Controllable Disorder in a Hybrid Nanoelectronic System: Realization of a Superconducting Diode

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We have studied a hybrid nanoelectronic system which consists of an AlGaAs/GaAs two-dimensional electron gas (2DEG) in close proximity (~ 70 nm) to an Al superconducting nanofilm. By tuning the current through the Al film, we can change the conductance of the 2DEG and furthermore vary the effective disorder in the Al superconducting film in a controllable way. When a high current is injected into the film, screening which couples the Al film and the 2DEG results in a collapse of anti-symmetric behavior in the current-voltage characteristics, $V(I) \sim -V(-I)$, which holds true in a conventional superconductor. Our results may open a new avenue of experimentally realizing a superconducting diode.

B elow a characteristic temperature, some metals such as Al, Pb and In lose their electric resistance abruptly, entering a superconducting state. Cooper pairs, which correspond to the formation of a many-body state of electrons, are the key ingredient in the BCS theory[1,2] for superconductivity observed in some metals. It is well known that a superconductor can sustain a dissipationless current, often termed a supercurrent. A switching from superconducting to dissipative conduction occurs when the current I through a superconductor approaches a critical value, resulting in a sudden appearance of a finite resistance. Similarly, the application of a magnetic field up to a critical value H_c can completely destroy the zero-resistance state, causing a superconducting transition.

With the presence of weak disorder, global phase coherence persists in a superconductor, and a BCS-type superconducting transition occurs either with increasing H or temperature T. In this case, phase correlations and spatial average of order parameter amplitude in a superconductor vanish simultaneously. However, for a highly disordered system, this description may not be valid. It has already been demonstrated both experimentally[3–6] and theoretically[7–9] that the nature of superconductivity can persist even on the insulating side of a field-tuned superconductor-insulator (SI) transition. In this high disorder regime, phase correlations and spatial average of order parameter amplitude do not need to vanish simultaneously. The most direct evidence for this is the observation of superconducting islands in the insulating regime, where the spatial average of order parameter amplitude remains finite[3,4]. The SI transition can be understood as a change of variable that is being pinned[10,11]. In the superconducting regime also known as phase-order one, the uncertainty in the number of Cooper pairs ΔN is much larger than that in phase $\Delta\theta$. In contrast, in the insulating regime characterized by increasing resistance with decreasing T, $\Delta\theta$ is much larger than ΔN, showing charge-order feature in this regime. Therefore one knows that superconductivity would be degraded by either reducing ΔN or enhancing $\Delta\theta$. It has been suggested that phase-charge duality[11] is important in granular superconductors[12], Josephson junction arrays[13], and homogeneous superconducting thin films with the presence of strong disorder[3]. However, in a weakly disordered superconductor, Cooper pairs cannot normally survive in the normal state even close to the superconducting transition due to strong stiffness of Cooper-pair phase correlations. Therefore it is difficult to study phase-charge duality in a weakly disordered superconducting system. Superconductivity is always degraded with increasing disorder as a result of enhanced repulsive Coulomb interactions between electrons which affects the formation of Cooper pairs[5,14]. Interestingly, a recent theoretical study demonstrates that strong screening of long-range Coulomb interactions leads to enhancement of superconductivity[15]. It has already been shown that a nearby, but electrically isolated two-dimensional electron gas (2DEG) can promote superconductivity in a 2D Josephson junction array[16]. To date, study of the presence of a 2DEG in close proximity to a weakly-disordered superconducting
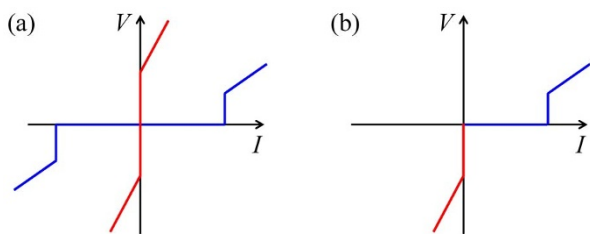
Figure 1 | Schematic diagrams showing (a) the antisymmetric current-voltage features $V(I)$ in the superconducting regime (blue line) and in the insulating regime (red line) in the ideal case. (b) The extreme case for the $V(I)$ characteristics of a superconducting diode.

system is still lacking. The nearby, but electrically isolated 2DEG may affect effective disorder in the superconducting film and thus superconductivity.

As shown in Fig. 1 (a), for an ideal case in the superconducting regime, when reversing the supercurrent flow, there is no voltage drop $V(I) = V(-I) = 0$. In the insulating regime, unless a high enough voltage is applied, there is no current flowing. Figure 1 (a) also illustrates that the current-voltage characteristics $V(I)$ always show antisymmetric behavior, i.e. $V(I) \approx -V(-I)$, in a single condensed-matter system. In contrast, diode behavior where $V(I) \neq -V(-I)$ is readily achieved in a semiconductor-based p-n junction. However, semiconductor-based devices cannot sustain high power density and the heat produced by the large current flowing through them would degrade the device performance and reduce its life-time. Superconductor, free of heating effects in the superconducting state, may be the most promising candidate for high-power applications. Therefore it is highly desirable to experimentally realize a superconducting diode, in which supercurrent can only flow in a specific direction. Interestingly, breakdown of antisymmetric feature is possible under the condition that the superconducting transition occurs at different magnitude of I when the current polarity is changed. An extreme case illustrating deviation from antisymmetric $V(I)$ is shown in Fig. 1 (b), where superconductor-insulator transition occurs at $I = 0$, resulting in an ideal superconducting diode. According to phase-charge duality, when either ΔN or $\Delta \theta$ is changed, the superconducting nature can be modified. In other words, finding a way to control the effective disorder within a superconductor is essential for preparing a superconducting diode.
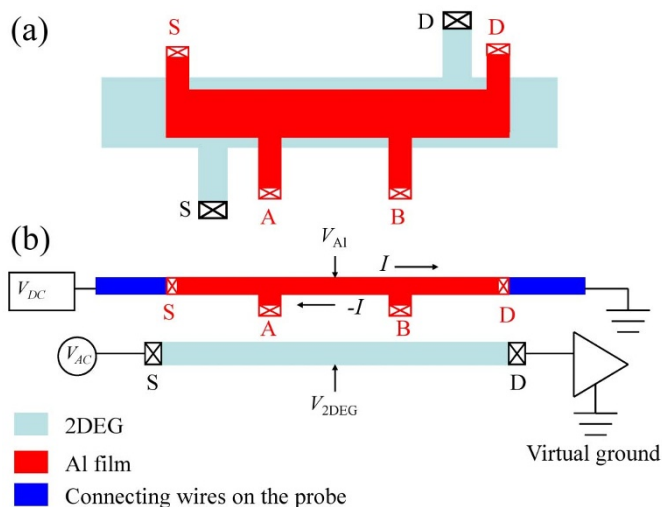

Figure 2 | (a) The sample layout, and (b) circuitry used in our work. S and D correspond to source and drain contacts, respectively. A and B are voltage probes.

In this paper, we report measurements on a hybrid nanofilm device which consists of a 2DEG in close proximity to (70 nm apart) an Al superconducting nanofilm. Schematic diagrams illustrating the sample geometry and measurement circuit are shown in Fig. 2 (a) and Fig. 2 (b). By utilizing the presence of the disordered 2DEG layer on a close-by superconductor, it is possible to control the effective disorder in the detected superconducting film. Moreover, it is shown that a quantum system can affect the nearby device, and in turn, the close-by device can perturb the quantum system itself. We show that when a large current is flowing through the Al film, the effective disorder within the Al nanofilm is varied under which deviation from the expected anti-symmetric $V(I)$ behavior and thereby diode-like behavior are observed. Temperature and magnetic field dependences of such an effect further supports that extra disorder has indeed been introduced into the Al superconducting layer. Most importantly, our results may open up a new avenue to prepare a superconducting diode.

Results

Before presenting our main results, it is important to understand both conductance measurements on our 2DEG as a function of voltage V_g applied on the Al film which acts as a front gate $G(V_g)$, and conductance measurements on the 2DEG as a function of current I flowing in the Al film $G(I)$. Such results are shown in the insets (a) and (b) of Fig. 3. By applying a sufficiently high negative V_g, we are able to deplete the 2DEG underneath the gate, thereby drastically reducing the two-terminal conductance between the source and drain contacts to the 2DEG. By applying a positive bias, we can increase the 2DEG density under the gate. As a result, G can be increased. We note that $G(I)$ and $G(V_g)$ show very similar behavior. In order to understand the observed $G(I)$ characteristics, we need to consider the wires on the top-loading probe which connect the Al film as shown in Fig. 2 (b). When $I > 0$, the potential of the Al film is higher than ground and virtual ground in the 2DEG circuit since there is a positive voltage drop in the wire connecting to the right of the Al film. Similarly, when $I < 0$, the potential of the Al film is lower than ground and virtual ground of the 2DEG circuit because there is again a positive voltage drop in the wire region along the current direction. Therefore increasing (decreasing) I in the Al film circuit effectively increases (decreases) the potential of the Al film with
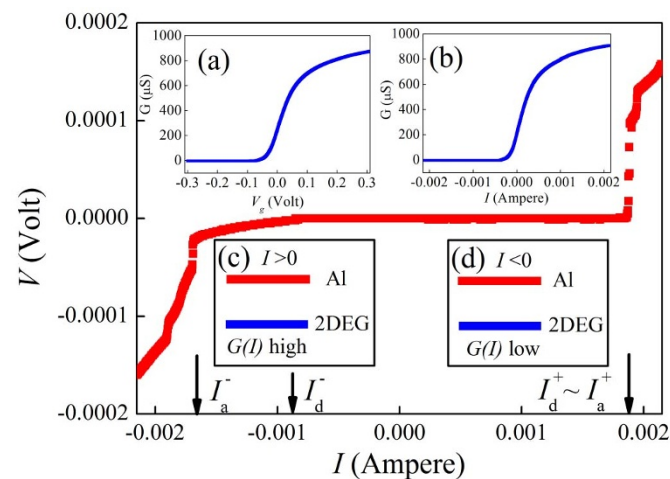

Figure 3 | **Four-terminal dc characteristics of the Al film $V(I)$ at $T = 0.33$ K.** Inset (a) Two-terminal ac conductance measurements of the 2DEG as a function of gate voltage applied on the Al film $G(V_g)$. Inset (b) Two-terminal ac conductance of the 2DEG as a function of current flowing through the Al film $G(I)$. Insets (c) and (d) show that the conductance of the 2DEG can be high (low) when $I (-I)$ flows through the Al film.

respect to ground and thus virtual ground of the 2DEG circuit. Such an effect may not be very pronounced in most cases. However, in our experiments, a very high current of about 2 mA is flowing through our Al film. The wires on the probe whose resistances are of order of 100 Ω and therefore a voltage drop of 0.2 V can be caused. Consequently $G(I)$ behaves like $G(V_g)$.

We now describe our main experimental findings. As shown in Fig. 3, for $I > 0$, there is an abrupt rise at $I_d^+ \sim I_a^+ = 1.9$ mA, where I_d^+ (I_d^-) and I_a^+ (I_a^-) correspond to the onset of dissipation current and the abrupt change in the voltage for $I > 0$ ($I < 0$), respectively. On the other hand, for $I_d^- \approx -0.9$ mA, we have already observed a dissipative voltage drop whose magnitude increases gradually with increasing $-I$. There also exists an abrupt voltage change at $I_a^- \approx -1.6$ mA for $I < 0$. For either $I > 1.9$ mA or $I < -1.6$ mA, unpaired electrons dominate the transport whereas for -1.6 mA $\leq I \leq -0.9$ mA both Cooper pairs and unpaired electrons contribute to the conduction. We note that the conductance of the 2DEG $G(I = 0.9$ mA$) \approx 780$ μS, which is much higher than $G(I = -0.9$ mA$) \approx 0$. Therefore when reversing the current polarity at a high I the conductance of the 2DEG and hence the effective disorder experienced by the Al nanofilm is vastly different as shown in the insets (c) and (d) of Fig. 3. Therefore the breakdown of $V(I) \approx -V(-I)$ as shown in Fig. 3 can be observed. In our system, the presence of the nearby, but electrically isolated 2DEG can break the antisymmetric behavior $V(I) \approx -V(-I)$, revealing a possible way to realize a superconducting diode. In order to further study this interesting effect, we perform measurements on an Al film of the same thickness but deposited on a GaAs semi-insulating substrate. In this case, there does not exist a 2DEG close to the Al film. In this control sample, anti-symmetric $V(I)$ characteristics are restored and the onset of dissipative conduction coincides with the emergence of an abrupt change in V for both $I > 0$ and $I < 0$ as illustrated in Fig. 4. In contrast, in our hybrid system for $I < 0$ the dissipative conduction occurs gradually with decreasing I below -0.9 mA and the superconductivity is completely destroyed at $I = -1.6$ mA. It can be seen clearly that the abrupt changes in V occur at the currents I_a^+ and I_a^- whose magnitudes are larger in our hybrid film system than that in the control one for both $I > 0$ and $I < 0$ showing that the presence of the 2DEG layer plays a role in both current directions. This result also reveals the disordered feature of 2DEG in the pinch-off regime where $G \approx 0$. In this regime, electrons are strongly localized in local domains, which is qualitatively
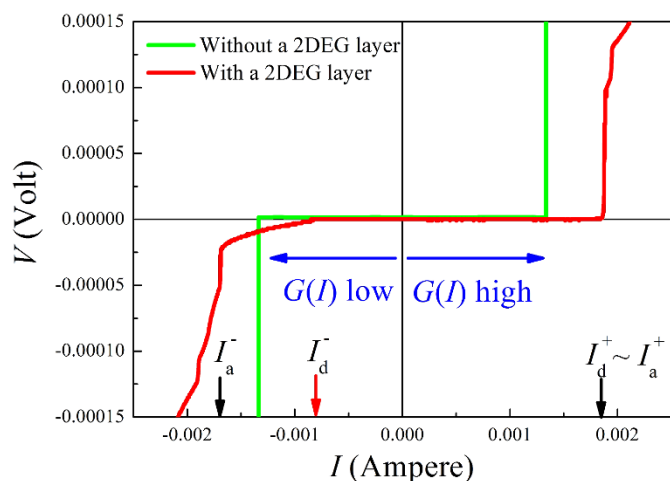
different from the so-called band insulator. In a band insulator there is no conducting electrons when T approaches zero. In a disordered 2DEG whose G is almost vanishing, local electron puddles can still screen Coulomb potential fluctuations in the Al film but this effect is not as pronounced as that for $I > 0$ where G is large. This can explain a slightly lower absolute value of I_a^- for $I < 0$ compared to that of I_a^+ for $I > 0$ in our hybrid system. Moreover, the fact that $-I_d^-$ is smaller than $-I_a^-$ for $I < 0$ indicates that Cooper pairs can coexist with unpaired electrons between the low-current superconducting and the high-current normal state.

To further study the observed disordered 2DEG effect on the superconducting Al film, both T-driven and H-driven superconducting transitions are measured. The $V(I)$ characteristics at various temperatures are shown in Fig. 5. With increasing T, the abrupt change in $V(I)$ occurs at a lower I. We can see that deviation from antisymmetric behavior persists up to $T = 1.13$ K. The $V(I)$ curve is almost linear at $T = 1.29$ K. Finally we see Ohmic behavior at $T = 1.36$ K. At the lowest temperature $T = 0.33$ K, I_a^+ coincides with I_d^+. However, with increasing T, it is found that I_d^+ can be different from I_a^+, which is ascribed to the reduced value of G, thereby increased the increased effective disorder experienced by the Al film with decreasing the current I necessary to destroy superconductivity. The inset of Fig. 5 shows $G(I)$ at the lowest and highest measurement temperatures. We can see that $G(I)$ shows a very weak T-dependence. Therefore both I_d and I_a are mainly determined by the measurement temperature itself and affected by the disordered 2DEG layer.

It is well known that applying a magnetic field can suppress superconductivity. Figure 6 shows the four-terminal $V(I)$ at various magnetic fields H. We can see that for $H \geq 4$ mT, the superconducting transition becomes broadened, and no abrupt changes in $V(I)$ are observed. That is, there is no clear difference between I_d^+ (I_d^-) and I_a^+ (I_a^-) for $H \geq 4$ mT. Moreover, the antisymmetric characteristics are restored for $H > 8$ mT. There are some differences between the T-driven and H-driven cases. By comparing the T-driven result for $T = 1.13$ K where an abrupt rise in V can still be found as shown in Fig. 5 with the H-driven one for $H = 8$ mT shown in Fig. 6 having similar I_d^+ near 0.5 mA, we suggest that T-driven and H-driven superconducting transitions are of different origins in our hybrid nanofilm system. As shown in the inset (b) of Fig. 6, $G(I)$ shows nominally no H dependence, similar to the data shown in the inset of Fig. 5. Therefore the superconducting transition is mostly determined by the applied magnetic field. It is known that from the resistive mid points at various T, that is, when the resistance of the Al film reaches half of the normal state at a certain H, we are able to determine
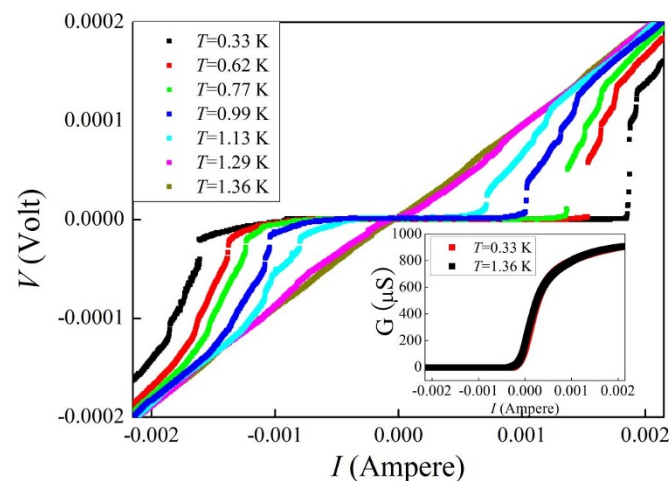

Figure 4 | Four-terminal current-voltage characteristic of the Al films $V(I)$ at the lowest temperature (0.33 K) with and without a 2DEG layer. Here I_d^+ and I_a^+ correspond to the onset of dissipation current and the abrupt change in the current for $I > 0$, respectively. In contrast, I_d^- and I_a^- correspond to the onset of dissipation current and the abrupt change in current for $I < 0$, respectively.

Figure 5 | Four-terminal current-voltage characteristics of the Al film $V(I)$ at various temperatures T. The inset shows $G(I)$ at the lowest (0.33 K) and highest measurement temperatures (1.36 K).
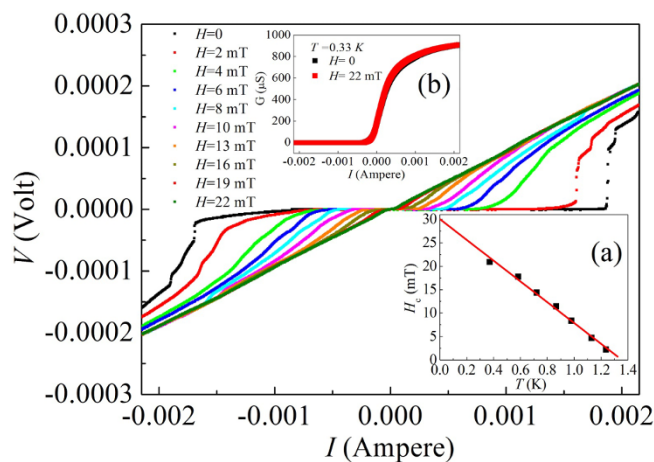
Figure 6 | Four-terminal current-voltage characteristics of the Al film $V(I)$ at various magnetic fields H. Inset (a) shows critical field H_c as a function of T. Inset (b) shows $G(I)$ at the lowest and highest magnetic fields.

$H_c(T)$[17]. Such results are shown in the inset (a) of Fig. 6. We can see that H_c shows a linear dependence on T, consistent with a dirty superconductor. At high T or high B with reduced I_d, the antisymmetric behavior are restored, which can be seen in Fig. 5 and Fig. 6, since there is no significant difference of G in different current directions and the Cooper pairs almost disappear. These results represent compelling evidence that effective "coupling" between electrons in the Al film and those in the 2DEG layer plays an essential role in breaking the antisymmetric $V(I)$ characteristics.

Discussion

We have observed clear deviation from the antisymmetric behavior in the I–V characteristics of the superconducting Al film, which results from the 2DEG back-action when a high current is injected into the Al film. It has been demonstrated that this process occurs as a result of controllable screening ability of disordered 2DEG layer on the close-by Al film. For $I > 0$, the 2DEG behaves as a metal gate in screening Coulomb potential fluctuations and therefore the superconductivity is promoted. For $I < 0$ the disordered 2DEG in its insulating state leads to introduction of extra disorder in the Al film and thereby superconductivity can be suppressed. Due to the breakdown of antisymmetric feature in the I–V relation our hybrid nanosystem provides an avenue to develop a promising superconducting diode device.

Methods

Fabrication of hybrid device. The AlGaAs/GaAs heterostructure LM4745 used in this work was grown on a GaAs semi-insulating (100) substrate using molecular beam epitaxy and consists of the following layer: 1 μm GaAs buffer layer, 20 nm undoped $Al_{0.33}Ga_{0.67}As$ spacer layer, 40 nm doped $Al_{0.33}Ga_{0.67}As$, and 10 nm undoped GaAs cap layer. On top of the AlGaAs/GaAs heterostructure, a 60-nm-thick Al film was deposited using electron gun evaporation. Both the AlGaAs/GaAs heterostructure and Al film were patterned into Hall bar geometry using standard optical lithography. A separate measurement on an ungated heterostructure cut from the same wafer shows that the 2DEG has a concentration of 2.5×10^{11} cm^{-2} and a mobility of 6×10^5 cm^2/Vs at 1.5 K.

Electrical measurements. Experiments were performed in a top-loading He^3 cryostat. Four-terminal dc $V(I)$ and two-terminal ac conductance G measurements were simultaneously performed on the Al film and the 2DEG, respectively. The magnetic field is applied perpendicular to the 2DEG and Al film planes.

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Acknowledgments

Author contributions

S.T.L., K.Y.C., T.L.L. and M.R.Y. measured the samples. S.D.L. and J.Y.W. fabricated the samples. S.T.L., T.M.C. and C.T.L. drafted the paper. C.T.L. and S.D.L. coordinated the project.

Additional information