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Section A

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Normal metal–insulator–superconductor junction technology for bolometers ☆

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Abstract

Normal metal–insulator–superconductor tunnel junctions are candidates for large-format arrays of ultra-low noise equivalent power bolometers. Using a wafer scale process we have fabricated devices with the required sub μm^3 volumes and ohmic superconductor–normal metal contacts for delivering power loads. Additionally, we demonstrate simultaneous tunnel junction thermometry and SQUID-based Johnson current noise thermometry.

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Keywords: NIS junction; Bolometer

New detectors for astronomical applications must be compatible with large format arrays. The SCUBA-2 camera with 10,240 pixels (eight subarrays with $32 \times 40 \times$ pixels each) and noise equivalent power (NEP) $\lesssim 3 \times 10^{-17}$ sets a high standard, but planned high altitude and space-based observatories require large-format ($10^3 - 10^5$ pixels) arrays of detectors with NEPs lower than $5 \times 10^{-18}\,\mathrm{W/Hz^{1/2}}$ for deep-space mapping in the far-infrared (1 mm–10 μm) wavelength band [1]. Hence, the detector community must deliver both lower NEPs for low background powers and large arrays.

Many researchers are looking toward microwave frequency division multiplexing (FDM) schemes as a viable method to read out kilopixel and larger scale arrays [2,3]. Therefore, particular emphasis has been placed on detector technology compatible with microwave readout. We have demonstrated high bandwidth and low-noise microwave readout of a superconductor–insulator–normal metal–insulator–superconductor (SINIS) hot-electron bolometer element [4]. Bolometer technology based on SINIS junctions and microwave FDM is a viable option for achieving the stringent requirements of future missions. In this article, we will highlight our recent progress in SINIS detector technology, focussing on fabrication and DC electrical testing of small AlMn-based SINIS devices and simultaneous SINIS and Johnson noise thermometry.

The NIS junction has been a subject of great interest both as thermometers for bolometers and for direct electronic refrigeration [5]. Early devices formed with Al superconducting layers and Cu or Ag normal metal layers were not stable and never approached theoretical refrigeration capabilities. Devices where both the normal metal and the superconducting leads are Al, with non-superconducting Al realized by adding a small (0.3%) Mn content to the normal metal island, have proven chemically stable and delivered significant electronic refrigeration [6].

We demonstrated high bandwidth and low-noise readout of a Al:AlMn SINIS bolometer element with a microwave reflectometer technique compatible with large format arrays [4]. We measured a noise equivalent temperature of better than $0.6\,\mu\mathrm{K/Hz^{1/2}}$ and inferred an electrical noise equivalent power of $7 \times 10^{-17}\,\mathrm{W/Hz^{1/2}}$ for a normal metal volume of $4.5\,\mu\mathrm{m}^3$ at an operating temperature of 270 mK.

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Using a pulsed bias technique we measured a thermal time constant of 1.2 μs at 270 mK. As a first effort, these results were promising, but to deliver higher performance we must produce smaller devices with lower electron–phonon thermal conductivity, operate at temperatures below 270 mK, and we also must demonstrate high-quality normal metal–superconductor (NS) contacts (without an insulating barrier) to deliver antenna coupled far-infrared or DC electrical power to the normal metal island [7].

We have extended our fabrication capabilities to produce devices with normal metal volumes smaller than 1.0 μm^3. Fig. 1(a) shows a micrograph of a NIS device with a normal metal volume of 0.3 μm^3. In addition to the tunnel junction, the device has two oxideless NS contacts for directly heating the normal metal island. In Fig. 1(b) we display current voltage characteristics of this device. This device has a predicted electron–phonon NEP contribution of $4 \times 10^{-19}\,\mathrm{W/Hz^{1/2}}$ at 100 mK.

Heating measurements on a symmetric device with two NIS junctions and two NS contacts are summarized in Fig. 2. This device has a normal metal volume of 3.75 μm^3. We show current voltage characteristics of the junctions at 100 mK for different power loads dissipated in the normal metal. The dynamic range of these devices is significant as evidenced by the six orders of magnitude power range (0.2 pW to 0.2 μW). The resulting high saturation power is quite practical for astronomical applications.

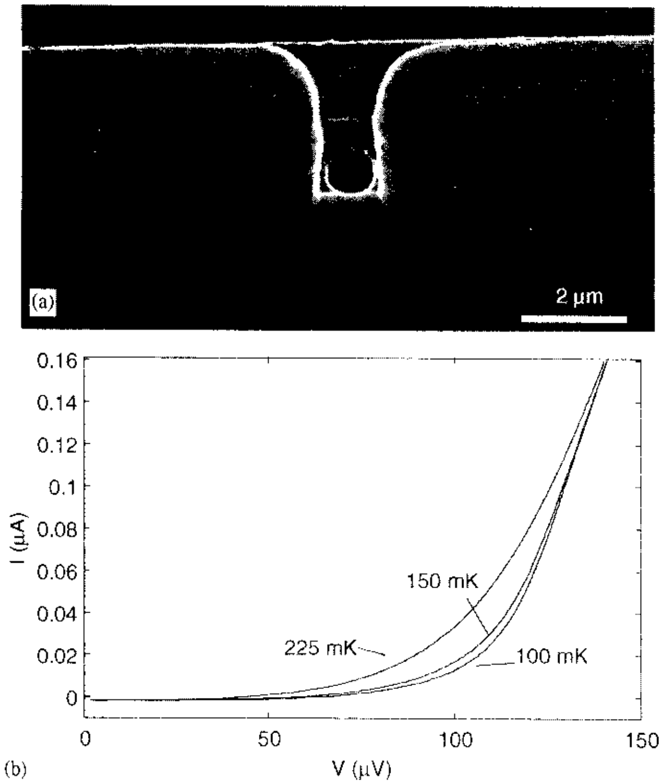

Fig. 1. Small NIS device with SN contacts. (a) SEM micrograph. A normal metal island with an active volume of 0.3 μm^3 is contacted with one NIS contact (center) and two NS contacts (left and right). (b) Low temperature current–voltage characteristics. The NIS junction is measured by sourcing current between the NIS contact and one of the NS contacts. Three temperatures are shown: 100, 150 and 225 mK. The normal state resistance of the NIS junction is 560 Ω.

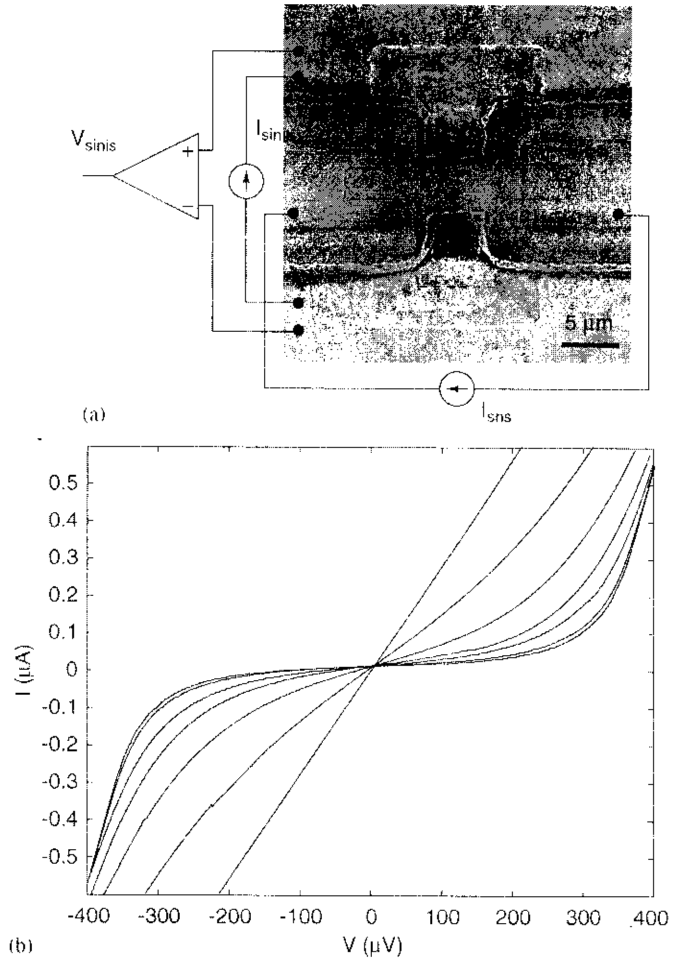

Fig. 2. Electron heating measurements. (a) Circuit schematic. We fabricated a device with two NIS junctions (top and bottom) and two NS contacts (left and right). The normal metal region is marked with a dashed line. A current I_{SNS} is passed through the NS contacts to heat normal metal region. The current–voltage characteristics of the junctions (two NIS junctions back to back to form SINIS) are measured while the normal metal is heated. (b) Normal metal heating. SINIS current voltage characteristics for different power load on the normal metal. The cryostat temperature is 100 mK and the power ranges from 0.2 pW to 0.2 μW in logarithmic steps.

From a diagnostic standpoint it is important to be able to perform electron thermometry without affecting the temperature of the electronic system. While the typical issue is thermometer heating, NIS junction-based thermometers can have significant cooling. At temperatures below 100 mK, it is also difficult to distinguish loss of temperature response from leakage currents or actual heating due to background noise levels. We have begun using simultaneous NIS thermometry and SQUID-based Johnson current noise thermometry on a normal metal element (Fig. 3). This should produce a reliable corroborative thermometer for sub 100 mK temperatures.

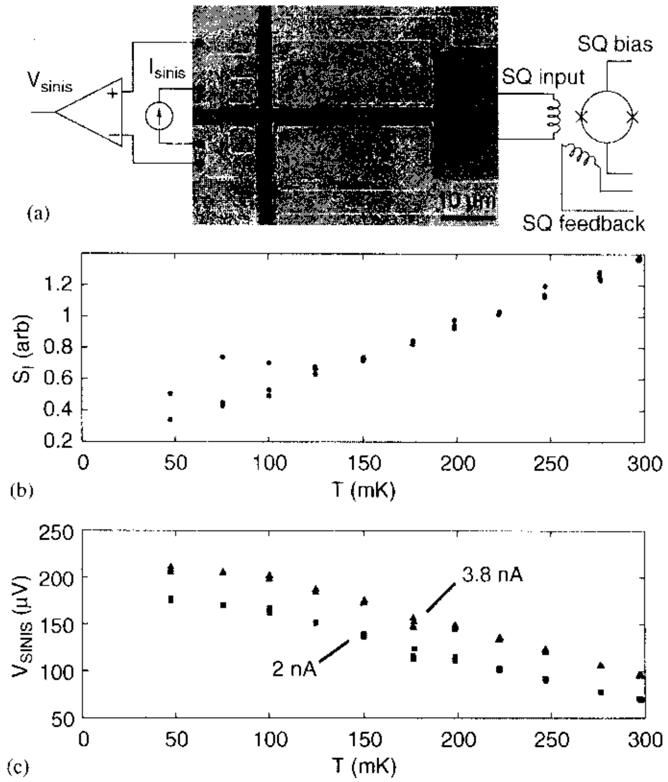

Fig. 3. Simultaneous Johnson noise and SINIS thermometry. (a) Circuit schematic. The normal metal region is marked with a dashed line. The electrical response characteristics of SINIS thermometer junctions (left side) are monitored using a current bias and a voltage measurement. A similar measurement circuit (not shown) is connected to the larger refrigerator junctions (center). The Johnson noise of a region of the normal metal is measured with a SQUID connected to the device via superconducting leads (right side). The first stage SQUID in the figure is measured with a 100 SQUID series array at 4 K (not shown). (b) Johnson noise thermometry. The current noise power S_I is measured as a function of cryostat temperature. The expected linear dependence is observed. Below 100 mK spurious events are likely due to interfering electrical noise coupling in via the junctions. The nature of these events is under investigation. (c) SINIS thermometry. As the cryostat temperature is raised from 50 to 400 mK, the voltage across the thermometer is monitored. Two different current bias are shown.

In summary, we have made progress towards the realization of large-format arrays of NIS bolometers read out with microwave FDM. We have improved and added to our fabrication capabilities to produce smaller size NIS devices with integrated SN contacts on the wafer scale. We have also incorporated the important diagnostic tool of Johnson noise thermometry. In the near future, we will combine the detector building blocks described here with microwave reflectometry at 100 mK temperatures in a adiabatic demagnetization refrigerator to test the limits of NIS bolometry.

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