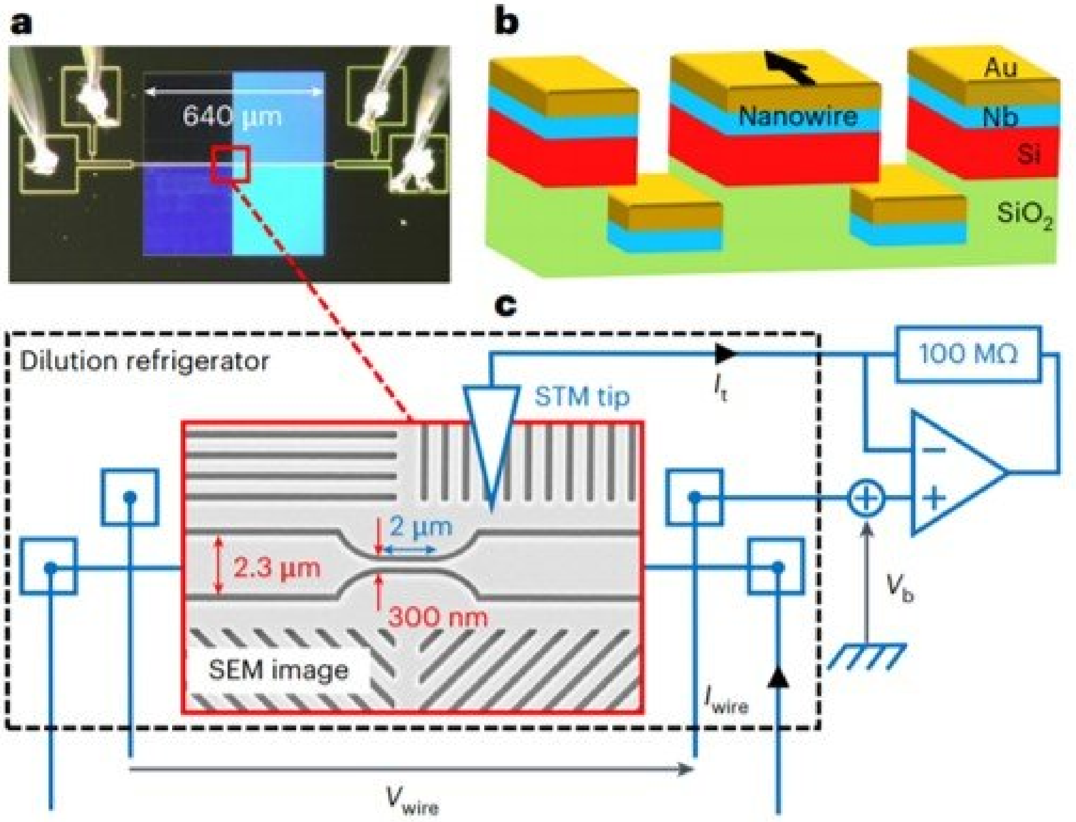
The dynamics of 'hotspot forming' high-energy quasiparticles in a superconducting nanowire

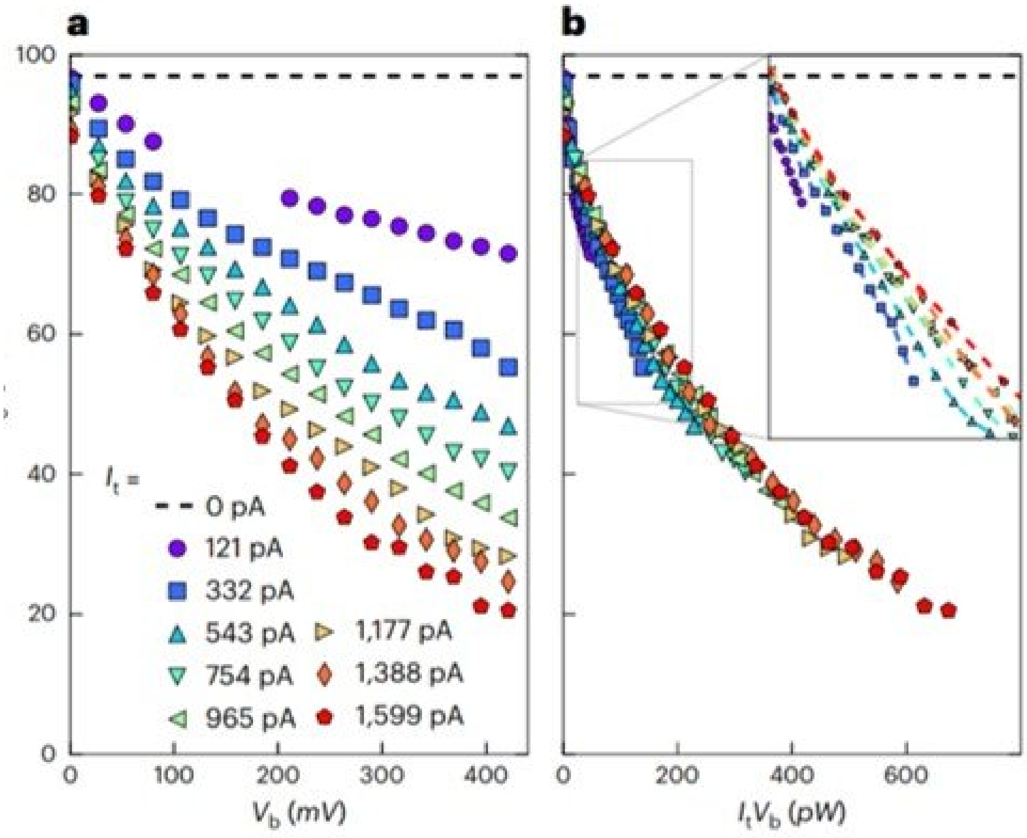
April 25 2023, by Thamarasee Jeewandara



Experimental set-up. a, A nanowire at the centre of a target of lines (blue squares) with four micro-bondings (at the edges). b, A schematic of the sectional view of a nanowire. c, The nanowire is scanned by an STM tip at a bias potential of V_b and tunnelling current of I_t while the I_{wire}–V_{wire} characteristic is monitored. Credit: *Nature Physics* (2023). DOI: 10.1038/s41567-023-01999-4

Energetic quasiparticles possess a collection of quantum characteristics that operate in a particle-like way in superconducting nanostructures, and they can undergo relaxation by involving many cascaded interactions between electrons, phonons and Cooper pairs. These interactions are significant to the performance of devices such as qubits or photon detectors, yet they remain to be well understood via quasiparticle regulated experiments. Typically, such experiments have incorporated solid-state tunnel junctions with a fixed tunnel barrier.

In a new report in *Nature Physics*, T. Jalabert and a team of researchers in France used a scanning tunneling microscope to independently tune the energy and rate of quasiparticle injections via the bias voltage and tunneling current. The high energy quasiparticles relied on the injected power and injection rate to yield a reduced critical current on the nanowire. The outcomes highlighted a thermal mechanism underlying the reduction of the critical current to provide insights into the rapid dynamics of a generated hot spot.

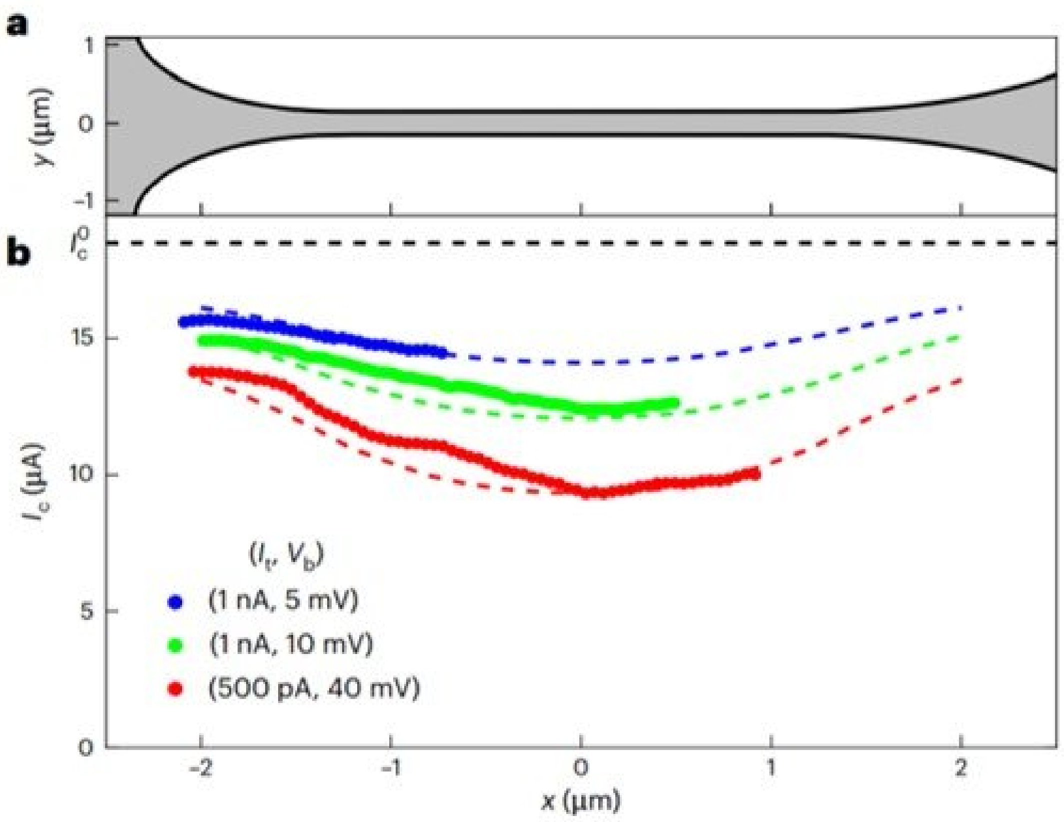


The critical current as a function of the bias voltage and injected power. Sample N03. a, The critical current as a function of the bias voltage V_b for different tunnelling currents I_t at T = 250 mK. The dashed line indicates the critical current value $I_c = 96.3\ \mu A$ when no quasiparticles are injected. b, The same data as a function of I_tV_b. The inset shows a zoom of the data in the gray rectangle. Credit: *Nature Physics* (2023). DOI: 10.1038/s41567-023-01999-4

The performance of superconducting devices

Superconducting devices are often limited or governed by quasiparticle dynamics, where excess quasiparticles are not beneficial for devices such as superconducting micro-coolers and superconducting qubits. However, knowing the precise mechanism underlying quasiparticle dynamics is important in order to optimize device performance and provide a prerequisite to operate photon detectors. Despite intense research efforts, physicists remain to understand the processes at risk during the energy relaxation of quasiparticles in current carrying superconductors.

In a recent proposal, experimental physicists had developed an all-metal Josephson field-effect transistor, which relied on regulating its critical current after applying a gate voltage. This gave rise to considerable controversy since it suggested a heating-effect after injecting high-energy quasiparticles. Previous experiments also routinely employed a method; however, it prevented the disentanglement between current and voltage effects, which Jalabert and colleagues overcame by using a scanning tunneling microscope (STM) to locally inject quasiparticles into a super-conducting nanowire and simultaneously measure its critical current.

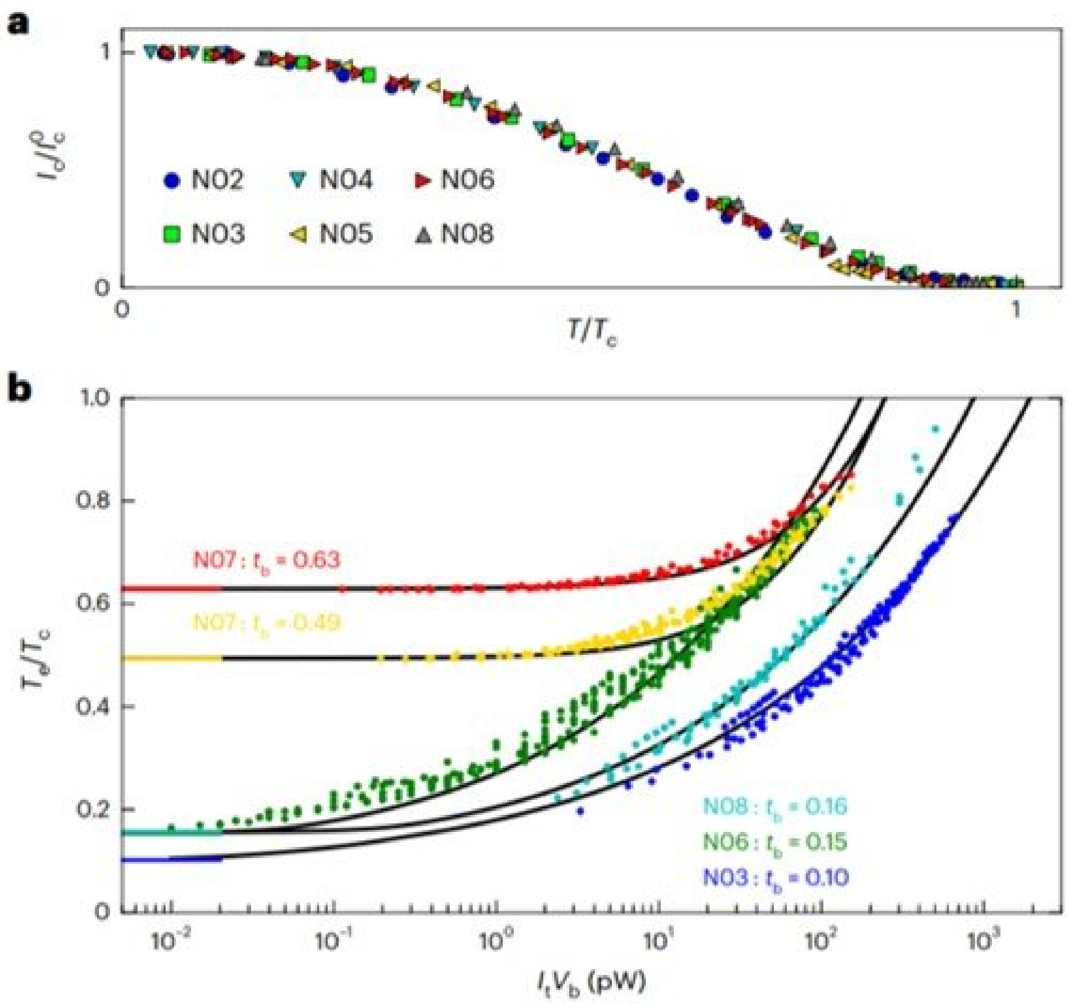


Scanning critical current microscopy. a, Nanowire shape. b, The critical current (dots) as a function of the STM tip position x along the nanowire and averaged along y for different tunnelling conditions at T = 180 mK and the critical current (dashed lines) obtained from the numerical solutions of equation (1) for $\Sigma = 6 \times 109$ W K^{-5} m^{-3}. Without injection current, $I_c = 18.5$ μA. Sample N06. Credit: *Nature Physics* (2023). DOI: 10.1038/s41567-023-01999-4

Experimental physics with scanning tunneling microscopy (STM)

The process of locating and contacting an individual nanostructure with a scanning tunneling microscope is challenging due to the intrinsic incompatibility of the microscope to isolate a nanostructure. Physicists and materials scientists had previously focused on combining atomic force microscopy and STM, although both methods are technically tedious. In this study, Jalabert and the team used STM to locate and measure the nanodevice and studied six superconducting nanowires with different niobium/gold nominal total thickness.

They measured the critical current after injecting quasiparticles in the middle of the nanowire, and noted how the critical current depended on the injected power. In a thermodynamic framework, each quasiparticle injected into the setup relaxed its energy to phonons, which thereby broke hundreds of Cooper pairs to generate many out-of-equilibrium quasiparticles that formed the so-called hotspot. This down-conversion cascade occurred in a very short time-frame in the order of picoseconds.

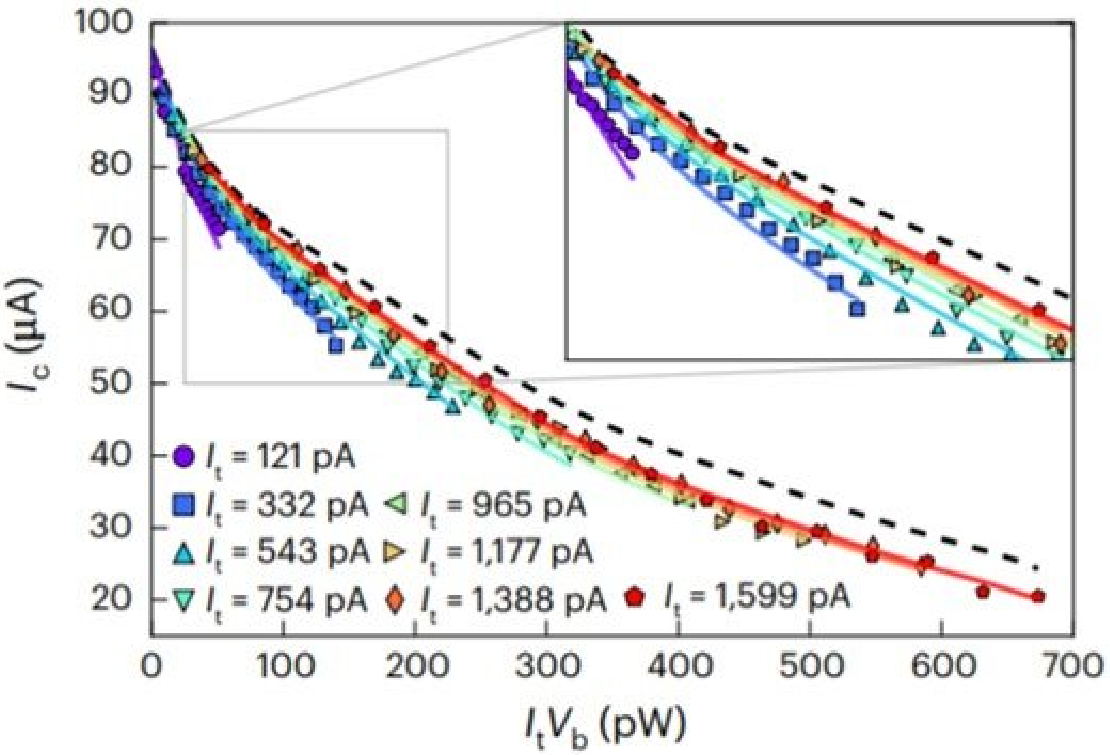


The effect of the power injected by quasiparticles on the electronic temperature. a, The normalized critical current measured without quasiparticle injection I_c(T/Tc) I0c, where I0c is the critical current value at T = 0 K as a function of the reduced temperature. b, The reduced electronic temperature as a function of the quasiparticle power injected by the STM tip. For the sake of completeness, in this set of experiments we varied and measured Tb with the help of a heater and a thermometer glued to the sample holder. Horizontal colored lines on the left indicate the corresponding reduced bath temperature t_b = Tb/Tc. Solid lines correspond to theoretical predictions of equation (1) with $\Sigma = 6 \times 10^9$, 6×10^9, 0.8×10^9 and 8×10^9 W K^{-5} m^{-32} for sample N03, N06, N08 and N07, respectively. Credit: *Nature Physics* (2023). DOI: 10.1038/s41567-023-01999-4

Hotspot dynamics

Using scanning tunneling microscopy, Jalabert and colleagues mapped the current as a function of the tip position for fixed tunneling conditions. As the position of the tip moved away from the leads or as the injected power increased, the critical current decreased further. The physicists determined the local electronic temperature from the measured critical current and noted a remarkable agreement between the one-dimensional heat model. All experimental data were in support of a hot quasiparticle-induced thermally driven reduction of the critical current. They showed how an excess of quasiparticles in the hotspot reduced the density of Cooper pairs available to carry the superfluid current, which agreed with previous studies.

The hotspot dynamics relied on the balance between the proliferating quasiparticles in the down-conversion cascade and their escape through diffusion. In the models described herein, only the growing number of out-of-equilibrium quasiparticles mattered. The time of hotspot formation was 40 picoseconds, which matched the time required for quasiparticle diffusion across the width of the nanowire. The team intend to conduct further studies to solve the coupled kinetic equations of interacting quasiparticles and phonons; beyond the scope of the present work.



Relaxation dynamics of the injected quasiparticles. The critical current I_c at a given power I_tV_b is more reduced when the quasiparticle injection rate is low. The solid lines are numerical fits with τrel = 40 ps. The dashed line is the stationary critical current I stat c .The inset is a zoom at low power. Credit: *Nature Physics* (2023). DOI: 10.1038/s41567-023-01999-4

Outlook

In this way, T. Jalabert and colleagues formed a powerful new method to study the dynamics of local quasiparticles in superconducting nanostructures to tune the tunneling rate and quasiparticle energy. The physicists used the experimental setup to show how the critical current of a nanowire could be significantly reduced by injecting a quasiparticle injection current of several magnitudes lower.

They credited the outcome to the phenomenon of thermal heating of quasiparticles; the results have an immediate impact on the function of superconducting nanodevices such as field-effect transistors and photon detectors, with added capacity to design superconducting quantum circuits with improved effects of quasiparticles in the future.

More information: T. Jalabert et al, Thermalization and dynamics of high-energy quasiparticles in a superconducting nanowire, *Nature Physics* (2023). DOI: 10.1038/s41567-023-01999-4

Citation: The dynamics of 'hotspot forming' high-energy quasiparticles in a superconducting nanowire (2023, April 25) retrieved 26 June 2024 from https://phys.org/news/2023-04-dynamics-hotspot-high-energy-quasiparticles-superconducting.html