Large Enhancement of Critical Current in Superconducting Devices by Gate Voltage

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The gate-voltage-induced suppression of critical currents in metallic superconductors observed recently [De Simoni et al., Nat. Nanotechnol. 13, 802 (2018)] has raised crucial questions regarding the nature and mechanism of the electric field effect in these systems. Here, we demonstrate an enhancement of up to 30 % in critical current in the type II superconductor NbN, micro- and nano superconducting bridges, tunable via a back-gate voltage. Our suggested plausible mechanism of this enhancement in critical current based on surface nucleation and pinning of Abrikosov vortices is consistent with expectations and observations for type-II superconductor films with thicknesses comparable to their coherence length. Furthermore we demonstrate infinite electroresistance and a hysteretic resistance dependence on the applied electric field which could lead to logic and memory applications in a superconductors-based low-dissipation digital computing paradigm. Our work thus provides the first demonstration of an electric field enhancement in the superconducting property in metallic superconductors, constituting a crucial step towards understanding of electric field-effects on the fundamental properties of a superconductor and its exploitation for future technologies.

Introduction.—Semiconductor-based field-effect transistors (FETs), which have been instrumental in the silicon revolution, operate through modulation of resistance between the source and drain electrodes via an applied gate voltage. This modulation, in turn, is achieved via a change in the charge carrier density resulting from the electric field generated by the gate voltage. The relatively low carrier densities in semiconductors allows for a strong resistance modulation with reasonable gate voltages thereby enabling broad functionalities. Such a field effect is not expected to work with metals, which have a very high charge density compared to what can be induced by a gate voltage, and was shown to be negligibly weak [1–2].

Considered immensely useful, gate-voltage modulation of superconductivity has been attempted for some time [3–6]. Conventional superconductors have been amenable to control via interaction with magnets [7–11], but not electric fields. The superconducting properties, such as the critical temperature \( T_c \), of metallic superconductors were found to be fairly insensitive to gate voltages [8–12], exhibiting a minuscule change of \( \sim 10^{-3}\% \). In contrast, unconventional superconductors based on strongly correlated oxides admit an efficient gate-modulation due to their relatively low carrier concentration [4–6]. The change in density of states at the chemical potential, which is associated with the gate-modulated carrier density, alters the superconducting order parameter and qualitatively explains the experimental observations discussed above [6–12]. This implies that superconducting properties, such as \( T_c \), can be enhanced (reduced) by an increase (decrease) in the density of states via a positive (negative) gate voltage. The change in superconducting properties is thus odd in the gate voltage, i.e. unipolar.

In contrast with previous literature and expectations [12–13], De Simoni and coworkers recently discovered a gate-voltage-induced suppression of the critical current \( (I_c) \) in type-I metallic superconducting bridges [13–15]. Furthermore, the observed suppression is even in the gate voltage, i.e. bipolar. Apart from the technological potential, these observations have raised two fundamental questions regarding (i) how a gate-voltage-induced electric field is experienced by a superconductor [12–13–16], and (ii) what mechanism causes a change in the \( I_c \). These crucial issues remain unaddressed thus far, although the possibility of metallic puddles creation [15], that could reduce the \( I_c \), has been floated. Other related mechanisms that may degrade superconductivity could be envisaged as accounting for the observed reduction.

Here, we demonstrate a bipolar gate-voltage-induced enhancement in the \( I_c \) of NbN-based superconducting bridges by 30%. We qualitatively discuss a possible mechanism for the critical current modulation that is consistent with the experiments. We hypothesize that the \( I_c \) in our films made from a type-II superconductor is determined by the Bean-Livingston barrier [17] for the vortices nucleating at a surface and tending to move across the film [18–19]. When the supercurrent is large...
enough, vortices are able to break the surface barrier and move, thereby causing dissipation and loss of superconductivity [18, 19]. A gate-voltage-induced enhancement of this surface barrier may account for our experiments and is consistent with related literature [18, 21]. Besides uncovering novel fundamental phenomena, we demonstrate infinite electroresistance, i.e. gate-voltage-controlled change in resistance between zero and a finite value, and hysteretic resistance variation vs. gate voltage. These two effects could be exploited for low-dissipation logic and memories based on superconductors. We further demonstrate that the observed phenomena work for bridges in the nanoscale providing a dissipation logic and memories based on superconducting film and the $\xi$ at Fermi level [24] and $\mu_0$ is magnetic permeability in vacuum. The Ginzburg-Landau coherence length is estimated as $\xi_{GL} = \sqrt{\hbar l R_N / N_F} e^2 \Delta_0 \approx 9 \text{nm}$, where $N_F = 1.65 \times 10^{28}/(m^3 eV)$ is the density of states in NbN at Fermi level [24] and $e$ is the electronic charge.

Further, the same $\mu$B was investigated for its electric field response by applying back-gate voltage as depicted in Fig. 1(a). Figure 2 (a) shows current-voltage characteristics of the $\mu$B at different back-gate voltages ($V_G$ varying from -80 V to +80 V) at 4.2 K. The $I_c$ enhances

![FIG. 1. NbN device schematics and characterization. (a) Schematic depicting the measurement geometry of NbN bridges. (b) Pseudo-color scanning electron micrographs (image taken with sample tilted by 55°) of the fabricated 100 nm wide NB (left) and 1 μm wide $\mu$B (right). (c) Resistance versus temperature variation for the $\mu$B device showing the superconducting transition at $\approx 10.8$ K. Inset shows current-voltage characteristics of the device at 4.2 K.]

![FIG. 2. Gate-voltage-control of the $\mu$B properties at 4.2 K. (a) Current-voltage characteristics for various values of the back-gate voltage $V_G$. (b) $I_c$ as a function of back-gate voltage. Scale on the right shows the corresponding enhancement percentage. (c) Resistance of $\mu$B as a function of back gate voltage at a constant current bias of 85 $\mu$A.]

Synthesis and Fabrication.—Niobium nitride (NbN) thin films with thicknesses $t = 10$ nm and 7 nm were grown on Si/SiO$_2$ substrates (Fig. 1). The 300 nm thick SiO$_2$ layer ensured electrical isolation between the superconducting film and the $p$-doped Si substrate acting as the gate. NbN thin films with Al$_2$O$_3$ ($t = 5$ nm) capping were grown in situ by reactive DC magnetron sputtering (for NbN) and by standard RF non-reactive magnetron sputtering (for Al$_2$O$_3$). Substrates were annealed at 573 K for 1 hour in UHV prior to the deposition. The base pressure of the sputtering chamber before the film deposition was below $5 \times 10^{-8}$ Torr. The multilayer structures were then converted via lithography into a microbridge ($\mu$B), with length $l = 10$ μm, width $w = 1$ μm, and thickness $t = 10$ nm, and a nanobridge (NB) with $l = 1$ μm, $w = 100$ nm, and $t = 7$ nm (Fig. 1). Negative-tone resist was spun on the film and exposed at 10 kV following a soft bake. The resulting pattern was developed and the samples were then Ar$^+$ ion-milled to fabricate the bridges.

Results.—We first present our experiments on the $\mu$B device. It was cooled down below its transition temperature into the superconducting state. A transition temperature $T_c \approx 10.8$ K can be seen in the temperature dependence of resistance shown in Fig. 1(c). The inset depicts the corresponding I-V characteristics at 4.2 K showing a $I_c$ of about 82.5 $\mu$A. The Bardeen-Cooper-Schrieffer (BCS) energy gap $2\Delta_0 = 4.05$ k$_B$T$_c$ corresponds to $\approx 4.16$ meV, where $k_B$ is Boltzmann constant [22, 23]. The London penetration depth is derived from the above parameters as $\lambda_L = \sqrt{\hbar / R_N w t / \pi \mu_0} \lambda_0 \approx 450$ nm, where $l = 10$μm, $w = 1$μm, and $t = 10$ nm are length, width, and thickness of the bridge, respectively. $R_N = 2$ $k$Ω is the resistance in the normal state at low temperature, and $\mu_0$ is magnetic permeability in vacuum.
FIG. 3. Back-gate-controlled switching between superconducting and normal states at different bias currents. Resistance of the µB as a function of back-gate voltage for bias currents of (a) 90 µA, (b) 92.5 µA, (c) 95 µA, and (d) 150 µA. Both forward and backward sweeps are shown.

with increase in gate voltage from ≈ 80 µA to 105 µA. The enhancement shows a nearly symmetric response with respect to the gate voltage polarity [Fig. 2 (b)] and is observed to be ≈ 30% which is the largest modulation to date [14]. As discussed below, the observed enhancement in the I_c, as compared to the previously reported suppression [14], may be attributed to our choice of superconductor (type II) and the film thickness, which is comparable to the superconducting coherence length. Next, we examine the resistance variation with gate voltage [Fig. 2(c)] biasing the device at a constant current of 85 µA. The device completely recovers the superconducting state from normal state for a finite value of gate voltage < 20 V. This modulation of resistance may be used to define an “electroresistance” ER, similar to the well-known magnetoresistance [25][28]. ER ≡ (R_{max} − R_{min})/R_{min}, which assumes infinite value for our µB. The response is symmetric with respect to gate voltage polarity and is a direct consequence of the gate-voltage-induced I_c enhancement. We rule out the possibility of such a response as being due to heating or electronic refrigeration effects as mentioned in Ref. [24] by highlighting that the measurements were performed by immersing the sample in a liquid Helium dewar. This helps maintain the sample in complete thermodynamic equilibrium.

We also study electric field-induced switching of the device by applying different bias currents (90 µA, 92.5 µA, 95 µA and 150 µA) as shown in Fig. 3. The back-gate voltage was scanned for both upward (negative to positive) and downward (positive to negative) directions. While we are successfully able to drive the system from superconducting to normal state and vice versa, we observe hysteresis with gate voltage sweeps as it approaches the transition voltage. With increase in the bias current, the gate voltage required for the transition is higher and the hysteresis becomes more prominent. This could arise as a consequence of charge pinning due to surface inhomogeneities in the thin film. The range over which the quasi-normal state exists broadens with increase in the bias current which may be attributed to inhomogeneous superconducting state at higher currents or intrinsic thermal excitation in the sample, and not due to phase dynamics in the superconductor. Such scaling of the area under the hysteresis curve with bias current makes our devices a potential candidate for cryogenic memory systems [14, 30]. However the hysteresis may weaken in thinner films [31]. When the bias current is set to a relatively large value of 150 µA, the system does not achieve the superconducting state [Fig. 3(d)] within the limits of gate voltage allowed by the SiO_2 dielectric.

In order to examine the dependence of gating effect on the bridge dimensions and probe the device scalability to nano-regime, we now present results for the NB device with thickness t = 7 nm (t < ξ_{GL}). Here, the aspect ratio w/l = 1/10 was kept the same as that of the µB. The resistance versus temperature curve in Fig. 4(a) shows a superconducting transition close to 12 K. However, the I-V characteristics show an additional normal metal behavior with finite resistance at 4.2 K [inset of Fig. 4(a)]. This appears to be the result of the edge disorder caused by Ar ion milling and the concomitant degradation of the nanowire causing a small drop in the T_c [32]. Further, we gate the NBs and observe a transition in the I_c-like feature [Fig. 4(b)], similar to that of the µB device discussed previously. On biasing with a constant current of 10 µA and scanning the gate voltage, the NB recovers the superconducting state with a much broader hysteresis [Fig. 4(c)] possibly due to increased charge pinning effects. The ER in this case is nearly 1400%, which is extremely large but finite since the NB does not transi-
Mechanism and discussion.—We now discuss a likely mechanism for the observed enhancement in the $I_c$. A dissipation-less charge current is carried by the Cooper pairs in a superconductor up to a maximum value $I_c$. A current larger than this value suppresses superconductivity, driving the system to its normal state. For superconducting layers with thickness $(t) \ll$ coherence length $(\xi)$, $I_c$ is the current at which the corresponding kinetic energy of Cooper pairs becomes large enough to cause destruction of the superfluid condensate [15, 19, 34]. In addition to this mechanism, for type II superconductor films with $t$ larger than or comparable to $\xi$, it becomes energetically favorable for vortices nucleating at one surface to move across to the other at large enough currents. This instability of the vortex system then determines the $I_c$ [18, 21].

For zero gate voltage and a current $I$, the superconducting gap is spatially homogeneous without any vortices in the film. However, as the current increases, vortices have a tendency to be nucleated and annihilated at the surface, where they are pinned on account of the free energy profile across the film thickness (Fig. 5), also known as Bean-Livingston barrier [17]. As the current increases, the barrier becomes weaker and the energy profile becomes monotonic at the $I_c$ [19]. This results in spontaneous nucleation of vortices at one surface propagating across the film to the other, where they are annihilated. We hypothesize that as the gate voltage is applied, the short ranged electric field and charge density thus created close to the surface also influence the vortex energy profile, causing an additional gate voltage-dependent barrier for vortex motion. A larger current is thus required for the vortices to overcome the total barrier (Fig. 5). Such an energy barrier may result from interfacial spin-orbit interaction, for example, and is expected to be even in the electric field. The suggested mechanism is thus consistent with our observation of $I_c$ enhancement essentially symmetric in gate voltage polarity as well as the relative insensitivity of $T_c$ to the gate voltage. We note that the possibility of a modification in the surface barrier for the vortices via an interfacial spin-orbit contribution to the free energy has been alluded to recently [35]. Furthermore, a possible role of magnetic impurities in determining the electric-field-induced vortex pinning in our devices cannot be ruled out. As detailed in the Supplemental Material [33], we have observed similar gating effects in NbN/GdN bilayer films, where the ferromagnetic GdN layer may play a role via exchange-coupling to the superconducting NbN layer.

Finally, we compare our observations and the proposed mechanism with related previous experiments [14, 15]. The crucial novelty in our case is the $I_c$ enhancement, as opposed to the previously reported suppression [14, 15]. The two features common to our experiments and previous studies [14, 15] are symmetric response with respect to the gate voltage polarity and the relative insensitivity of $T_c$ to the gate voltage. The previous experiments [14, 15] have speculated their observed suppression in the $I_c$ as being due to an electric field induced spatial modulation of the order parameter in the superconductor [14] or creation of metallic puddles [15]. Such models do not seem to permit an enhancement in the $I_c$. The mechanism that we propose here attributes the $I_c$ magnitude to vortices as is typically the case for films made of type II superconductors with thicknesses comparable to or larger than their coherence length [18, 21]. This model allows for enhancement as is observed in our experiment and is consistent with other features of the data. At the same time, it is suggestive of the observed suppression for films much thinner than the coherence length [18, 21], which do not support vortices. In such thin films, the effect of gate-voltage-induced free energy contribution can be expected to strain the superconducting state as the thickness is insufficient for the order pa-
rameter to accommodate the change. This may result in puddle formation or similar degrading effects on the superconducting order thereby reducing the $I_c$.

**Conclusion.**—We have demonstrated gate-voltage-induced enhancement by up to 30% in $I_c$ of NbN-based superconducting bridges. The qualitative model that we put forward explains our experiments in terms of gate-voltage-controlled surface pinning of vortices. Capitalizing on this voltage control, we demonstrate infinite electroresistance and hysteretic resistance variation in our devices making them promising candidates for logic and memory applications. Our work thus provides fundamental new insights into the field-effect in superconductors paving the way for an even larger voltage-controlled enhancement of superconducting properties and developing novel low-dissipation computing paradigms.

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