Phonon Cooling of Nanomechanical Beams with Tunnel Junctions

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We demonstrate electronic cooling of 1D phonon modes in suspended nanowires for the first time, using normal-metal-insulator-superconductor (*N-I-S*) tunnel junctions. Simultaneous cooling of both electrons and phonons to a common temperature was achieved. In comparison with nonsuspended devices, better cooling performance is achieved in the whole operating range of bath temperatures between 0.1–0.7 K. The observed low-temperature thermal transport characteristics are consistent with scattering of ballistic phonons at the nanowire-bulk contact as being the mechanism limiting thermal transport. At the lowest bath temperature of the experiment ~100 mK, both phonons and electrons in the beam were cooled down to 42 mK, which is below the refrigerator base temperature.

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The ability to cool both the electrons and phonons of a mesoscopic device below the temperature of its surrounding bath is potentially valuable for all areas of low-temperature physics, and could prove especially useful for applications such as nanobolometry in submillimeter telescopes [1,2], quantum computing [3], and cooling of nanomechanical oscillators into their quantum-mechanical ground state [4]. In the sub-Kelvin temperature range, the thermal coupling between a nanoscale device and its thermal bath becomes very weak [1,5,6], leading easily to overheating problems due to even tiny dissipated power levels (~ fW) from the measurement signals and external noise. A direct cooling method can therefore be extremely valuable, as it actually takes advantage of the weakness of the thermal coupling.

A tunnel junction can be used for direct cooling at sub-Kelvin temperatures, if one of the electrodes is superconducting and the other in normal state, i.e., with a normal-metal-insulator-superconductor (*N-I-S*) structure [7–9] (Fig. 1). If fabricated on bulk substrates, only sizeable electron cooling can be achieved due to the strong weakening of electron-phonon interaction with temperature [6,10,11]. To be able to cool the phonons, the phonon thermal conductance out of the device needs to be small enough to become the bottleneck for the heat flow. Using this idea, cooling of phonons in thin but large insulating membranes has been demonstrated with large area tunnel junction coolers [12–14], but direct phononic cooling of a nanoscale (1D) device has only been suggested theoretically [15]. In this work, we demonstrate significant NIS-junction cooling of both electrons and phonons in suspended 1D nanowires to a common temperature below the bath temperature of the refrigerator, and present quantitative results on the phonon thermal transport processes involved. In our 1D geometry, phonon cooling is approximately 2 orders of magnitude more effective than in the 2D case [14] in terms of the cooling power required to achieve a given temperature reduction.

All suspended nanowires have a length of either 10 or 20 μm, width 200 or 300 nm and thickness 60 nm, and were fabricated to form bilayers of evaporated copper (30 nm) on silicon nitride (30 nm) using *e*-beam lithography, vacuum evaporation, and reactive ion etching (see [16]). The Cu/SiN wire is connected to the substrate by four freestanding bridges with a length 5 μm, and width 150 nm [Fig. 1(c)]. The outer bridges are also Cu/SiN bilayers of thickness 60 nm, and connect the Cu wire (total length 20 or 30 μm) to wider (1 μm) superconducting Al electrodes on the bulk substrate via two larger area [0.35 $(\mu\text{m})^2$] NIS-junction coolers. The cooler junctions must be located on the bulk substrate to avoid serious backflow of dissipated heat from the superconductor into the nanowire [17]. The inner bridges have a composition Cu/Al/SiN (thickness 90 nm), connecting Al leads with Cu quasiparticle traps to two smaller [0.05 $(\mu\text{m})^2$] thermometer NIS-junctions located on the suspended nanowire. Since the measured phonon thermal conductance from the narrow bridges to the bulk substrate is approximately an order of magnitude smaller than the thermal conductance between the electrons and the phonons (detailed discussion below), phonon transmission becomes the thermal bottleneck. Thus, both the electrons and the phonons in the suspended wire have a common temperature and can be cooled simultaneously in our sample geometry, in contrast to a recent report on electron cooling in nanowires [18].

Measurements were performed in a ^{3}He–^{4}He He dilution refrigerator with a base temperature of ~50 mK with several stages of filtering in the wires [16]. In the experiment, the temperature of the nanowire was measured as a function of the bias voltage across the cooler junctions [16]. Schematic of the measurement setup is shown in Fig. 1(c). Using this simple measurement, we obtain temperature response curves that typically look like Fig. 1(d) as a function of the cooler bias and refrigerator bath temperature T_{bath}. As expected from theory [9], the maximum cooling is obtained at cooler voltage $V \sim 2\Delta/e$, where

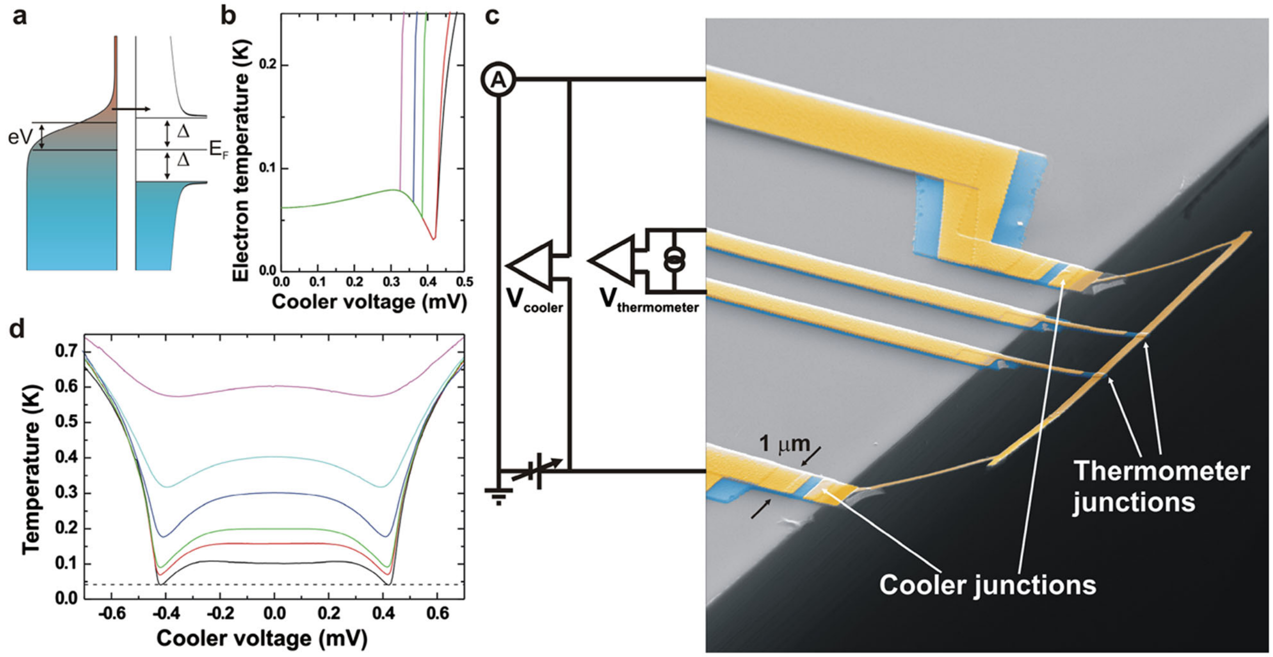

FIG. 1 (color online). (a) Schematic of the operation principle of an NIS tunnel junction cooler. The superconducting gap Δ filters through only hot electrons from the normal metal. Heat is removed from the normal metal and injected into the superconductor, which must be efficiently removed by quasiparticle traps [9]. (b) Theoretically calculated cooling curves vs bias voltage with different hot quasiparticle removal (trapping) efficiencies. The curves with less cooling correspond to worse trapping efficiency (effectively hotter superconductor). (c) Schematic of the measurement setup and a scanning electron micrograph of a typical suspended sample. Yellow color indicates Cu (normal metal), blue Al (superconductor). Cooler junctions are located at the edge of the substrate, whereas the thermometer junctions are at the center of the nanowire [16]. (d) Measured temperature of a typical nanowire sample as a function of cooler voltage at bath temperatures 50, 160, 200, 300, 400, and 600 mK, dashed line corresponds to 42 mK.

$\Delta = 215\ \mu$eV for our samples. Two main observations are immediately apparent: (i) At the lowest bath temperature 50 mK, where the nanowire has a temperature 100 mK at zero cooler bias (due to noise power of $\sim$6 fW radiated from higher temperature parts of the circuit), the lowest temperature achieved around $V \sim 2\Delta/e$ was 42 mK, a reduction of $\sim$60 mK. (ii) The cooler clearly still works at bath temperatures as high as 600 mK. These are the main results of this work, and in the following we elaborate on the physics by comparing samples of different sizes and results between suspended wires and wires on bulk substrates.

Cooler samples on bulk substrates were fabricated with the same metal film and tunnel junction geometry as the suspended samples during the same fabrication run [16]. Figure 2(a) shows the measured cooling (ratio of measured temperature to the bath temperature) vs bath temperature at optimal cooling bias for a suspended (green) and a bulk (black) sample, both with wire lengths 20 μm and similar junction properties, whereas Fig. 2(b) shows it for longer 30 μm wires. Clearly, the suspended samples in both cases show better cooling ($\sim$20% improvement at 300 mK) extending to much higher bath temperatures (up to $\sim$600 mK), pointing to a difference in the dissipation mechanisms between the bulk and suspended samples. A further confirmation of the differences can be seen by comparing the $T(V_{\mathrm{cooler}})$ curves [16]. In addition, in Fig. 2(c) we compare cooling for three suspended samples in pairs: Two samples have different nanowire sizes but the same tunnel junction properties ($L = 20\ \mu$m, $w = 200$ nm (black) and $L = 30\ \mu$m, $w = 300$ nm (green), $R_T \sim 3$ kΩ), whereas the third sample (red) has the same size as the longer wire of the previous pair, but more transparent tunnel barriers ($R_T \sim 1.7$ kΩ). It is quite clear that the size of the suspended nanowire has no effect on the cooling behavior, whereas the tunnel resistance R_T has a stronger effect, as expected by theory [16]. This size-independence proves that neither 3D [10] nor 1D [15] electron-phonon (e-ph) interaction limits the heat flow in the suspended samples, unlike in bulk coolers, where a strong volume dependence is observed [9] due to the 3D e-ph interaction [clearly noticeable by comparing the bulk results in Figs. 2(a) and 2(b)]. We can thus deduce that electrons and phonons in the suspended wire are in quasiequilibrium (common temperature) and are therefore both cooled simultaneously. Moreover, we have observed that there are no temperature gradients within the wire [16] so that electronic diffusion [19] is not operational either. This means that heat flow is limited by phonon transmission (phonon thermal conductance), and must be dominated by the interface between the suspended wire and the bulk because of the lack of wire length dependence.

In quantitative terms, the heat flow between the substrate and the suspended nanowire is determined by the power

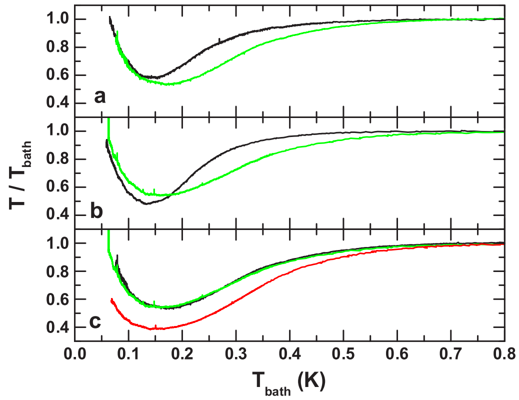

FIG. 2 (color online). (a) Temperature of a cooled suspended (green) and bulk (black) 20 μm long nanowires normalized with the bath temperature T/T_{bath} vs T_{bath}. The cooler is biased to the optimal cooling voltage, while the bath temperature is changed. Both samples have an electron gas volume $\Omega = 0.17\ \mu\mathrm{m}^3$ and a tunneling resistances $R_T \sim 3\ \mathrm{k}\Omega$ for suspended and $R_T \sim 4.4\ \mathrm{k}\Omega$ for bulk sample. At the low-temperature regime, cooling efficiency is limited by the junctions, whereas at higher temperatures cooling behavior is different due to the different dissipation mechanisms (e-ph interaction for bulk samples vs phonon transport for suspended samples). (b) The same, but for longer 30 μm long wires with $\Omega = 0.36\ \mu\mathrm{m}^3$ and $R_T \sim 3\ \mathrm{k}\Omega$. (c) The same, comparing the two suspended samples in (a) (black) and (b) (green) with a third suspended sample (red) with $\Omega = 0.36\ \mu\mathrm{m}^3$ and $R_T = 1.7\ \mathrm{k}\Omega$.

balance condition $P_{\mathrm{heat}} = P_{\mathrm{cool}}$, where the heat flow from the surroundings P_{heat} equals the cooling power of the junctions $P_{\mathrm{cool}} = 2\dot{Q}_{\mathrm{cool}}$, where $\dot{Q}_{\mathrm{cool}}$ is the cooling power of a NIS junction [16]. Regardless of the limiting heat transport mechanism (e-ph interaction or phonon thermal conductance), we can generally write

$$2\dot{Q}_{\mathrm{cool}} = A(T_{\mathrm{bath}}^n - T_{\mathrm{nw}}^n) + \beta(2\dot{Q}_{\mathrm{cool}} + IV_{\mathrm{cool}}), \qquad (1)$$

where the first term on the right describes the heating from the environment (T_{nw} is the nanowire temperature), and the second backflow of dissipated heat $2\dot{Q}_{\mathrm{cool}} + IV_{\mathrm{cool}}$ from the superconductor to the normal metal ($0 \leq \beta \leq 1$) due to nonequilibrium recombination phonons and back tunneling [20]. Here I is the current though the cooler junctions and V_{cool} the voltage across them, A is a parameter describing the strength of the heat flow between the nanowire and the bath, and the exponent n depends on the heat flow mechanism. In the calculation of $\dot{Q}_{\mathrm{cool}}$ we have taken into account a measured broadening of the quasiparticle density of states due to lifetime effects [21] and/or two-electron Andreev processes [16,22], because of its strong influence on cooling efficiency [9,23]. In the case of 3D (1D) electron-phonon mediated heat flow $A = \Sigma\Omega$, where Σ is the electron-phonon coupling constant and Ω the electron gas volume (length for 1D), and $n = 3$–6 depending on the level of purity of the metal film and the phonon dimensionality [6,15,24]. In contrast, if the heat flow is limited by phonon transmission at the nanowire-bulk boundary (suspended samples), A is not dependent on Ω, and $n = 2$–6 depending on phonon mode and dimensionality [5,25–27].

To understand the transport process, we performed a complementary heating experiment without cooler tunnel junctions but with the same nanowire width $w = 300$ nm and thickness $t = 60$ nm (length was $L = 24\ \mu$m). In that experiment we substituted the cooler tunnel junctions by direct contact between the normal metal (Cu) and a superconductor (Nb). These NS junctions work as good electrical contacts but, on the other hand, as nearly perfect thermal barriers so that Joule heating power $P_{\mathrm{in}} = IV$ is dissipated uniformly in the normal metal and $P_{\mathrm{in}} = A(T_{\mathrm{nw}}^n - T_{\mathrm{bath}}^n)$. (Details in [16]). Figure 3(a) shows the result of such an experiment, where the temperature of the nanowire is plotted as a function of the heating power in log-log scale. We notice that the data are well described by a transition from a power law with $n \sim 2.8$ at low temperatures to a power law with $n \sim 6$ at high temperatures. The thermal conductance $G = dP/dT$ at 200 mK is 0.4 pW/K (at 100 mK extrapolated to 0.12 pW/K), which can be

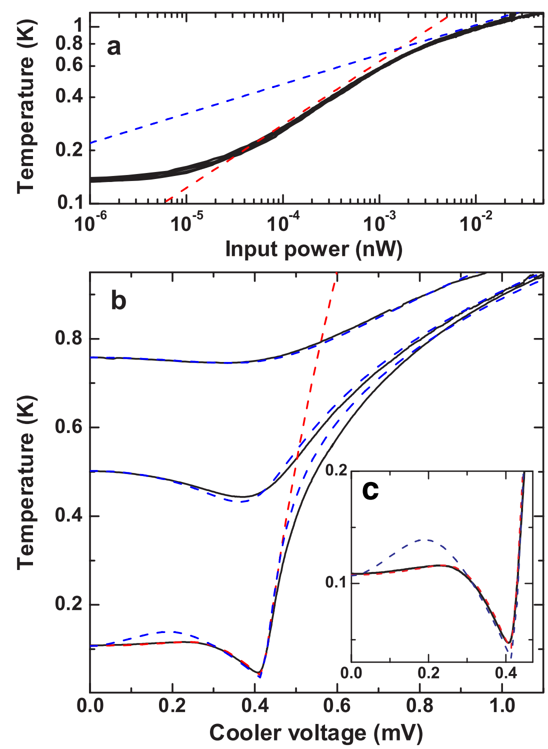

FIG. 3 (color online). (a) Heating experiment: temperature of a suspended nanowire as a function of input dc power. Red and blue dashed lines correspond power laws $n = 2.8$ and $n = 6$, respectively. The low-temperature saturation is likely due to absorbed noise power of $\sim$6 fW. $A = 4.3\ \mathrm{pW/K}^{2.8}$ for the low-temperature power law $n = 2.8$. (b) Temperature of a suspended nanowire as a function of cooler voltage, experimental data are shown as black solid line. The red and blue dashed lines correspond to thermal model of Eq. (1) with $n = 2.8$ and $n = 6$, respectively. For the $n = 2.8$ model, we used the value for A determined from the heating experiment (no fitting). Inset is zoom-in to the cooling region of the low-temperature data in (b).

compared with a value for calculated 1D e-ph limited conductance [15] (using known Cu parameters) at 200 mK, 5.2 pW/K (at 100 mK 1.3 pW/K), confirming that phonon transport limits the heat flow at low temperatures.

The measured power laws for suspended nanowires can then be used in the thermal model of the coolers, Eq. (1). Figures 3(b) and 3(c) show cooler data in comparison with the two power laws, $n = 2.8$ (red) and $n = 6$ (blue). Good agreement is achieved with the low bath temperature data, if a transition from a $n = 2.8$ power law into a $n \sim 6$ is assumed, in agreement with the heating experiment. We would like to stress that simply fitting the cooler data with different power laws directly is nearly impossible, as the cooler model is quite insensitive to the value of n. At bath temperatures $T_{\mathrm{bath}} > 0.4$ K, $n = 6$ fits fairly well the full range of bias values, but is not consistent with an e-ph limited heat flow, as the parameter A is much smaller than what is expected from e-ph theory [16].

To understand this behavior, we note that the phonons in the wire have a crossover from 3D to 1D behavior when the thermal wavelength of the lowest energy transverse modes $\lambda_T = hc_t/(2.8k_BT)$ becomes larger than the wire thickness and width, which is estimated to take place around $T \sim 0.4$ K using a value $c_t = 4300$ m/s for the Cu/SiN bilayer. This estimate is not far from the observed transition temperature seen in Fig. 3(b). Thus, we believe that in the low-temperature regime $T < 0.4$ K, the nanowire phonons are one dimensional. In the ballistic 1D limit with no scattering at the nanowire-bulk contact $n = 2$ is expected [5]. However, in our sample geometry the nanowire-bulk contact is abrupt, leading to strong scattering and predicted power laws between $n = 2.5$–3.5 for 1D-2D scattering [26], or $n = 4$–6 for 1D-3D scattering [27]. We thus conclude that our observed $n = 2.8$ is consistent with 1D-2D boundary limited phonon scattering, which is plausible based on the device details [16]. The value of the measured thermal conductance [Fig. 3(a)] per conduction channel $G/16$ (four legs with four phonon branches) is also consistent with boundary scattering, as it can be expressed in units of the quantum of thermal conductance [5] $G_0 = \pi^2 k_B^2 T/(3h)$ as $G/16 \sim 0.13G_0$ at 200 mK.

In conclusion, we have demonstrated electronic cooling of phonon modes of a suspended nanowire, where scattering of phonons at the nanowire-bulk contact limits the thermal transport. In comparison with nonsuspended devices, better cooling performance is achieved in the whole operating range of bath temperatures. The minimum temperature reached in our best device was 42 mK, starting from an initial temperature of 100 mK. This limit is mostly determined by the superconducting material itself (Al), and thus the minimum temperature could be extended below 10 mK by using an additional tunnel junction cooler with a lower superconducting gap [28]. The advantages of tunnel junction coolers are: (i) ease of integration into a nanoscale system and compatibility with existing fabrication processes, (ii) simple operation by only dc voltage source, and (iii) the ability to cool both electrons and phonons simultaneously. This last point is significant for ultrasensitive nanobolometers [1,2], as both the electron and the phonon temperatures contribute to their performance (noise equivalent power), and also for nanomechanical oscillators, where the phonon modes need to be cooled.

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[28] Note that for much shorter wires of length ~ 1 μm, 1D electron-phonon coupling will become dominant at low temperatures, so that phonon cooling will become impossible.