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Refrigeration of separate, user-supplied payloads with Normal–Insulator–Superconductor tunnel junctions ☆

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ABSTRACT

Normal metal–Insulator–Superconductor (NIS) tunnel junctions can be used to selectively remove the hottest electrons in the normal metal, thereby causing it to cool. NIS tunnel junctions have already been used to cool lithographically integrated payloads [1], but this requires integration of two disparate fabrication processes. To increase the flexibility of NIS refrigerators, we have designed a stage cooler based on NIS tunnel junctions that will be able to cool arbitrary, user-supplied payloads from 300 mK to 100 mK. This stage cooler can be backed by a helium-3 refrigerator to provide a lightweight and simple means of reaching 100 mK in space applications. In this paper, we describe the design of our stage cooler and present calculations of the cooling power and time required to reach 100 mK.

1. Introduction

Low temperature detectors that operate at 100 mK, such as Transition Edge Sensors (TESs), can be used for measurements of unprecedented sensitivity from microwave to gamma-ray wavelengths [2]. In order to use these detectors in space, simple and reliable techniques for reaching low temperatures are required. Helium-3 refrigerators are simple and space-proven [3], but can cool only to base temperatures of around 300 mK.

Dilution refrigerators (DRs) and adiabatic demagnetization refrigerators (ADRs) can reach 100 mK temperatures, but have drawbacks for space applications. DRs are complicated and require a He-4/He-3 mixture that, so far, has been vented into space, limiting mission lifetime. ADRs do not use liquid cryogens, but they require tesla-scale magnetic fields that necessitate heavy magnetic shielding.

To achieve lower temperatures and take advantage of the simplicity of He-3 refrigerators, Normal metal–Insulator–Superconductor (NIS) tunnel junctions can be used as an additional refrigeration stage to cool sensors and other low-power payloads from 300 mK to below 100 mK. NIS refrigerators backed by closed-cycle, helium-3 refrigerators have the advantages of providing continuous cooling power, are small, are simple to use, require only a simple DC voltage bias, have no moving parts that can malfunction, and require no consumables, which make them ideal for space applications. In addition to improving the base temperature of helium-3 refrigerators, NIS coolers can also be used to extend the hold time and/or simplify the design of ADRs.

In previous work, we used NIS junctions to cool an X-ray TES from 300 mK to 190 mK and successfully operated the sensor with an energy resolution of 9.5 eV FWHM at 5.9 keV [1]. The NIS circuitry was fabricated on chip along with the TES detector, which maximized cooling performance but increased the complexity of detector fabrication. To simplify fabrication, we are developing NIS circuits capable of cooling macroscopic user-supplied payloads from 300 mK to 100 mK. In this paper, we describe this stage cooler and our ongoing efforts to cool separate, user-supplied payloads with NIS tunnel junctions.

2. NIS stage cooler

Fig. 1 is a photograph of our prototype NIS stage cooler. The NIS stage cooler is designed to cool a suspended Cu cold stage from 300 mK to 100 mK. The cold stage has a usable surface area of 2.54 cm $\times$ 2.54 cm where the user can attach a separate payload. The stage area was chosen for mechanical convenience; there is no fundamental obstacle to much larger stages. The NIS junctions will be used to cool the phonon system in a membrane that will then be connected to the cold stage through gold wire bonds, as shown in Fig. 2.

The cold stage in the center of Fig. 1 is supported by Kevlar, which was chosen because of its strength and low thermal conductivity at cryogenic temperatures. In order to measure the base temperature and cooling power of our stage cooler, we require four wires for thermometry and two wires for a heater. Six NbTi wires are spot-welded to the stage to provide these electrical connections. The stage cooler is surrounded by a 300 mK shield, not

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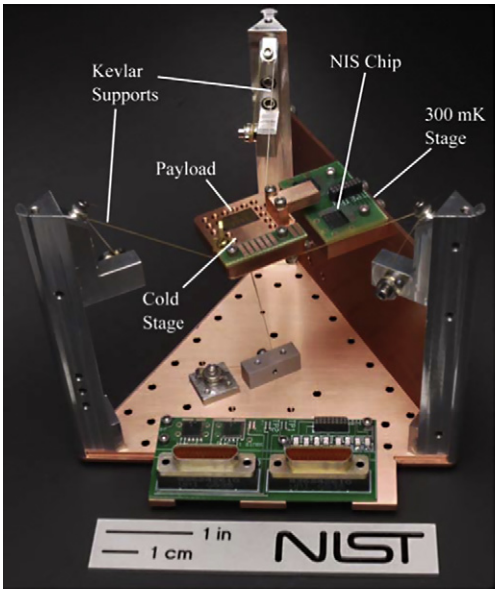

Fig. 1. Photograph of our prototype NIS stage cooler. The base, 300 mK stage and the cold stage are made of copper, and the support towers are made of aluminum. There are connections for 48 external wires provided by two micro D25 connectors.

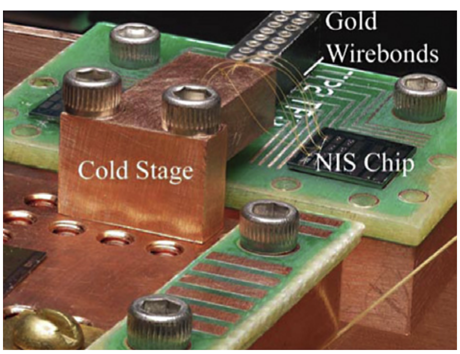

Fig. 2. Close-up picture of NIS junctions wirebonded to the cold stage, which shows that it is possible to connect the NIS junctions to the cold stage.

shown in the picture, to prevent 4 K radiation from overwhelming the NIS refrigerators.

Our initial design is to use two chips, each with one membrane cooled by about 8 NIS junctions. However, there is no obstacle to having multiple cooled membranes on a single Si chip. In the future, we plan to use devices with many more NIS junctions and membranes to increase the cooling power of our stage cooler.

3. NIS cooling

NIS junctions act as refrigerators by selectively removing the hottest electrons from a normal metal. At zero voltage bias, the Fermi levels in the normal and superconducting electrodes of the junction are equal and there are no available states for the electrons in the normal metal to tunnel to, and therefore no electrical current flows. When a voltage bias comparable to the gap energy of the superconductor is applied to the junction, the electrons with the highest energy, the hottest electrons, are able to tunnel from the normal metal into available states in the superconductor. We now describe a thermal model commonly used for NIS refrigerators that can be used to model the performance of our NIS stage cooler [4].

The current in an NIS junction is given by the following equation:

$$I_{\mathrm{NIS}} = \frac{1}{eR_n}\int_0^{\infty}[f_N(E-eV_b)-f_N(E+eV_b)]\frac{|E|}{\sqrt{E^2-\Delta^2}}\mathrm{d}E \tag{1}$$

where e is the electron charge, R_n is the normal state resistance, which is typically about 5.4 Ω for our devices, V_b is the bias voltage, f_N is the Fermi function of the normal metal, Δ is the energy gap in the superconductor, which is 189 μeV for our Al devices, and E is the energy of an electron with respect to the Fermi energy. The power deposited into the normal metal of an NIS junction is shown in the following equation:

$$P_N = \frac{1}{e^2R_n}\int_{-\infty}^{\infty}(E-eV_b)[f_S(E)-f_N(E-eV_b)]\frac{|E|}{\sqrt{E^2-\Delta^2}}\mathrm{d}E \tag{2}$$

where f_S is the Fermi function of the superconductor. This power is negative during refrigeration. This cooling can be applied to the phonon system by extending the normal metal onto a suspended thin membrane where electron–phonon coupling will cool the phonons in the system [5]. In order to calculate the base temperature of an NIS junction, we are required to solve a power balance equation for the normal metal, as shown in the following equation:

$$P_N(T_e,T_b)+\beta P_S(T_e,T_b)+\Sigma\Omega\left(T_p^6-T_e^6\right)+I^2R_{pad}+I^2R_{leak}=0 \tag{3}$$

The βP_S term represents heat flow due to the quasiparticle back flow from the superconductor. It is represented as a percentage of the power deposited into the superconductor given by $P_S = IV - P_N$. In our devices, we measure $\beta = 0.02$. The $\Sigma\Omega\left(T_p^6-T_e^6\right)$ term represents heat flow due to the electron–phonon coupling, where Σ is the electron–phonon coupling constant, which we have measured to be 2–3 nW/(μm^3 K^6) for our devices, Ω is the volume of the normal metal, 6.8 μm^3, and T_e, T_b and T_p are the electron, bath and phonon temperatures, respectively. In our model, we set T_p equal to the bath temperature. The I^2R_{pad} term is the Joule heating from the resistance of the normal metal, R_{pad}, which is 0.56 Ω for our devices. The I^2R_{leak} term is heating that arises from imperfections in the junctions. The junctions are modeled as having a parallel resistance that represents the leakage. Typically for our junctions, R_{leak} is on the order of 15 kΩ.

We have recently demonstrated a two junction NIS refrigerator that cools from 300 mK to below 100 mK, which is modeled well by Eq. (3) (O'Neil et al. [9]). Using the parameters from these devices in our calculations, we can numerically solve Eq. (3) to find the base temperature of the NIS stage cooler. By adding an additional constant term to the power balance equation, we can find the cooling power at a specific temperature or assess the effect of a payload on refrigerator base temperature.

4. Heat leaks

In addition to the NIS cooling power, the cold stage will also experience power loads due to three unavoidable heat leaks: the Kevlar supports, the measurement wires and black body radiation. We have taken steps to minimize each source and present the calculations of the expected heat loads.

Modeling the Kevlar supports and the measurement wires as a 1-D homogeneous material with the two endpoints at constant temperatures, the power load on the stage is given by Fourier's law, shown in the following equation:

$$P = -\frac{A}{x}\int\kappa(T)\mathrm{d}T \tag{4}$$

where P is the power load, x is the length, κ is the thermal conductivity and A is the cross-sectional area. Since the temperatures at the end points are fixed, the power can be minimized by increasing