to an e^2/h plateau¹¹; our data cannot distinguish between helical and spin-polarized pictures. Although we do not observe hysteresis, the coercive field could be below the resolution of our data (~ 5 mT), especially for small ferromagnetic patches^{9,16,17}. Note that zero-field broken degeneracy in a QPC has also been reported in structures with an engineered in-plane electric field²⁹, which is absent in our device.

The QPC structure at $H = 0$ (Fig. 3c) remains largely unchanged from the $\mu_0 H = 0.25$ T case, except for a slight splitting and sharpening of resonances. For $H = 0$, however, two peaks emerge near zero bias between 1.9 and 2.05 V, and evolve into one peak above 2.05 V. We ascribe these peaks to a single superconductor–normal (SN) interface; an SNS junction would give a large superconducting peak at zero bias²⁷. For this gate voltage range, inelastic scattering probably transforms the junction into two

Figure 3 | Quantum point contact. **a**, Two-terminal differential conductance versus source-drain bias voltage V_{SD} for top gate voltages from 1.76 V (violet) to 2.24 V (red), with no adjustments for contact resistance. A magnetic field of 0.25 T is applied to suppress superconductivity. The curves cluster near e^2/h and $2e^2/h$, as well as at the half-integers $e^2/2h$ and $3e^2/2h$ for higher V_{SD} . **b**, Same data as in **a** but the V_{TG} range is offset by 60 mV to correct for hysteresis and align features with **c**. The crossing resonances track the subband minima. **c**, Two-terminal dI/dV as in **a** and **b** but with $H=0$ so that the banks are superconducting. Split peaks emerge around zero bias, merging into one strong superconducting peak at the highest V_{TG} . Right panel: $V_{TG}=2.02$ V (red dashed line in left panel). The dashed black curve is a fit of the double peak region to BTK theory ($R_{int}=1.87 e^2/h$, $\Delta=71 \mu\text{eV}$, $\Gamma=15 \mu\text{eV}$ and $Z=0.48$; standard deviations from the genetic fitting algorithm are smaller than 1%). **d**, Differential conductance from **b** and **c** at $V_{SD}=0$, showing the plateau structure. **e**, Cartoon of the electron distribution that gives rise to the quantum point contacts (QPC) behaviour. A normal channel (blue) beneath the top gate forms two superconductor-normal (SN) interfaces, but owing to sample inhomogeneity only one interface is narrow enough to create a QPC in this gate voltage window. For $V_{TG} < 1.8$ V, the narrowest end of the channel completely closes, leading to a tunnelling IV curve (Fig. 1c); for $V_{TG} > 2.2$ V, the channel widens, yielding a superconducting IV curve.

SN interfaces in series, with current flow shaped by the higher-resistance interface. The peaks are fitted well by the Blonder–Tinkham–Klapwijk (BTK) theory of SN interfaces,

$$\frac{dI}{dV} = \frac{1+Z^2}{R_{int}} \int_{-\infty}^{\infty} -f'(E-eV)(1+A(E; \Delta, \Gamma, Z) - B(E; \Delta, \Gamma, Z)) dE \quad (1)$$

where $f(E)$ is the Fermi function, $A(E)$ and $B(E)$ are probabilities of Andreev and normal reflection, and Γ characterizes lifetime broadening³⁰. The interface barrier strength Z accounts for elastic scattering, including reflections due to Fermi wavevector mismatch²⁷. R_{int} is the interface resistance in the absence of superconductivity, and equals the geometrical Sharvin resistance for $Z=0$. The right panel of Fig. 3c shows the high quality of the fit to equation (1) for a representative V_{TG} (2.02 V). $R_{int}=0.53 h/e^2$, which nearly agrees with the normal-state QPC resistance $0.58 h/e^2$ at $V_{TG}=2.02$ V. We thus conclude that the QPC itself is the SN interface that dominates the transport behaviour, as depicted in Fig. 3e.

The situation of a single-mode quantum wire in contact with a superconductor has been theoretically analysed³¹, and results in lineshapes nearly identical to BTK, justifying our use of equation (1). However, the small resonances that track the subband edges (moving diagonally in Fig. 3c) overlap the split peaks at some gate voltages—for example, $V_{TG}=1.98$ V. To improve BTK fitting, we therefore divide the data of Fig. 3c by those of Fig. 3b. The resulting normalized dI/dV traces and fits are shown in Fig. 4a. With increasing V_{TG} , split peaks merge into a single zero-bias peak, which

reaches the theoretical maximum conductance enhancement of 2 for an SN junction with zero barrier. As V_{TG} increases, the extracted Z remains near 0.5 until the middle of the normal-state $2e^2/h$ plateau (2.03 V), where Z begins to drop to zero (Fig. 4b). The extracted Δ is 60–90 μeV , except near the plateau transitions (1.97 V and 2.05 V): there the normal-state conductance varies significantly at low bias, making both our normalization and our BTK model less accurate. Although statistical errors are small, systematic errors due to background features are significant (Supplementary Information). For $V_{TG} > 2.12$ V, the normalized conductance at zero bias grows larger than 2 and strong dI/dV dips surround the central peak, signalling the transition to SNS behaviour.

A QPC with conductance e^2/h is a half-metal, which typically gives zero Andreev reflection probability at an s -wave superconductor interface. But, in our sample, introducing superconductivity enhances the zero-bias conductance above e^2/h (Fig. 3d), suggesting significant Andreev reflection. This conundrum may be resolved by spin-flip Andreev reflections resulting from spin–orbit coupling in the superconductor³², dephasing³³, magnetization gradients³⁴, and/or impurities³⁵. Such processes would restore a BTK-like lineshape for split peaks on the e^2/h plateau (Supplementary Information).

The BTK model yields spectroscopic information that agrees with our expectations for the superconducting state. $\Delta(T)$ extracted from BTK fits on the $2e^2/h$ plateau (Fig. 4c) follows the BCS prediction²⁷ (Fig. 4d). Γ grows slightly as Δ is suppressed to zero with increasing temperature, in agreement with tunnelling measurements on $\text{LaAlO}_3/\text{SrTiO}_3$ (ref. 24; the upturn in Γ for

Figure 4 | Quantum point contact spectroscopy of the superconductor. **a**, Normalized dI/dV for $1.91 \text{ V} < V_{\text{TG}} < 2.12 \text{ V}$, calculated by dividing the data in Fig. 3c by the data in Fig. 3b. Dashed black curves are BTK fits. Traces for $V_{\text{TG}} < 2.12 \text{ V}$ are successively offset downwards by $0.2 e^2/h$. **b**, Extracted barrier strength Z (right axis) and gap Δ (left axis). The voltages corresponding to the 1 and $2 e^2/h$ plateaux at $\mu_0 H = 0.25 \text{ T}$ are indicated with light and dark grey shading, respectively. The data at 1.98 V did not have well-defined peaks to fit. **c**, Peaks at top gate voltage $V_{\text{TG}} = 2.03 \text{ V}$ for various temperatures, and BTK fits with $Z = 0.5$ to the double peaks. Traces for $T > 14 \text{ mK}$ are successively offset downwards by $0.4 e^2/h$. **d**, Extracted values of Δ and the broadening parameter Γ versus temperature. Dashed red curve is a fit of Δ to weak-coupling BCS theory. **e**, Peaks at $V_{\text{TG}} = 2.08 \text{ V}$ for various perpendicular magnetic fields, and BTK fits with $Z = 0.4$. Traces for $H > 0$ are successively offset downwards by $0.2 e^2/h$. Fits are not possible above 0.14 T owing to the increasingly relevant background features. The V_{TG} values quoted for **c** and **e** do not correspond exactly to V_{TG} in **a** owing to gate hysteresis on the order of 50 mV . **f**, Extracted values of Δ and Γ versus magnetic field. Statistical error bars for all fits are smaller than the markers; systematic error is discussed in the Supplementary Information.

$T < 200 \text{ mK}$ probably reflects elevated electron temperature, see Supplementary Information). In contrast, as the applied perpendicular magnetic field H increases, Δ stays constant whereas Γ increases markedly (Fig. 4e,f). This behaviour results from pair-breaking in a magnetic field and is observed in other superconductors such as Nb and Sn (ref. 36).

Our experiment illustrates the feasibility of clean transport measurements in nanostructured 2D oxide systems. Our demonstration of magnetism and tunable superconductivity in a single material with strong spin-orbit coupling lays the foundation for a host of interesting experiments. The gating technique presented here is generic, and can be implemented on other high-density surface electron systems.

Methods

Our samples are fabricated on TiO_2 -terminated (100) strontium titanate substrates ('SrTiO₃ STEP substrates' from Shinkosha). Ohmic contacts and a large coplanar electrode are patterned by photolithography, followed by ion milling⁴ and evaporation of titanium and gold. The nanoscale gate is then defined in PMMA resist by 100 kV electron-beam lithography. Following development and an ultraviolet ozone clean, 5 nm of alumina is grown via atomic layer deposition, a 5 nm titanium/ 35 nm gold stack is deposited by evaporation, and the sample is immersed in acetone for liftoff. Finally, the mesa structure (Supplementary Information) is defined by a hard-baked photoresist mask.

Before measurement, a small drop of the ionic liquid 1-ethyl-3-methylimidazolium bis(trifluoromethanesulphonyl)amide (EMI-TFSI) is applied to the sample, which is then baked free of water in a tube furnace at 120°C , under a 0.5 slm flow of argon. The sample is loaded into the vacuum chamber of our dilution refrigerator, which is cryopumped by a surface at 77 K . To minimize sample-degrading electrochemical effects, we cool the sample to 265 K before polarizing the liquid with 3.1 V on the coplanar electrode. We gradually cool the polarized sample to liquid helium temperatures over 36 h , and then activate our dilution unit to reach 14 mK .

Received 6 January 2014; accepted 1 July 2014;
published online 31 August 2014

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Acknowledgements

We thank J.-M. Triscone and J. Mannhart for helpful discussions concerning this work, and S. Ilani for broader discussions concerning the properties of STO. Sample fabrication was supported by the Air Force Office of Science Research, Award No. FA9550-12-1-02520. Sample measurement was supported by the MURI Program of the Army Research Office, Grant No. W911-NF-09-1-0398. Development of the ionic liquid gating technique was supported by the Center on Nanostructuring for Efficient Energy Conversion (CNEEC) at Stanford University, an Energy Frontier Research Center funded by the US Department of Energy, Office of Basic Energy Sciences under Award No. DE-SC0001060. P.G. acknowledges support from the DOE Office of Science Graduate Fellowship Program. M.L. acknowledges support from Samsung and Stanford University. J.R.W. and D.G.-G. acknowledge support from the W. M. Keck Foundation.

Author contributions

P.G. designed the experiment, fabricated the sample, and performed the measurements. All authors contributed to data analysis. P.G. prepared the manuscript with input from all authors.

Additional information

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Competing financial interests

The authors declare no competing financial interests.