InAs nanowire superconducting tunnel junctions: spectroscopy, thermometry and nanorefrigeration

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We demonstrate an original method – based on controlled oxidation – to create high-quality tunnel junctions between superconducting Al reservoirs and InAs semiconductor nanowires. We show clean tunnel characteristics with a current suppression by over 4 orders of magnitude for a junction bias well below the Al gap $\Delta_0 \approx 200 \, \mu$eV. The experimental data are in close agreement with the BCS theoretical expectations of a superconducting tunnel junction. The studied devices combine small-scale tunnel contacts working as thermometers as well as larger electrodes that provide a proof-of-principle active cooling of the electron distribution in the nanowire. A peak refrigeration of about $\delta T = 10 \, \text{mK}$ is achieved at a bath temperature $T_{\text{bath}} \approx 250 - 350 \, \text{mK}$ in our prototype devices. This method opens important perspectives for the investigation of thermoelectric effects in semiconductor nanostructures and for nanoscale refrigeration.

The control over the heat flow and the local electron distribution in a nanodevice represents a crucial experimental challenge [1–3] with an important impact both on the solution of key open problems in fundamental physics and on development of future device applications [4, 5]. In particular, the recent progress of thermoelectric physics in nanostructured materials offers fascinating new perspectives for the realization of more efficient solid-state heat pumps for energy conversion [6–8] and/or for the creation of self-cooling nanodevices where the electron or the phonon system in the active region can be refrigerated below the phonon bath [3, 4]. The progress in these fields calls for the development of novel methods to reliably control heat and measure the device thermoelectric parameters with a nanometer-scale precision [9–12]. Local electronic cooling can be relevant for improving the device performance either in terms of noise, sensitivity or decoherence [4] and for finding a role in advanced applications, including topological quantum computation [13–16] and ultrasensitive radiation detection [17, 18]. In addition, the manipulation of heat is at the basis of the emerging field of coherent caloritronics [1, 19–21] and it could be crucial in solving important standing fundamental problems in condensed matter physics, including quantum thermodynamics and the study of the elusive Majorana fermions in solid-state systems [13, 22, 23].

Hybrid architectures combining superconductive elements with normal metals represent a bright example of refined technology to locally measure and manipulate heat at low temperatures and have been the subject of an intense research effort [3–5]. In particular, devices integrating normal-insulator-superconductor (NIS) tunnel junctions between a normal metal (N) and Al [24] or other superconductors (S) [25, 26] have yielded the demonstration of significant nanorefrigera-
The sample was imaged at 50° to refrigerate its electron system below the bath temperature. Two larger contacts are fabricated at the two ends of the nanowire and are used to extract hot carriers from the InAs nanowire. Two inner 200 nm-wide contacts are used to measure the electron temperature in the InAs nanostructure. InAs nanowire. Two inner 200 nm-wide contacts are used to measure the electron temperature in the InAs nanostructure. Two larger contacts are fabricated at the two ends of the nanowire and are used to extract hot carriers from the InAs and to refrigerate its electron system below the bath temperature. The sample was imaged at 50° angle. (b) Local thermometry is achieved by biasing the inner contacts with a constant current $I_{bias}$ and by measuring the resulting voltage drop $V_{th}$ in four-wire scheme; refrigeration is achieved by biasing the outer contact with a voltage $V_{refr}$. (c) Cross-sectional view of the tunnel junction along the dashed red line in (a): the NIS barrier is obtained by a controlled in-situ oxidation of a non-superconductive Al layer containing Mn impurities with a thickness of 50 nm. A conventional 50 nm-thick superconductive Al layer is evaporated on top of the oxide barrier. A thin 5 nm layer of Ti is deposited between the NW and the AlMn film to promote adhesion.

FIG. 1. Device architecture. (a) Scanning electron micrograph of a typical device: four tunnel junctions are created between the superconductive electrodes (S) and an n-doped InAs nanowire. Two inner 200 nm-wide contacts are used to measure the electron temperature in the InAs nanostructure. Two larger contacts are fabricated at the two ends of the nanowire and are used to extract hot carriers from the InAs and to refrigerate its electron system below the bath temperature. The sample was imaged at 50° angle. (b) Local thermometry is achieved by biasing the inner contacts with a constant current $I_{bias}$ and by measuring the resulting voltage drop $V_{th}$ in four-wire scheme; refrigeration is achieved by biasing the outer contact with a voltage $V_{refr}$. (c) Cross-sectional view of the tunnel junction along the dashed red line in (a): the NIS barrier is obtained by a controlled in-situ oxidation of a non-superconductive Al layer containing Mn impurities with a thickness of 50 nm. A conventional 50 nm-thick superconductive Al layer is evaporated on top of the oxide barrier. A thin 5 nm layer of Ti is deposited between the NW and the AlMn film to promote adhesion.
FIG. 2. Tunnel spectroscopy. (a) Selected IV curves for a typical SI(NW)IS configuration involving the inner device contacts, in the presence of a small out-of-plane magnetic field of 3.3 mT. (b) Same in semi-log scale. At zero bias, the current I is strongly quenched by the superconductive gap in the Al contacts, demonstrating the achievement of high-quality tunnel junctions. Selected experimental data (dots) are compared to BCS theory (solid lines), with good agreement. (c) As expected for a well-behaved tunnel junction, the differential conductance \( G = dI/dV \) is proportional to the convolution of the density of states on the N and S sides of the junctions and the derivative of the Fermi-Dirac distribution. A gap of \( \Delta_0 \approx 208 \pm 1 \) meV can be deduced from a theoretical fit of the experimental data using BCS theory. (d) Normalized zero-bias conductance vs bath temperature.

FIG. 3. Magnetic field suppression. The junctions display a non-trivial behavior as a function of the magnetic field \( B \), as visible from the IV curves in panel (a) and from the corresponding differential conductance traces in panel (b). In particular, normalized differential conductance at \( B = 0 \) highlights the presence of a double step in the density of states. The possible origin of this phenomenon is a residual pairing on the NW side of the tunnel junctions (see text). The full evolution of the effect is better visible in panel (c), reporting the conductance colorplot versus \( B \). A small magnetic field \( (\approx 3 \) mT) quenches the residual proximity in the NW while the rest of the evolution can be understood as due to the quenching of superconductivity in the Al electrodes, as also visible from the evolution of zero-bias conductance in panel (b). The arrows in panel (c) indicate the intermediate values of magnetic field for the plots in panels (a) and (b). (d) The evolution of the normalized zero-bias differential conductance as a function of \( B \) indicates a critical field of Al of about 100 mT.
Superconducting tunnel contacts can be used both for measuring the electronic temperature and to actively cool the electron distribution in the NW [4]. The inner narrower contacts have a larger barrier resistance and are more suited for a local probing of the temperature. The typical response voltage $V_{th}$ for one of the inner SI(NW)IS junctions is plotted in Fig. 4a, for different values of the current bias $I_{bias}$. A responsivity up to about 0.6 mV/K is obtained for a 20 pA bias (see Fig. 4b). The wider tunnel contacts fabricated at the end of the NWs were used to demonstrate local refrigeration of an individual NW. Two devices, named A and B, were tested in such a cooling configuration: the corresponding steady-state temperatures for different bias voltages $V_{refr}$ are plotted in Fig. 4c. The electronic temperature $T_e$ have been extracted from the thermometer calibration of Fig. 4a. The largest cooling is achieved for $|qV_{refr}| \approx \Delta_0$, while heating is obtained for larger bias, as expected for a single NIS cooler [4]. This behavior is consistent with a non-ideal behavior of the current devices, where typically one of the two cooling contacts is too transparent. The minimum electron temperatures $T_{e,min}$ for different bath temperatures are plotted in the upper panel of Fig. 4d. The top temperature reduction $\delta T_{max} = T_{bath} - T_{e,min}$ having its maximum value 10 mK at $T_{bath} \approx 250 - 350$ mK is shown in the lower panel. While the cooling effect remains modest, it demonstrates that our tunnel junction can be effectively used to reduce the electronic temperature in an individual NW. Various non-ideal factors hamper the device performance in the current architecture: (i) the tunnel barrier cools the whole AlMn region, which is wider than the NW (see sketch in Fig. 1c); (ii) the barrier opacity is still not optimal, and typically one of the two contacts of the refrigerator is too transparent. A possible route for achieving a better performance consists of patterning different geometries for the AlMn layer and for the Al layer, so to achieve tunnel junctions which are more controlled and have a smaller area in correspondence with the NW body.

In conclusion, we have demonstrated an original technique for the fabrication of superconducting tunnel junctions on InAs-based semiconductor NWs. The junctions have been shown to be suitable for low-temperature thermometry, and electronic cooling was demonstrated at optimal biasing conditions. The relatively small cooling observed in the present devices does not represent a fundamental limitation and can be largely improved by using an optimized contact geometry. This technology can have a large impact in cryogenic circuits requiring local cooling, and can benefit a large number of nanoscience applications.
fields, such as sensing, quantum computation and quantum technology in general.

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Methods. Selenium-doped InAs NWs were grown by chemical beam epitaxy on an InAs 111B substrate. Gold catalyst colloid nanoparticles with 40 nm of diameter were dispersed on the substrate and InAs NWs were grown at 400 °C for 60 mins using tertiarybutylselenine (TBA) (1.5 Torr), trimethylindium (TMI) (0.6 Torr) and tertiarybutylselenide (DtBSe) (0.3 Torr). Then the growth temperature was increased to 440 °C and the growth was proceeded for another 50 mins. NWs typically had a diameter \(d = 90 \pm 10 \text{ nm}\) and length \(\approx 2.5 \mu\text{m}\). E-beam lithography has been performed using positive PMMA (AR-P 679.04), 20 kV acceleration voltage and a dose 320 \(\mu\text{C/cm}^2\). Development was done in a 1 : 3 solution of AR 600-56 PMMA developer and isopropanol and possible residuals of the resist were removed with plasma oxygen cleaning. Just before the evaporation the samples were immersed for one minute in a 48 °C (NH\(_4\))\(_2\)S\(_x\) solution to remove native oxide from to top of the NW to minimize unwanted scattering in the interface of the contacts. After this they were immersed for one minute in water and quickly rinsed in isopropanol before moving them into the ultra-high vacuum evaporator with a base vacuum of \(10^{-10}\) Torr. The first 5 nm-thick Ti layer was evaporated with 1 A/s rate to provide a sticking layer. 50 nm-thick Al\(_{0.98}\)Mn\(_{0.02}\) layer was then evaporated on top of the Ti with 1.5 A/s rate. Subsequently the samples were drawn back to the loading chamber for the oxidation in 0.2 – 0.4 Torr of O\(_2\) for 5 minutes. The final evaporation was then completed again in the main chamber to obtain 50 nm-thick pure Al layer with 1.5 A/s rate. Lift-off was done in 50 °C acetone before finally rinsing the samples with isopropanol. For measuring, the samples were bonded with Al wires to 24-legged sample holder thus providing six NW devices to be measured with a single bonding. All the measurements were performed in a cryo-free \(^3\)He/\(^4\)He dilution refrigerator with a base temperature of 30 mK. First the junctions were characterized applying voltage bias with a DC voltage source and measuring the current through room-temperature current preamplifier varying cryostat temperature and off-plane magnetic field. Filtering included two low-pass RC filters and two LC \(\pi\)-filters anchored at base temperature, and an additional LC \(\pi\)-filters stage at room temperature.

The theoretical comparison for the measured data was acquired using BSC theory for SINIS tunnel junctions assuming quasi-equilibrium of the electrons in the normal metal. The current \(I\) through a SINIS junction as a function of bias voltage \(V\) can be expressed as:

\[
I(V) = \frac{1}{\epsilon R_N} \int_{-\infty}^{\infty} n_S \left[ f_N(E - eV/2) - f_N(E + eV/2) \right] dE, \tag{1}
\]

where \(R_N\) is the total normal-state resistance of the junction,

\[
n_S = \text{Re} \left[ \frac{E + i\gamma\Delta}{\sqrt{(E - i\gamma\Delta)^2 - \Delta^2}} \right] \tag{2}
\]

is the normalized density of states in the superconductor [4] with Dynes parameter \(\gamma\) measuring the life-time broadening of the quasi-particles or photon assisted tunneling leading to non-ideal behavior of the superconductor [38]. Also the temperature dependence of \(\Delta(T)\) is taken into account as well. In the above expression,

\[
f_N(E) = \frac{1}{\epsilon E/k_B T_N + 1} \tag{3}
\]

is the Fermi–Dirac distribution of the normal metal. Conductance was obtained by differentiating Eq. (1).

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