A superconducting switch actuated by injection of high-energy electrons

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Recent experiments with metallic nanowires devices seem to indicate that superconductivity can be controlled by the application of electric fields. In such experiments, critical currents are tuned and eventually suppressed by relatively small voltages applied to nearby gate electrodes, at odds with current understanding of electrostatic screening in metals. We investigate the impact of gate voltages on superconductivity in similar metal nanowires. Varying materials and device geometries, we study the physical mechanism behind the quench of superconductivity. We demonstrate that the transition from superconducting to resistive state can be understood in detail by tunneling of high-energy electrons from the gate contact to the nanowire, resulting in quasiparticle generation and, at sufficiently large currents, heating. Onset of critical current suppression occurs below gate currents of 100fA, which are challenging to detect in typical experiments.

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Superconducting circuits, thanks to their ultra-low power consumption and high speed, offer great promise as building blocks for quantum computing architectures and related cryogenic control electronics. In this context, it is especially intriguing to develop switching devices that can be electrically tuned between a superconducting and a resistive state at high frequency. Ultimately, such a three-terminal device would enable novel functionalities for which no semiconducting counterpart exists, such as cryogenic switches, ultra-sensitive detectors, amplifiers, circulators, multiplexers, and frequency tunable resonators\textsuperscript{13–15}. Several electrically controlled superconducting switches based on the injection of out-of-equilibrium quasiparticles in Josephson junctions have been realized\textsuperscript{16–19}. However, Josephson junctions typically come with limited source-drain critical currents and the requirement to operate in magnetic field-free environments. Consequently, architectures that do not rely on Josephson junctions are subjected to intense study. Such pioneering approaches are based on three or four terminal devices where electrical currents\textsuperscript{13}, locally generated Oersted fields\textsuperscript{14} or heat\textsuperscript{15–17} drive a superconducting channel normal. Finally, recent experiments suggest that moderate electric fields might affect superconductivity in metallic nanowires\textsuperscript{18,19}. Controlling superconductivity in metallic devices via gate voltages would be appealing, however, a satisfactory explanation for the observed phenomena was not provided, yet.

Here, we report an experimental investigation of metallic nanowires subjected to electric fields. Our findings rule out any variation of superconducting properties as a direct consequence of the applied electric field, as suggested in refs.\textsuperscript{18,19}. On the other hand, we highlight the importance of tunneling and field emission from the gate electrode. Detailed measurements indicate that relatively few electrons, injected at energies several orders of magnitude higher than the superconducting gap, trigger the generation of a large number of quasiparticles and weaken superconductivity. This is in stark contrast to previously demonstrated devices actuated by quasiparticle injection at low energy\textsuperscript{10,15,17}, where gate currents comparable to the device critical current (a few μA) were needed for switching. For larger gate currents, injected electrons locally increase temperature and drive the nanowires normal. We characterize the effect of electron injection into nanowires in terms of their critical current and its dependence on gate voltage, temperature, and magnetic field. This basic characterization is performed with different substrates and superconductors. We then investigate how injected quasiparticles influence superconductivity along the length of the channel in a region free of electric fields. After presenting the experimental observations, we will elaborate on their physical origins.

Results

Basic characterization. A typical device is shown in Fig. 1a together with its measurement setup: it consists of a 2 μm long, 80 nm wide TiN wire (blue) with a TiN side gate (red). Wire and side gate are separated by an 80 nm wide gap. Gates and nanowires were defined by electron beam lithography and dry etching of a TiN film deposited on an intrinsic Si substrate (gray). Measurements were performed by low-frequency lock-in techniques by passing a source-drain current $I_{SD}$ in the nanowire and recording the resulting voltage $V$. Gate voltage $V_G$ was applied via a source-measure unit, which also recorded the current $I_G$ entering the gate contact. A second side gate (gray) was not operated in this work and left grounded. Further details on materials, samples fabrication, and measurement techniques are reported in the Methods Section. At $V_G = 0$, the nanowire showed a critical current $I_C = 45$ μA, measured sweeping $I_{SD}$ in either direction starting in the superconducting state. In contrast, when sweeping $I_{SD}$ from the normal state towards zero, superconductivity was re-established below the retrapping current $I_R = 1$ μA. Figure 1b shows the nanowire differential resistance $dV/dI_{SD}$, measured while sweeping $I_{SD}$ in the positive direction. The inset gives the temperature dependence of $I_C$ and $I_R$. The large difference between $I_C$ and $I_R$, especially marked at low temperature, is likely owing to self-heating when the nanowire is in the normal state, together with the difficulty in extracting heat via the substrate or the leads\textsuperscript{20}. Figures 1c, d show $I_C$ and $I_G$, respectively, as a function of $V_G$. For $V_G \sim \pm 2.5$ V, just before $I_G$ reached detection level (~100 fA in our setup), $I_C$ started
Fig. 2 Temperature and magnetic field dependence. a Critical current \( I_C \) of the device presented in Fig. 1 as a function of gate voltage \( V_G \) for various temperatures \( T \) (see legend). b Critical current \( I_C \) of the device presented in Fig. 1 as a function of out-of-plane magnetic fields \( B_\perp \) (see legend). Gray arrows indicate the gate voltage where \( I_C \) starts decreasing.

Fig. 3 Critical current suppression in various superconductors. a, b Critical current \( I_C \) and gate current \( I_G \) as a function of gate voltage \( V_G \) for a TiN wire on a 25 nm thick SiO\(_2\) film thermally grown on Si substrate. The wire is 2 \( \mu \)m long, 80 nm wide, and 20 nm thick. c, d Critical current \( I_C \) and gate current \( I_G \) as a function of gate voltage \( V_G \) for a Ti wire on Si substrate. The wire is 2 \( \mu \)m long, 200 nm wide, and 30 nm thick. e, f Critical current \( I_C \) and gate current \( I_G \) as a function of gate voltage \( V_G \) for a Nb wire on Si substrate. The wire is 2 \( \mu \)m long, 200 nm, wide, and 13 nm thick.

Temperature and magnetic field dependence. Figure 2a, b show the gate voltage dependence of \( I_C \) for various temperatures \( T \) and out-of-plane magnetic fields \( B_\perp \), respectively. Neither temperature nor field affected the \( I_G \) vs. \( V_G \) characteristics of Fig. 1d (see Supplementary Note 1), and resulted in identical \( V_C \) values for complete suppression of superconductivity in the nanowires, up to the critical temperature and critical field. On the other hand, the increase of \( I_C \) suppression systematically moved to higher \( V_G \) for higher temperatures (see gray arrows). A more complicated dependence was observed as a function of \( B_\perp \).

Critical current suppression in various superconductors. Suppression of \( I_C \) concomitant to, or slightly anticipating, the onset of \( I_G \) above detection level was confirmed for over 20 TiN devices, characterized by various gate shapes, nanowire widths (40, 80, and 200 nm), nanowire lengths (650 nm, 1 and 2 \( \mu \)m), and gate-to-wire separations (80 and 160 nm, see Supplementary Note 3). Similar behavior was also observed on devices with a different substrate than Si or with a different superconductor than TiN. Figures 3a, b show measurements performed on a TiN device as that of Fig. 1a, but deposited on a 25 nm SiO\(_2\) layer thermally grown on Si. Despite the vastly different operational range of \( V_G \) with respect to that of Fig. 1, suppression of \( I_C \) still coincided with the onset of \( I_G \). Devices with a SiO\(_2\) interlayer further showed a characteristic asymmetry of the \( I_C \) vs. \( V_G \) curve, with a sharper suppression of \( I_C \) for negative than for positive \( V_G \). Given the sharp termination of the gate electrode, and the large electric field reached on SiO\(_2\) substrates, emission of electrons from the gate is expected to be easier for negative gate biases. In the present case, detection of small gate current asymmetries is hindered by spurious current leakage in the measurement setup for high gate biases. Figure 3c, d show \( I_C \) and \( I_G \) respectively, as a function of \( V_G \) for a Ti nanowire as that of Fig. 1a, but with 200 nm width and 30 nm thickness. In this case, the normal state was reached for \( I_C \) as low as 30 pA for positive \( V_G \). Figure 3e, f show \( I_C \) and \( I_G \) respectively, as a function of \( V_G \) for a Nb nanowire as that of Fig. 1a but with 13 nm thickness. Similarly to the previous cases, \( I_C \) started decreasing with \( I_G \) still below 100 fA. However complete suppression of \( I_C \) required \( I_G \geq 20 \) nA. Overall, these results indicate that the switching mechanism presented here is generic, and not linked to specific superconductors or substrates. On the other hand, data also suggests that small gap superconductors (e.g., Ti) require considerably less gate current for switching to occur with respect to superconductors with larger gaps (e.g., TiN or Nb).

Spatially resolved suppression of the critical current. Measurements presented so far were conducted in relatively short nanowires, where sharp transitions from zero resistance to the normal state were observed. We complement these observations with measurements on a long, multi-terminal nanowire, which allow us to investigate how superconductivity is affected away from the electron injection point, along the nanowire length. The device shown in Fig. 4a consists of six TiN segments of 1 \( \mu \)m length and 80 nm width (named A to F). Each segment \( j \) is controlled by a nearby gate, with gate voltage \( V_G \) and corresponding gate current \( I_G^j \). In a first measurement configuration (Configuration 1), schematically shown in Fig. 4b, \( I_{SD} \) was passed between contacts 1 and 9, that is the DC current is the same for every segment. As \( I_{SD} \) was ramped, voltages \( V_J \) across the six segments were simultaneously recorded. Critical currents \( I_{CR}^j \), defined as the values of \( I_{SD} \) where segment \( j \) turned resistive, are reported in Fig. 4b as a function of \( V_G \), with the corresponding gate current \( I_G^j \) shown in Fig. 4d. Configuration 1 highlights two regimes. For \( I_{SD} > I_{CR} \), switching in all the segments happened simultaneously. For \( I_{SD} < I_{CR} \), switching was sequential: the further away a segment was from the biased gate, the larger was the gate current required to suppress its critical current. We contrast this
behavior with the results obtained using Configuration 2, schematically shown in Fig. 4c. In this case, $I_{SD}$ is routed in one segment only. The critical currents of the six segments were extracted in six separate measurements as $V_{G}^{A}$ was biased (see Fig. 4c). Routing $I_{SD}$ far from the electron injection point avoids the simultaneous switching observed in Fig. 4b, highlighting instead spatial dependence of the critical current also for $I_{SD} > I_{G}$. In Fig. 4e, we plot the critical current suppression factor $S$ as a function of distance $\Delta x$ between injection point and segment. The suppression factor for a segment $j$ is defined as $S' = (I_{C,j} - I_{C,j}^0)/I_{C,j}^0$, where $I_{C,j}^0$ is the critical current of a segment for zero gate voltage. A fit to an exponentially decaying function $\exp(-\Delta x/\lambda)$ (solid line in Fig. 4f), yields a characteristic decay length $\lambda \sim 1.8 \mu m$.

**Discussion**

After presenting the experimental results, we now discuss the origin of the observed phenomena. Injected electrons reach the superconductor in a deep out-of-equilibrium state, with energies of the order $eV_{G}$, much larger than the superconducting gap $\Delta (\Delta = 500 \mu eV$ for TiN$^{21}$). As each electron relaxes to the gap edge by inelastic scattering with other electrons and phonons, up to $eV_{G}/\Delta \sim 10^5$ quasiparticles are generated within the nanowire. A sufficiently high concentration of quasiparticles drives the nanowire normal by quenching the superconducting gap$^{22}$ and suppression of the depairing critical current$^{23}$, leading to a switch to the normal state. The closer $I_{SD}$ is to $I_{C}$, the more sensitive the device becomes, so that relatively few injected electrons can trigger a normal state transition. Indeed, half of the suppression of $I_{C}$ takes place for gate currents below the noise floor of our setup, where the power provided by the gate voltage source is less than 300 W and unlikely to result in any relevant temperature increase. Indeed, a temperature increase $\sim 1.5 \, K$ would be needed for an appreciable variation of $I_{C}$ to be detected (see Fig. 1b). This can be excluded at such small gate currents. Such behavior is reminiscent of superconducting nanowire single-photon detectors (SNSPDs)$^{24,25}$, where the strike of a visible or infrared photon promotes a single electron to high energy, which in turn triggers the generation of a large amount of quasiparticles as it relaxes. In the present case, high-energy charge carriers are provided directly by the gate current. Owing to their close proximity, gate, and nanowire are coupled by phonons, so that dissipation of the injected energy and generation of quasiparticles occurs on both sides. Figures 2a, b show rich physics at low values of $V_{G}$, with the initial suppression of $I_{C}$ moving to higher and higher gate voltages as temperature increases (see gray arrows). This behavior presumably reflects the increase of quasiparticle density in the wire with temperature, requiring more electrons to be injected before a sizable effect on $I_{C}$ is observed. Systematic studies of the more complicated variations of $I_{C}$ vs. $V_{G}$ as a function of $B_{j}$ could shed new light on the physics of field repulsion and vortex penetration in nanowires$^{26}$.

For gate currents several orders of magnitude larger, the power provided to the device is significant and likely to result in an increase of the local lattice temperature. We estimate the minimum power required for keeping the nanowire in the normal state as $P_{R} = I_{R}^2 R_{N}$, which is Joule heating in the normal state and at the retrapping current. For the device of Fig. 1 we obtain $P_{R} = 1.6 \, nW$. This power is similar to one provided by the gate voltage source at the point where superconductivity is suppressed $P_{G} = V_{G} I_{C}$. For the device of Fig. 1, we obtain $P_{G} = 0.61 \, nW$. The difference between $P_{R}$ and $P_{G}$ is readily accounted for by considering that a significant fraction of $P_{G}$ is not dissipated in the nanowire but in the gate electrode and in the surrounding environment. Furthermore, quasiparticles generated within the nanowire spread over a distance longer than the nanowire length, so that a fraction of them thermalizes in the leads (see the following discussion). The relation $P_{G} = 4P_{R}$ is closely followed also for the devices of Fig. 3. The consistency is remarkable considering that dissipated power in the Nb wire ($P_{R} = 29 \, nW$) is three orders of magnitude larger than for the Ti wire ($P_{R} = 23 \, pW$).

After determining that small currents of high-energy electrons are responsible for weakening the superconducting properties, we discuss in more detail how the transition to the normal state takes place. The device of Fig. 1 showed a sharp transition from superconducting to its normal state resistance for any gate voltage. This behavior might appear surprising considering that the gate acts on a short portion of the nanowire. With reference to Fig. 4, we demonstrated that the sharp transition to the normal state resistance is a result of the measurement configuration.
Indeed, $I_C$ is first reduced in a region close to the point of electron injection. As $I_{SD}$ is increased, that region switches to the resistive state and becomes a hotspot due to the large $I_{SD}$ flowing in the nanowire. For $I_{SD} > I_N$ the hotspot warms up the surrounding metal via Joule heating, resulting in a further spreading of the normal region. This process rapidly turns normal the entire nanowire length along the path of $I_{SD}$. For $I_{SD} < I_N$ the power dissipated in the hotspot is insufficient to trigger the transition to the normal state in the nearby metal. In this case, considerable gate currents are needed for influencing the regions of the nanowire, which are furthest away via diffusion of energetic quasiparticles and heat. In Configuration 2, $I_{SD}$ does not intersect the point of electron injection (except for segment A) and simultaneous switching is prevented and the critical current is lowest at the point of injection and restored at large distances. The characteristic length scale of 1.8 µm is presumably related to the diffusion length of long-lived quasiparticles. A framework for calculating quasiparticle density profiles has been put forward for SNSPDs in ref. 26 and is compatible with our experimental results.

Recent work argued on the effect of electric fields on the critical current of metallic nanowires, using a similar device as that of Fig. 1a. From a qualitative standpoint, the modulation of current of metallic nanowires, using a similar device as that of Fig. 4). We further note that the gate current needed for affecting extend far beyond the gate induced electric leading to identical results). Second, suppression of superconductivity and heat. In Configuration 2, $I_{SD}$ does not intersect the point of electron injection (except for segment A) and simultaneous switching is prevented and the critical current is lowest at the point of injection and restored at large distances. The characteristic length scale of 1.8 µm is presumably related to the diffusion length of long-lived quasiparticles. A framework for calculating quasiparticle density profiles has been put forward for SNSPDs in ref. 26 and is compatible with our experimental results.

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Acknowledgements
We thank A. Pushp, B. Madon, and M.A. Mued for deposition of the TiN films. We thank G. Salis, W. Riess, S. Olivadese, and J. Bulzacchelli for fruitful discussions. A. Olziersky, S. Paredes, and U. Drechsler for technical help. F. Nichele acknowledges support from the European Research Commission, grant no. 804273.

Author contributions
F.N. conceived the experiments. A.F. and F.N. designed the samples. S.H and P.G. deposited the Ti and Nb films. M.F.R. and D.Z.H. fabricated the devices. M.F.R., A.F., D.Z.H., and F.N. performed the measurements. M.F.R., A.F., D.Z.H, H.R., and F.N. interpreted and analyzed the data. A.F. and F.N. wrote the manuscript.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41467-021-21231-2.

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Peer review information Nature Communications thanks Alfredo Levy Yeyati and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

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