High resolution x-ray transition-edge sensor cooled by tunnel junction refrigerators

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We demonstrate cooling of an x-ray transition-edge sensor (TES) using solid-state refrigerators based on normal-metal/insulator/superconductor (NIS) tunnel junctions. We are able to operate the NIS refrigerators at a starting temperature of 260 mK, which is 75 mK above the TES transition temperature (185 mK), and still achieve high quality x-ray spectra with an energy resolution of 9.5 ± 0.3 eV full width at half maximum at 5.9 keV. The maximum cooling achieved by the NIS refrigerators is 110 mK, from a starting temperature of 300 down to 190 mK. © 2008 American Institute of Physics. [DOI: 10.1063/1.2913160]

Normal-metal/insulator/superconductor (NIS) tunnel junctions can be used as solid-state refrigerators with the potential to cool from 300 to 100 mK.1,2 Biasing an NIS junction causes the hottest electrons in the normal metal to tunnel across the insulator barrier into the superconductor, which cools the remaining normal-metal electrons. Extending the normal metal onto a membrane as a cold finger cools both the electrons and lattice of the electrically separate membrane.3,4 In previous work, we dramatically increased the size and cooling power of NIS junctions.5,6 Here, we demonstrate the successful integration of NIS refrigerators with a separate, technologically useful payload.

The payload is a superconducting transition-edge sensor (TES) designed for x-ray detection. TESs are a critical technology for high-resolution x-ray spectroscopy, especially for applications in materials analysis and astronomy.7,8 X-ray TESs are superconducting thin films typically operated near 100 mK for optimal performance. Traditional refrigerators used to reach 100 mK, adiabatic demagnetization refrigerators (ADRs) and dilution refrigerators, have drawbacks for some applications due to their complexity and size. Examples include commercial x-ray microanalysis systems and space-borne detectors. Combining NIS refrigerators with a sorption-pumped 3He system (base temperature 260 mK), which is relatively inexpensive and small, provides a third option for cooling devices to 100 mK. Alternatively, combining NIS refrigerators with an ADR allows for more design options, including extended hold times, reduced mass, and lower stray magnetic fields from the ADR.

An x-ray TES with integrated NIS refrigerators is shown in Fig. 1(a). The TES is suspended on a 500 nm thick low-stress SiN membrane that is connected to the substrate through four 39 µm wide by 23 µm long corner legs and one 33 µm wide by 110 µm long side leg. The TES is a 250 µm by 250 µm bilayer of Mo and Cu, with a critical temperature \( T_c = 185 \text{ mK} \) and a normal-state resistance \( R_{n,TES} = 16.2 \text{ mΩ} \). Three normal-metal Cu bars are added to control the transition width and noise characteristics.9 A bismuth absorber (not shown), 1.55 µm thick, is deposited over the TES to increase x-ray absorption. The TES is voltage biased with a shunt resistor \( R_{sh} = 727 \text{ µΩ} \) and readout by two stages of superconducting quantum interference devices (SQUIDs). To measure the performance of the TES, an \(^{55}\text{Fe} \) x-ray source is used to irradiate the TES through a 250 µm diameter collimator.

A pair of NIS refrigerator junctions, each 15 µm wide by 25 µm long, is located on the bulk substrate at each corner of the membrane [Fig. 1(b)]. The normal-metal electrodes of the junctions are Al doped with Mn to suppress superconductivity and the superconducting electrodes are elemental Al. The eight junctions in series have a normal-state resistance \( R_{n,NIS} = 36 \text{ Ω} \) and zero-bias leakage resistance \( R_{b} \sim 540 \text{ kΩ} \). The normal metal of each junction pair extends onto the membrane as a cold finger. An additional layer of Cu is added to the cold fingers to increase the thermal conductivity.4

Completed devices are cooled in an ADR, allowing NIS and TES behavior to be characterized down to an ADR temperature \( T_{ADR} \) of 50 mK.

Johnson noise thermometry (JNT) is used to measure the temperature of the unbiased TES without dissipating any power. A Helmholtz coil outside the dewar is used to apply a perpendicular magnetic field of 440 µT, which suppresses the TES \( T_c \) from 185 to below 50 mK, making it possible to use JNT at all ADR temperatures. The magnetic field has only a small effect on the NIS \( I-V \) curves and does not significantly change the cooling performance. The current noise

![FIG. 1. (Color online) (a) TES x-ray sensor integrated with NIS refrigerators (Bi absorber not shown). Four pairs of NIS refrigerators are located at the corners of a SiN membrane (dashed outline). Y-shaped cold fingers extend from the normal metal of the NIS junctions onto the membrane. (b) False-color SEM image of membrane corner.](image-url)
The SQUIDs and kB and the TES NIS refrigerators reduces the temperature of the cold fingers. Where the IN power fig. 2, which can be solved for the reduced TES temperature of 300 mK to a reduced TES temperature of 300 mK. We have previously fabricated devices with more transparent tunnel junctions and a reduced power return (β = 4%). A further reduction in β is attainable by improvements in the design of the quasiparticle traps, which trap and thermalize power deposited in the superconductor.

With the NIS refrigerators on, we are able to operate the TES at ADR temperatures above Tc by cooling the cold fingers below Tc. When the TES is biased and dissipating power, the TES I-V curves [fig. 3(a)], combined with a separate measurement of the thermal conductance of the membrane Gmem [fig. 3(b)], can be used to determine the cooling provided by the NIS refrigerators when under load. TES I-V curves alone are insufficient because biasing the NIS refrigerators increases the total thermal conductance between the TES and the substrate. We have directly measured Gmem in a separate test device where the cold fingers and NIS junctions were replaced by a Cu film that extended onto the substrate around the full perimeter of the TES. At a TES bias power of 22 pW, the NIS refrigerators reduce the effective bath temperature of the TES from 260 to 162 mK. Hence, the 22 pW load from the biased TES reduces the cooling by 7 mK from the unbiased case in fig. 2(a).

Figure 4(a) shows an NIS-cooled TES x-ray spectrum taken at an ADR temperature of 260 mK, which is 75 mK above the TES Tc. A theoretical fit to the Mn Kα complex yields an energy resolution of 9.5 ± 0.3 eV full width at half maximum (FWHM) at 5.9 keV. This resolution is an improvement over previous work using superconducting detectors at cryostat temperatures above 200 mK. As a further comparison, current microanalysis systems employ Si-based detectors with an energy resolution of 130 eV at 5.9 keV, which is insufficient to resolve many technologically important x-ray lines. Our present resolution of 9.5 eV is by no means the physical limit. We calculate that the resolution can be improved to 5 eV by reducing the size of the TES and halving the steepness of the superconducting transition. Improvements in NIS cooling performance [fig. 2(a)] will also require additional improvements in the coldness of the NIS refrigerators.
to obtain the heat capacities and derivatives of the TES resistance, and a current noise fit to obtain the excess noise parameter.\textsuperscript{14–16} We have also measured the long-term stability (6 h) of the x-ray pulse heights and saw no difference with the NIS refrigerators either off or on.

In conclusion, we have used JNT to measure NIS cooling down to starting temperatures of 60 mK, achieving a maximum reduction of 110 mK from an ADR temperature of 300 mK. We have demonstrated successful cooling of a high-resolution x-ray TES using NIS refrigerators, allowing the TES to be operated at ADR temperatures above $T_c$. We have achieved an energy resolution of $9.5 \pm 0.3$ eV (FWHM) at 5.9 keV at an ADR temperature of 260 mK (75 mK above the TES $T_c$). The use of integrated NIS refrigerators makes the remarkable performance of modern cryogenic sensors available from 300 mK platforms.

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