Preprint
UCRL-JC-137836

A New Idea for a Solid-State Microrefrigerator Operating Near 100mK

J.N. Ullom, M.L. van deg Berg, S.E. Labov

This article was submitted to Applied Superconductivity Conference 2000, Virginia Beach, VA, September 17-22, 2000

September 18, 2000

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

This work was performed under the auspices of the United States Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

A New Idea for a Solid-State Microrefrigerator Operating Near 100 mK

Joel N. Ullom, Marcel L. van den Berg, Simon E. Labov

***Abstract*—We propose a new design for a solid-state microrefrigerator based on Normal-Insulator-Superconductor (NIS) tunnel junctions. These devices are a promising means of providing continuous refrigeration from 0.3 to 0.1 K without vibration or moving parts. Previously, the area and cooling power of NIS refrigerators have been limited by heating of the superconducting electrode. This problem can be overcome by using a superconducting single crystal as both the substrate and superconducting electrode of the NIS junction. In this paper, we briefly explain the benefits of our new design and describe experimental progress towards building such a device.**

***Index Terms*—microrefrigeration, normal-insulator-superconductor tunnel junctions, tunneling**

I. Introduction

Normal-Insulator-Superconductor (NIS) tunnel junctions are a promising technology for cooling to temperatures near 0.1 K from bath temperatures near 0.3 K [1, 2]. These ultralow temperatures are desirable for the operation of thin-film sensors which measure the energy deposited by particles and photons with great accuracy [3]. When a NIS junction is biased at a voltage V slightly below Δ/e, where Δ is the energy gap of the superconductor, current flow through the junction preferentially removes the hottest electrons from its normal electrode. Refrigeration is therefore achieved in a solid-state device that operates without vibration or moving parts.

The area of the NIS junction is a critical factor in device performance. Large area junctions are desirable because they yield larger cooling powers. However, NIS devices have only realized their theoretical performance and cooled from 0.3 to 0.1 K in devices whose junctions have submicrometer dimensions [2]. The maximum reduction in temperature achieved in devices whose junctions have dimensions of 10-20 micrometers is less than 5 mK [4]. In large area junctions, electrons which tunnel into the superconductor as quasiparticle excitations leave the junction area slowly because to do so they must diffuse a distance of 10-20 microns in a film that is a few hundred nanometers thick. The accumulation of quasiparticles in the superconducting electrode degrades refrigerator performance through two mechanisms: first, recombination phonons which reexcite the normal electrode, and second, a reduction in the energy removed from the normal electrode [5].

We propose here a new design for NIS refrigerators whereby the junction area is limited only by the need for a defect-free tunnel barrier. We propose to combine the substrate and superconducting electrode in a macroscopic superconducting single crystal. The long quasiparticle mean-free-path and large volume of such a crystal will prevent the accumulation of quasiparticles near the junction which degrades the performance of thin-film devices. For aluminum, the superconductor of choice for cooling near 0.3 K, crystals with residual resistance ratios of 45,000 are possible, corresponding to electronic mean-free-paths of order a millimeter [6].

II. Device Design and Benefits

A cross-sectional view of a NIS refrigerator based on a superconducting crystal is shown in Fig. 1. The refrigerated normal electrode is located on top of the superconducting crystal. Two additional superconducting leads make contact to the normal electrode. The first is a ground contact and the second forms a NIS junction whose current-voltage characteristics are used to measure the temperature of the normal electrode. The underside of the superconducting crystal is coated with a normal metal. Quasiparticles and phonons which enter this metal create electronic excitations, and their energy is removed from the crystal.

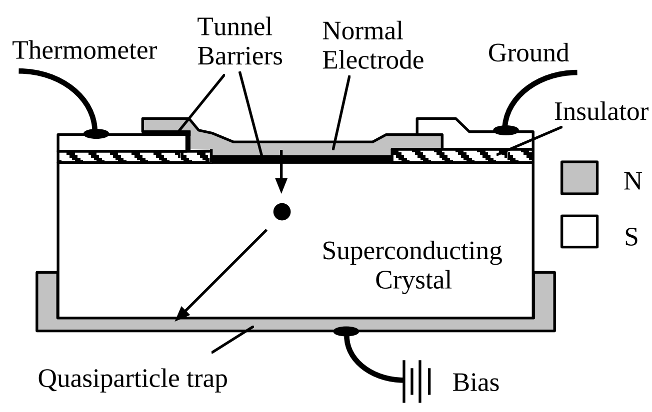

Fig. 1. Cross-sectional view of the proposed solid-state microrefrigerator. An electrical bias is applied between the normal electrode and the single crystal superconducting electrode. The normal electrode is refrigerated by the tunneling of hot electrons into the superconducting crystal. Excitations in the crystal move readily to a normal metal trap on its underside.

Proper calculation of the quasiparticle density in the

Manuscript received Sept. 18, 2000. This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48. J. N. Ullom is with Lawrence Livermore National Laboratory, Livermore, CA 94550 USA (telephone: 925-424-6777, e-mail: ullom1@llnl.gov). M. L. van den Berg and S. E. Labov are also with Lawrence Livermore National Laboratory.

superconducting electrode of the device of Fig. 1 requires solution of the diffusion equation with a source term due to current flow and loss terms due to quasiparticle recombination and trapping. Only a simple estimate of the density will be presented here. We equate the quasiparticle creation rate, $\sim I/e$, from a current I through the refrigerator junction with the loss rate, N/τ_{loss}, where N is the product of the quasiparticle density n and the effective volume of the crystal V, and τ_{loss} is the quasiparticle lifetime. Hence, $n = (I/e)(\tau_{loss}/V)$. If the thickness of the crystal is d, then a reasonable estimate of the effective volume V is d^3. We are currently working with Al crystals with a residual-resistance-ratio near 10^4, corresponding to an electronic mean-free-path of 460 μm. This long mean-free-path is comparable to the thickness of slices of the crystal that are practical to handle. Hence, quasiparticle transport from the junction to the normal trap on the underside of the crystal is quasi-ballistic and $\tau_{loss} \approx 10\, d/v_f$ where v_f is the Fermi velocity. The factor of 10 is a rough effort to account for the energy-dependence of the quasiparticle group velocity and the probability of trapping. For $d = 1$ mm, τ_{loss} is given by 5 ns. For a current $I = 1.7$ μA, the quasiparticle density n is then 5×10^4 per mm^3. In contrast, the same current has been calculated to produce $n = 10^{13}/mm^3$ in a thin film device with a square junction of area 400 μm^2 [5]. Hence, the proposed design incorporating a superconducting crystal reduces the quasiparticle density by more than eight orders of magnitude. While the assumption of ballistic transport through the crystal is likely optimistic, the message of the preceeding estimate is clear: the proposed design will eliminate heating of the superconducting electrode. Quasiparticles do not accumulate near the junction because of their long mean-free-path in the crystal and because of the three-dimensional geometry. Furthermore, quasiparticle recombination is reduced because the quasiparticle population is diluted in the large volume of the crystal.

III. Experimental progress

The primary experimental challenge for our new design is preparation of the single crystal substrate. Extreme smoothness is required since the polished surface of the crystal must, with very little modification, form one electrode of the tunnel junction. Imperfections in the surface reduce the resistance of the tunnel barrier and cause leakage currents which degrade device performance. We are exploring a range of mechanical, chemical, and electrochemical polishing techniques. An atomic-force-microscope image of a polished Al crystal is shown in Fig. 2. The RMS roughness is less than 1 nm in each of the outlined regions. The full area of the image is 400 μm^2. Tunnel junctions have previously been fabricated on superconducting single crystals for X-ray and gamma-ray detectors [7]. Based on this body of work, we are optimistic that the surface smoothness shown in Fig. 2 is adequate for device fabrication.

The second requirement for the single crystal substrate is preservation of the crystalline order at the surface. Polishing techniques which produce extreme smoothness can simultaneously deform and damage the crystal lattice. This damage will slow the motion of quasiparticles away from the junction. Measurements of the Laue pattern from the crystal shown in Fig. 2 indicate that the single crystal structure has been preserved.

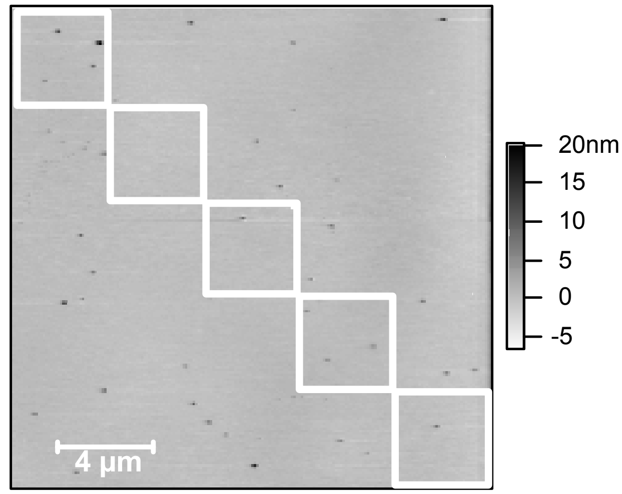

Fig. 2. Atomic-force-micrograph of a polished Al crystal. The RMS roughness is less than 1 nm in all the outlined regions. The RRR of this crystal before cutting was roughly 10^4.

IV. Conclusions

We have proposed a new design for NIS tunnel junction refrigerators in which the superconducting electrode is a superconducting single crystal. The proposed design will eliminate effects that have previously limited the junction area and cooling power of these devices. Preparation of Al crystals suitable for device fabrication is underway.

Acknowledgment

The authors wish to thank Mark Wall, Aleksandr Noy, and Jennifer Klare for expert assistance with crystal preparation and characterization.

References

[1] M. Nahum, T. Eiles, J. M. Martinis, "Electronic microrefrigerator based on a normal-insulator-superconductor tunnel junction," *Appl. Phys. Lett.*, vol. 65, pp. 3123-5, 1994.

[2] M. M. Leivo, J. P. Pekola, and D. V. Averin, "Efficient peltier refrigeration by a pair of normal metal/insulator/superconductor junctions," *Appl. Phys. Lett.,* vol. 68, pp. 1996-8, 1996.

[3] N. E. Booth, B. Cabrera, and E. Fiorini, "Low-temperature particle detectors," *Annu. Rev. Nucl. Part. Sci.*, vol. 46, pp. 471-532, 1996.

[4] P. A. Fisher, J. N. Ullom, and M. Nahum, "High-power on-chip microrefrigerator based on a normal-metal/insulator/superconductor tunnel junction," *Appl. Phys. Lett.*, vol. 74, pp. 2705-7, 1999.

[5] J. N. Ullom and P. A. Fisher, "Quasiparticle behavior in tunnel junction refrigerators," *Physica B*, vols. 284-288, pp. 2036-8, 2000.

[6] F. R. Fickett, "Aluminum 1. A review of resistive mechanisms in aluminum," *Cryogenics*, vol. 11, pp. 349-367, 1971.

[7] M. P. Bruijn, F. B. Kiewiet, M. L. van den Berg, O. J. Luiten, P. A. J. de Korte, A. W. Hamster, C. G. S. Brons, and J. Flokstra, "High quality superconducting tunnel junctions on Nb and Ta single crystals for

radiation detection," *Appl. Phys. Lett.*, vol. 71, pp. 1252-4, 1997. See also H. Netel, "Low Temperature Gamma-Ray Spectrometers Based on Bulk Superconducting and Dielectric Absorber Crystals," Ph.D. Thesis, University of Twente, 1999.