A Miniature Adiabatic Demagnetization Refrigerator with a Magnetoresistive Heat Switch

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Abstract. We present the design of a novel, miniature ADR with no moving parts, which could be used to cool detectors for astrophysics research, semiconductor analysis, and mass spectrometry. The miniature ADR relies on the development of a magnetoresistive heat switch. We present measurements of the thermal conductivity of a single-crystal tungsten heat switch at temperatures below 4 K and magnetic fields below 0.9 Tesla.

INTRODUCTION

The detection of small signals from sources of interest has been an aim of science for many generations. In the past fifty years there has been a revolution in techniques and instruments used to achieve these goals. Much of the progress can be attributed to the development of state-of-the-art detectors such as bolometers and microcalorimeters. These detectors typically require cooling to temperatures around 100 mK, and while detector development has experienced great growth, the development of new refrigeration technology still lags behind. Adiabatic Demagnetization Refrigerators (ADRs) have been used for many years to reach temperatures below 1 K and have been used in recent experiments with very sensitive detectors. Unfortunately, ADRs have traditionally been bulky, expensive, difficult to construct, and occasionally unreliable. It is our goal to develop a Miniature Adiabatic Demagnetization Refrigerator (MADR) that will be a reliable, simple, continuous cooling solution for many different applications.

CONVENTIONAL ADRS

ADRs are composed of three main components; a paramagnetic refrigerant, a magnet, and a heat switch. The refrigerant is typically in the form of a "salt pill," and the magnet is typically superconducting. The cooling power of the ADR comes from the conversion of thermal entropy into the spin entropy of a paramagnetic salt's electrons. A cycle of an ADR begins with the heat switch "on," i.e. maintaining thermal contact between the salt pill (which houses the paramagnetic salt) and the thermal reservoir. A 3 to 4 Tesla magnetic field is applied to the salt, causing the

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spins of the salt's electrons to align in an isothermal process. The heat switch is then turned "off", breaking thermal contact with the bath. Next, the magnetic field is slowly reduced in an adiabatic process. The change in temperature occurs because during the isothermal process the relative number of atoms in each state changes to many more atoms in the lowest state than in the highest state, and the energy separation between each state increases. During the adiabatic demagnetization, the relative number of atoms in each state remains the same as after the isothermal process, but the separation between each energy level returns to the original value. So, because of the large population differences and small energy level separations, the final temperature is lower than the starting temperature [1].

A typical ADR uses a 100 to 1000 cm^3 salt pill (depending on desired hold time) placed in the bore of a superconducting solenoid with a gas-gap or mechanical heat switch. Such a setup can be rather bulky with the salt pill alone being in excess of 10 cm in length. Aside from size, the mechanical heat switches pose a reliability risk to experiments in remote environments. And while typical hold and cycling times of 36 hours and 30 minutes respectively give duty cycles with nearly 99% efficiency, ADRs do not posses the continuous cooling ability of dilution refrigerators. For smaller scale experiments, it is often the case that the additional 250mK or so of additional temperature range that an ADR has does not have the allure of the simpler setup of a ^{3}He refrigerator.

A NOVEL APPROACH

To address the problems of conventional ADRs described above, we present the design of a novel miniature adiabatic demagnetization refrigerator in Figure 1. All components of the MADR are incorporated to accommodate a simple planar geometry, which allows for easy assembly and access to all parts. Two 1 cm^3 salt pills are used to speed up cycling time and to allow for continuous cooling. Magnetoresistive heat switches as suggested in [2] are used instead of mechanical or gas-gap switches to address size and reliability issues. Also, miniature magnets (not pictured) with flux-concentrating rare earth metals holmium and vanadium permendur are used to provide the necessary magnetic fields [3,4].

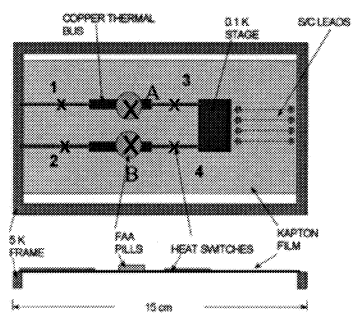

FIGURE 1. Design for the MADR with all components incorporated onto a planar layer of copper-clad Kapton® available from DuPont. An 'X' indicates areas where magnetic field is applied by miniature superconducting magnets (not shown) located above and below the plane of the MADR.

Simulations using data from [5] for the material-based heat switch and the known performance of the paramagnetic salt ferric ammonium alum (FAA) have shown that the MADR will be able to cool an experimental stage to below 0.1 K from thermal reservoirs of less than 5 K. Unlike conventional ADRs, which use a single salt pill to cool a cold stage in one shot, the MADR is designed to alternately operate 2 salt pills rapidly. Heat from cold stages of 100's of grams can be removed in multiple cycles until the desired operating temperature is reached. Once there, one pill will provide temperature control until its cooling power is exhausted, while the other is prepared for its next cooling cycle. Such operation will allow for continuous cooling from a helium bath. The power requirements for the MADR will be less than 50 W because of the small inductances of the magnets.

A MAGNETORESISTIVE HEAT SWITCH

After rejecting superconductors as potential heat switches due to their low on/off ratio at liquid helium temperatures, we examined metals that exhibit magnetoresistance. After considering single-crystal beryllium, cadmium, and gallium, we determined that single-crystal tungsten would best fit our needs based on data presented in [5,6] and material properties. Tungsten has a zero-field thermal conductivity on the order of 1000 W/cmK at liquid helium temperatures [5]. When a magnetic field of ~1 Tesla is applied perpendicular to the direction of heat flow, the thermal conductivity typically drops by 4 orders of magnitude. This occurs due to the loss of electron momentum in the transverse direction as the electrons spiral around the magnetic field lines.

We obtained a single-crystal of tungsten oriented along the 100 axis with dimensions 0.5 X 0.5 X 20 mm from MR Semicon, Inc. to ensure that tungsten is a viable heat switch option. The dimensions were selected to allow for adequate thermal conductivity in the "on" state for rapid salt pill cycling and to maintain a small enough heat leak in the "off" state so that the hold time for a single salt pill was longer than the cycling time. With an applied field of 2.2 Tesla we expect an "off" state heat flow of 8.4 _W from 2.5 K to 0.1 K, which corresponds to a 190 s hold time for a 1 cm^3 salt pill operating at 0.1 K. We expect an "on" conductivity > 100 W/cmK for the tungsten based on Batdalov's measurements [5]. This conductivity could be limited by the boundary resistance at the copper-tungsten junction and at the Kapitza resistance between the salt and the thermal bus. We are currently examining what effects these resistances will have and how to reduce them. In Figure 2, we show that our low field measurements agree well with power law fits to the thermal conductivities presented in [5]. We were unable to make thermal conductivity measurements at fields greater than 7.8 KG due to problems with our magnet system, but we expect high field measurements in the near future.

CONCLUSIONS

The miniature adiabatic demagnetization refrigerator described here will provide a continuous cooling option for many experiments without the complexities of dilution refrigerators. Possible applications include cosmic microwave background observations, diffuse X-ray background observations, mass spectrometry [7], X-ray microanalysis [8], and thermal neutron detection [9]. A vital part of the development of the MADR is the testing and incorporation of a single-crystal tungsten magnetoresistive heat switch, which allows the refrigerator to cool continuously with no moving parts.

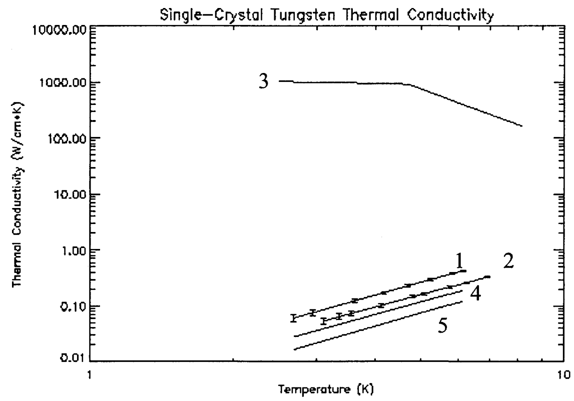

FIGURE 2. Measured thermal conductivity of single-crystal tungsten and power law fits to data from Batdalov and Red'ko. We have fits to our measured data at 5.95 KG, 7.8 KG, and fits to Batdalov and Red'ko's data at no field, 5.95 KG and 7.8 KG for curves 1 through 5, respectively. All measurements were fit to the form aT^b, with results of a = 0. 0059, 0.00405, 0.003, 0.0016 and b = 2.36, 2.28, 2.44, 2.53 for the curves 1, 2, 4, and 5, respectively. Curve 3 is fit with a line of form $-50T + 1150$ for temperatures below 4.7 K and a $T^{-3.1}$ power law for temperatures above 4.7 K.

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