Nonreciprocal transport in the gate-induced strontium titanate polar superconductor

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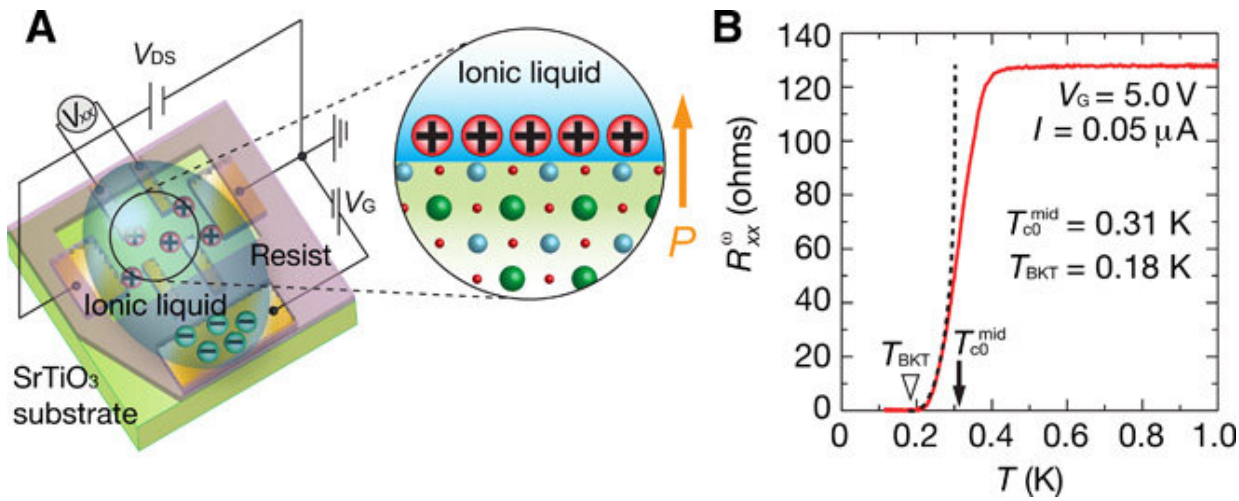


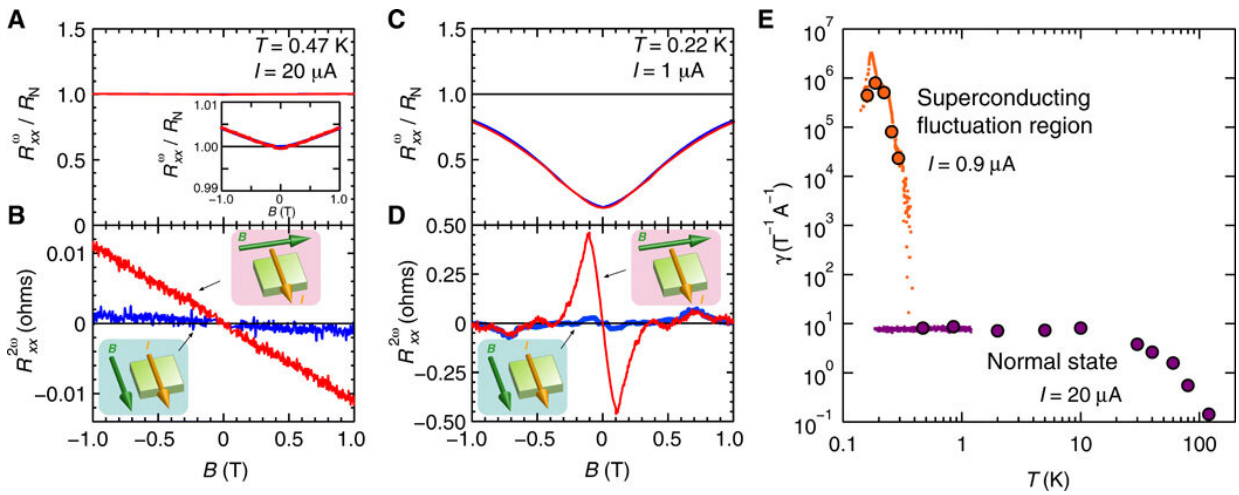
Device image and gate-induced superconductivity in SrTiO3. (A) Schematic image of SrTiO3-EDLT. (B) Longitudinal first harmonic resistance Rωxx as a function of temperature T under zero magnetic field. The applied current was 0.05 μA, which can be regarded as low-current limit. Transition temperature defined by the midpoint of the resistive transition is estimated as Tc0 = 0.31 K (black arrow). Black dashed line shows fitting curve by the Halperin-Nelson formula, where RN = 128 ohms is the normal-state resistance (T = 1.0 K), b = 1.17 is a dimensionless constant, and TBKT = 0.18 K is BKT transition temperature (white triangle). The applied gate voltage VG is 5.0 V at T = 260 K. Credit: Science Advances, doi: 10.1126/sciadv.aay9120

In materials science, two-dimensional electron systems (2DES) realized

at the oxide surface or interface are a promising candidate to achieve novel physical properties and functionalities in a rapidly emerging quantum field. While 2-DES provides an important platform for exotic quantum events including the quantum Hall effect and superconductivity , the effect of symmetry breaking ; transition from a disorderly state in to a more definite state, on such quantum phases remain elusive. Nonreciprocal electrical transport or current-direction-dependent resistance is a probe for broken inversion symmetry (presence of a dipole), as observed on several noncentrosymmetric crystals and interfaces. In a new report, Yuki M. Itahashi and a team of scientists in applied physics, nanosystems and materials science in Japan and the U.S. reported nonreciprocal transport at the surface of a 2-D superconductor made of the superconducting material strontium titanate ($SrTiO_3$). The team observed gigantic enhancement of the nonreciprocal region in the superconducting fluctuation region—at six orders of magnitude larger compared to its normal state. The results are now published on *Science Advances* and demonstrate unprecedented characteristics of the 2-D polar superconductor.

Polar conductors or superconductors are potential material platforms for quantum transport and spintronic functionalities, with inherent nonreciprocal transport that reflects the elusive property of time-reversal symmetry breaking (i.e. breaking conservation of entropy). Recent experiments have extended to the superconducting state to observe a large nonreciprocal response and physicists are keen to examine the nonreciprocity around superconducting transition in a simple electron system. For this, Itahashi et al. engineered chromium/gold (Cr/Au) electrodes on the atomically flat surface of $SrTiO_3$ and placed ionic liquid on the top to form an electric double layer transistor (EDLT) to realize a Rashba superconductor; based on the Rashba effect, with an ion-gating technique on the $SrTiO_3$ material surface. The scientists then measured the first and second harmonic electronic transport using a standard lock-in technique to measure nonreciprocal charge transport

and quantify time-reversal symmetry breaking in the system. Nonreciprocal transport is also an effective tool to identify Cooper pairs, where a pair of electrons overcome their usual repulsion to share a quantum state for nonreciprocal paraconductivity in superconductors, which Itahashi et al. also intended to quantify in the Rashba superconductor.

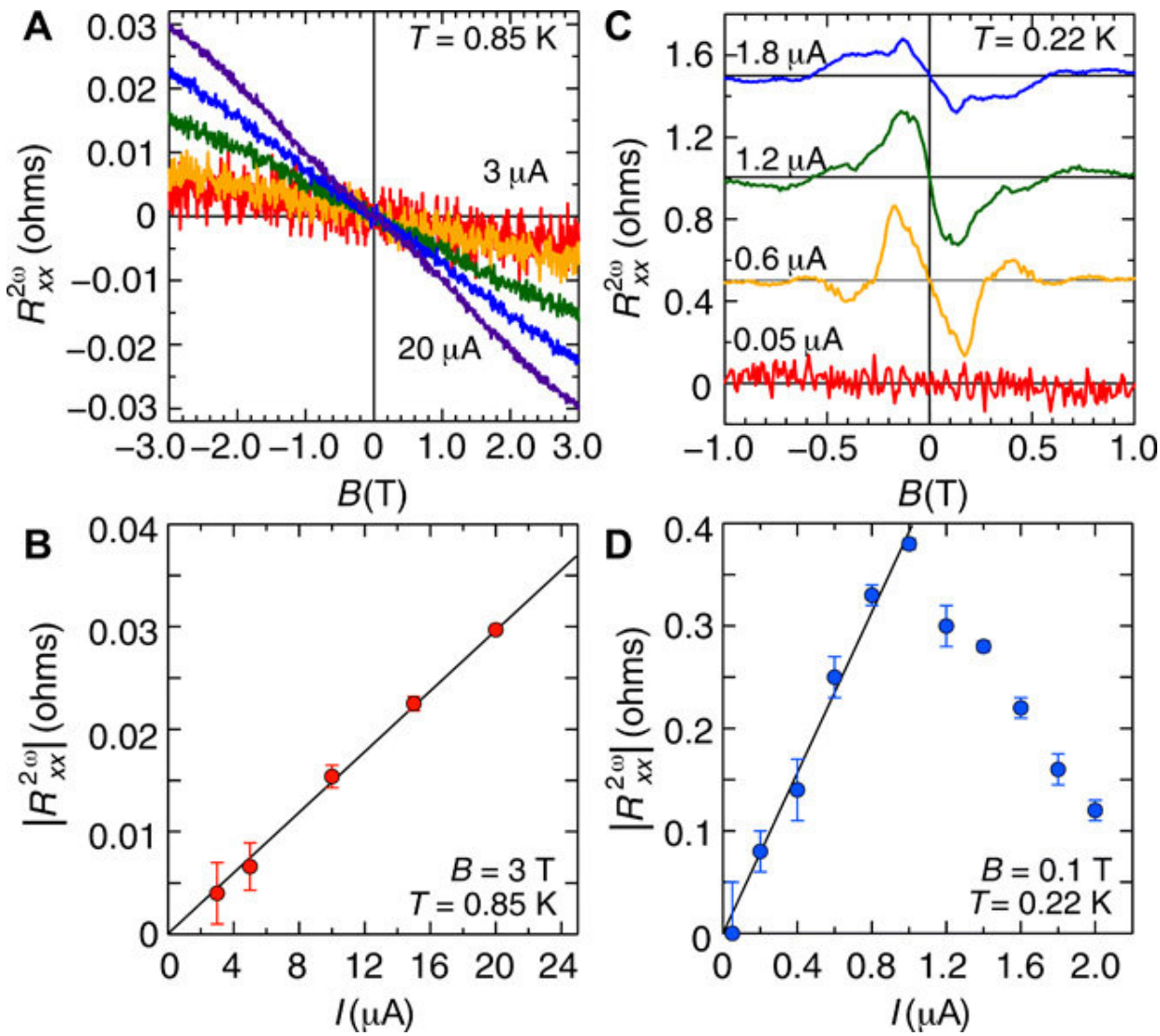


Magnetotransport of gate-induced 2D SrTiO3 for both the normal and superconducting states and enhancement of the nonreciprocal transport in the superconducting fluctuation region. (A) First and (B) second harmonic magnetoresistance (Rωxx and R2ωxx, respectively) above Tc0 (normal state, T = 0.47 K and I = 20 μA) as a function of in-plane magnetic field B perpendicular (red) or parallel (blue) to I. Insets in (A) and (B) show the magnified view of Rωxx(B) and schematics of the measurement configuration (directions of B and I), respectively. (C) Rωxx and (D) R2ωxx below Tc0 (superconducting fluctuation region, T = 0.22 K and I = 1 μA) as a function of in-plane B perpendicular (red) or parallel (blue) to I. In (A) to (D), Rωxx is normalized by the normal-state resistance RN = 128 ohms, and Rωxx/R2ωxx is symmetrized/anti-symmetrized as a function of B. (E) Temperature dependence of γ=2R2ωxxRωxxBI in the normal state (I = 20 μA) and superconducting fluctuation region (I = 0.9 μA). Purple (normal state) and orange (superconducting fluctuation region) circles were extracted from the

measurement of magnetic field scan of R2ωxx at low B below 0.1 T, while purple (normal state) and orange (superconducting fluctuation region) dots were plotted from the temperature scan of R2ωxx under B = 3 and 0.05 T, respectively. Credit: Science Advances, doi: 10.1126/sciadv.aay9120

The scientists initially detailed the first harmonic resistance (FHR) corresponding to linear resistance near superconducting transition for a gate voltage of 5.0 V. The results showed a temperature dependence at the low current limit (I = 0.05 μA). Then they focused on second harmonic resistance (SHR) and credited nonreciprocal charge transport observed at the surface of $SrTiO_3$ to the polar symmetry within the superconducting fluctuation region and in the normal state. The team observed magneto-transport in gate induced 2-D $SrTiO_3$ within a magnetic field (B) perpendicular to the current (I) for normal and superconducting states—with enhanced nonreciprocal transport in the superconducting fluctuation region. To compare the magnitude of nonreciprocity between the normal state and region of superconductivity fluctuation, they calculated the coefficient of nonreciprocal magnetoresistance (γ), which depended on the temperature within the regions.

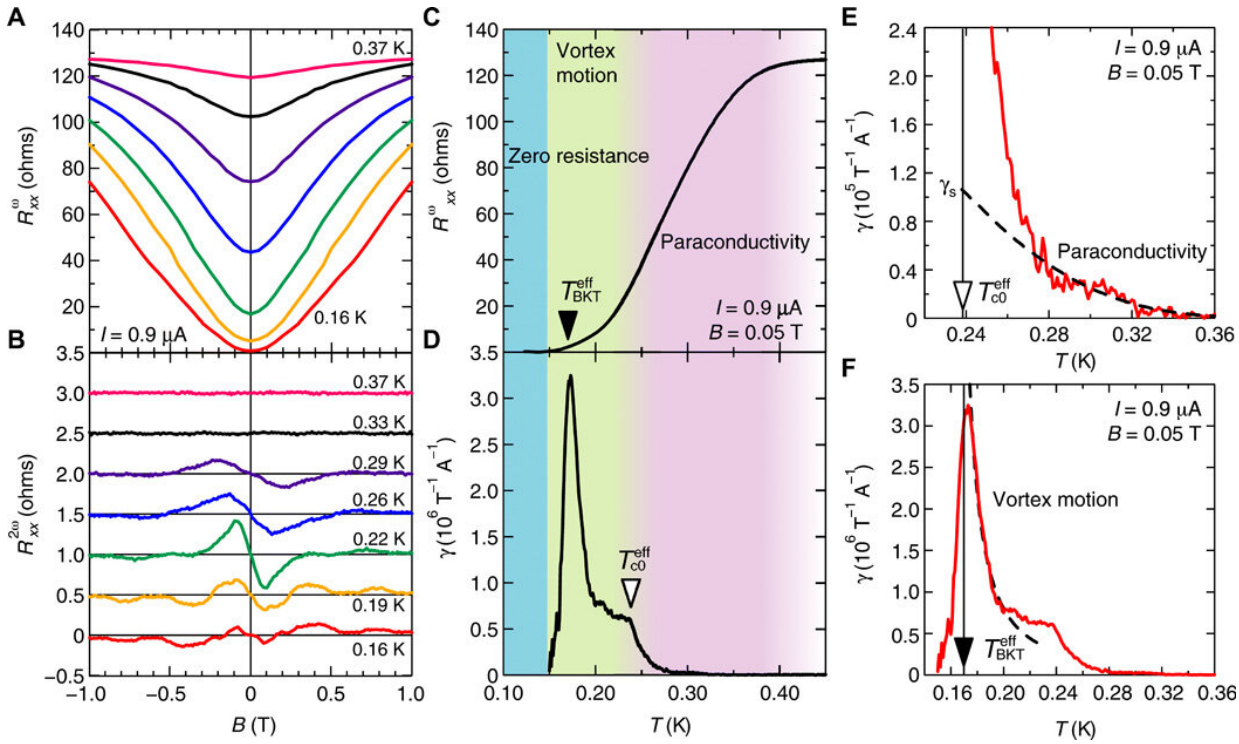
The team subsequently measured the dependence of the second harmonic signals on current (I), in the normal state and in the superconducting fluctuation region. In the normal state, the SHR showed an almost linear dependence on the current. In the superconductivity fluctuation region at a magnetic field of 0.1 Tesla, the SHR increased linearly, reached a maximum at around 1 μA and suppressed—to indicate suppression of superconductivity by the high current.



Current dependence of the second harmonic magnetoresistance in the normal and the superconducting fluctuation region. (A) Second harmonic magnetoresistance R2ωxx at T = 0.85 K under I = 3 μA (red), 5 μA (orange), 10 μA (green), 15 μA (blue), and 20 μA (purple). R2ωxx is antisymmetrized as a function of B. (B) ||R2ωxx|| at B = 3 T as a function of I, which is extracted from (A). Black solid line shows linear fitting as a function of I. (C) Magnetic field dependence of ||R2ωxx|| at T = 0.22 K under I = 0.05 μA (red), 0.6 μA (orange), 1.2 μA (green), and 1.8 μA (blue). Each curve is shifted vertically by 0.5 ohms and antisymmetrized as a function of B. (D) Current dependence of ||R2ωxx|| at B = 0.1 T, where R2ωxx is regarded as a linear function of B. In low-current region (I ≤ 1 μA), ||R2ωxx|| linearly increases (black solid line) with I. Credit:

Science Advances, doi: 10.1126/sciadv.aay9120

To further investigate the possible origin of nonreciprocal superconducting transport in the system, the scientists measured the temperature dependence of FHR and SHR during the transition. To accomplish this, they noted magnetic field dependence of FHR and SHR at various temperatures and specifically observed SHR to be largely enhanced during superconducting transport. Although Itahashi et al. applied a relatively large current and in-plane magnetic field, they recorded zero-resistance state at the lowest temperature. The results implied the existence of the Berenzinskii-Kosterlitz-Thouless transition (BKT transition), named after a team of Nobel prize-winning condensed matter physicists. It describes phase transitions in 2-D systems in condensed matter physics approximated by a XY model in order to understand unusual phases or states of matter in superconductors.



Temperature dependence of the magnetoresistance and the nonreciprocal transport. Magnetic field dependence of (A) the first (Rωxx) and (B) the second (R2ωxx) harmonic magnetoresistance at T = 0.16 K (red), 0.19 K (orange), 0.22 K (green), 0.26 K (blue), 0.29 K (purple), 0.33 K (black), and 0.37 K (pink), respectively. In (B), each curve is shifted vertically by 0.5 ohms. Rωxx/R2ωxx is symmetrized/antisymmetrized as a function of B. Temperature variation of (C) Rωxx and (D) γ under B = 0.05 T and I = 0.9 μA. In this region, R2ωxx is linear as a function of B and I. Rωxx/γ is symmetrized/antisymmetrized as a function of B. Characteristic structure (kink structure around T = 0.24 K and peak structure around T = 0.17 K) appears in (D), according to which we can identify two regions of the nonreciprocal transport of different origins, i.e., paraconductivity region and vortex region. At the lowest temperature, zero-resistance state is observed, where Rωxx and γ becomes negligibly small. Magnification of γ in (E) paraconductivity region and (F) vortex region. Black dashed line in (E) shows fitting curve by γ(T)=γs(1−R(T)RN)2, and black dashed line in (F) indicates fitting curve by γ(T)=C(T−TeffBKT)−3/2. Normal-state resistance RN = 128 ohms is defined as Rωxx at T = 1.0 K. Credit: Science Advances, doi: 10.1126/sciadv.aay9120

In this way, Yuki M. Itahashi and colleagues proposed nonreciprocal transport in noncentrosymmetric (without inversion symmetry) 2-D superconductors within a magnetic field. The nonreciprocal transport originated from amplitude fluctuation from the normal to the superconducting state. Temperature dependence of the coefficient of nonreciprocal magnetoresistance (γ) observed in the experiments agreed well with the microscopic theoretical picture of free motion for thermally excited vortices and antivortices in polar 2-D superconductors. The nonreciprocal response is therefore a powerful tool to understand the nature of noncentrosymmetric superconductors.

Itahashi et al. believe that nonreciprocal transport could appear

universally for different materials at interfacial superconducting systems with polar symmetry. The results provide information on previously unknown functions of superconductivity and important information on the electronic state and pairing mechanisms in noncentrosymmetric superconductors—as an important topic for further investigation. The work highlighted nonreciprocal transport in interfacial superconducting systems such as gate-induced 2-D superconductor $SrTiO_3$. The team probed the marked jump of nonreciprocal transport from the normal to superconducting states as direct evidence for giant enhancement of nonreciprocal transport in the system. The results offer important insight into polar superconductors and pave a new way to search for hitherto unknown emergent properties and functionalities at 2-D oxide interfaces and superconductors.

More information: Yuki M. Itahashi et al. Nonreciprocal transport in gate-induced polar superconductor SrTiO3, *Science Advances* (2020). DOI: 10.1126/sciadv.aay9120

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