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A piezoelectric cryogenic heat switch

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We have measured the thermal conductance of a mechanical heat switch actuated by a piezoelectric positioner, the PZHS (PieZo electric Heat Switch), at cryogenic temperatures. The thermal conductance of the PZHS was measured between 4 K and 10 K, and on/off conductance ratios of about 100–200 at lowest and highest measures temperature were achieved when the positioner applied its maximum force of 8 N, respectively. We discuss the advantages of using this system in cryogenic applications, and estimate the ultimate performance of an ideal PZHS. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4876483]

I. INTRODUCTION

Heat switches are used to control the transfer of heat between objects at different temperatures, and are particularly important in cryogenic environments. Applications in this context include minimizing the parasitic heat load from a cryocooler in a redundant refrigeration system,[1] connecting instruments to and from a cryo-radiator,[2] and transferring heat from a salt pill in an adiabatic demagnetization refrigerator (ADR).[3] Many types of cryogenic heat switches exist, including gas gap, mechanically actuated, superconducting, and fluid-loop based.[4] In this work, we describe the construction and characterize the performance of a novel mechanical cryogenic heat switch actuated by a piezoelectric positioner, the PZHS (PieZo electric Heat Switch).

Our motivation in developing the PZHS stems from the fact that many NASA science missions require cryogenic capabilities; consequently, heat switches often play a critical role in the success of these experiments. Since efficient photon detection tends to be greatly enhanced at lower temperatures ($T \leq 1$ K),[5] ADRs are firmly entrenched as NASA's preferred technology for detectors operating in this temperature regime. Current state of the art ADRs use multiple gas gap heat switches to transfer heat from the salt pill during the magnetization (heat rejection) stage of the refrigeration cycle. Although these heat switches have demonstrated the performance required, for example, by the Astro-H mission,[6] their use is limited to either very low ($T < 0.3$ K) or relatively high ($T \sim 5$ K) cryogenic temperatures. In addition, the hermetic joints required to contain the ^{3}He exchange gas within the switch housing have shown vulnerability to the mechanical stresses associated with thermal cycling and vibration. The PZHS is thus an attractive alternative technology to a gas gap heat switch, since this device has an essentially unlimited range of cryogenic operating temperatures, is mechanically robust, and is free from hermetic sealing requirements. In the remainder of this paper we will discuss the design and construction of the PZHS test apparatus, the measurements carried out to characterize the system, our experimental results, and plans for future work.

II. PZHS DESIGN AND CONSTRUCTION

The principle of operation of the PZHS is elegantly simple; our experimental apparatus for demonstrating this device is shown in Fig. 1. Two high-conductivity metallic plates act as independent thermal reservoirs, with one mounted to a support structure and the other fastened to the mobile stage of a piezoelectric positioner (an attocube ANPz101).[7] When the positioner is energized with a series of positive voltage ramps, the lower plate moves upwards until mechanical contact is established with the upper plate. In this configuration, the switch is closed, and heat transfer occurs between the two plates. After the desired heat transfer is complete, energizing the positioner with negative voltage ramps moves it downwards until mechanical contact is lost between the plates, leaving the switch open.

The key figure of merit for this device is the *switching ratio*, *S*, defined by

$$S \equiv \frac{k_c}{k_o}, \tag{1}$$

where k_c and k_o are the thermal conductance of the PZHS when closed and opened, respectively. Proper engineering of a heat switch thus consists of maximizing k_c while minimizing k_o. When the switch is open, during steady state operation,

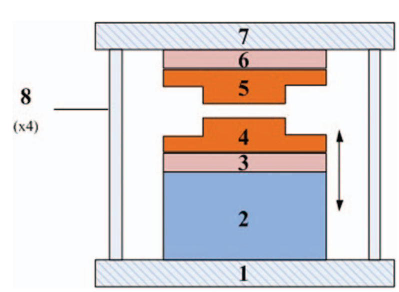

FIG. 1. A schematic of the PZHS design: 1 – Base support plate. 2 – Piezoelectric positioner. 3 – Lower insulator. 4 – Lower conductor. 5 – Upper conductor. 6 – Upper insulator. 7 – Top support plate. 8 – Structure columns (×4).

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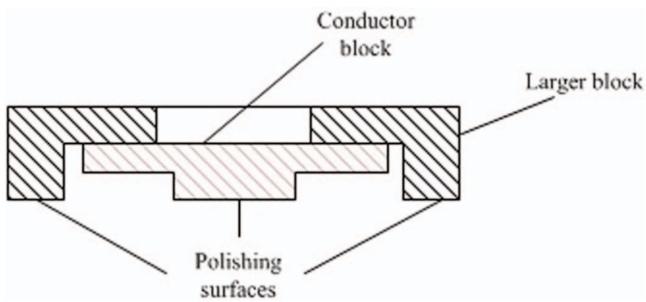

FIG. 2. Lapping method for the copper plates to ensure flat, parallel, and smooth PZHS mating surfaces.

parasitic heat flows from the high to low temperature reservoir via the structure columns. To mitigate this, and consequently minimize k_o, the columns were constructed from G-10 hollow rods, and the plates were mounted on Vespel SP1 insulators. To maximize k_c, the upper and lower plates were made from ultra high purity (99.999%) copper, with a contact area of 1.45 $\times$ 1.45 cm.[2]

With the expectation that the PZHS performance would be limited by the joint conductance, we paid particular attention to the preparation of the plate surfaces, striving to make them as flat and as parallel as possible. This would have the effect of increasing the effective PZHS contact area and thus enhancing k_c. Our method is shown in Fig. 2. The switch plates were bolted to a larger, hollowed out block, with walls slightly higher than the plate itself. This assembly was then placed on a lapping table, and the switch surfaces were sanded by pouring isopropanol alcohol on sand paper of progressively finer paper grits, culminating in the use of a special cotton impregnated with metal polish. Once the surfaces were immaculate, the switch plates were cleaned and gold plated with $\sim$1 μm of Au. The plating prevents tarnishing of the copper, and also acts as a "cushion" to the switch surfaces, further enhancing the effective contact area. Table I summarizes the properties of the main components of the PZHS.

TABLE I. Properties and dimensions of major components of our PZHS.

Parts	Material	Dimension
Upper and lower conductor	99.999% pure copper	Contact area square of 1.45 cm on each side
Upper and lower insulator	Vespel SP-1	7 mm thick square block
Support columns	G-10	4.3 cm long, 6.3 mm OD, 3.2 mm ID

In order to establish the desired temperature of the reservoirs independently, a small thermometer and heater were mounted on each plate, and the temperatures were maintained using a Proportional-Integral-Derivative controller (PID). To allow for reasonable thermal time constants ($\sim$ minutes), thin *electrically insulated* copper wires were attached from each reservoir to the cold stage of the test cryostat, a cryocooler with a base temperature of $\sim$3 K. Contact between the plates was checked using a two-wire resistance measurement. With the switch open, no continuity was observed; with the switch closed, continuity was confirmed, with a measured resistance of $\sim$80 Ω. We note that all of our closed switch data were obtained with the positioner applying its maximum specified force of 8 N. A photograph of the complete PZHS assembly is shown in Fig. 3.

III. EXPERIMENTS AND RESULTS

Figure 4 shows a simplified schematic of the conductance network in our PZHS test apparatus. The upper switch plate, lower switch plate, and cryocooler cold plate temperatures are labeled T_U, T_L, and T_b, respectively. The conductance of the mechanical joint is k_c, while the upper switch plate is connected to the cold plate through a conductance k_U, and the lower switch plate is connected to the cold plate through a conductance k_L. With the switch open, $k_c = 0$, and k_U and k_L can be determined as a function of temperature by setting T_U

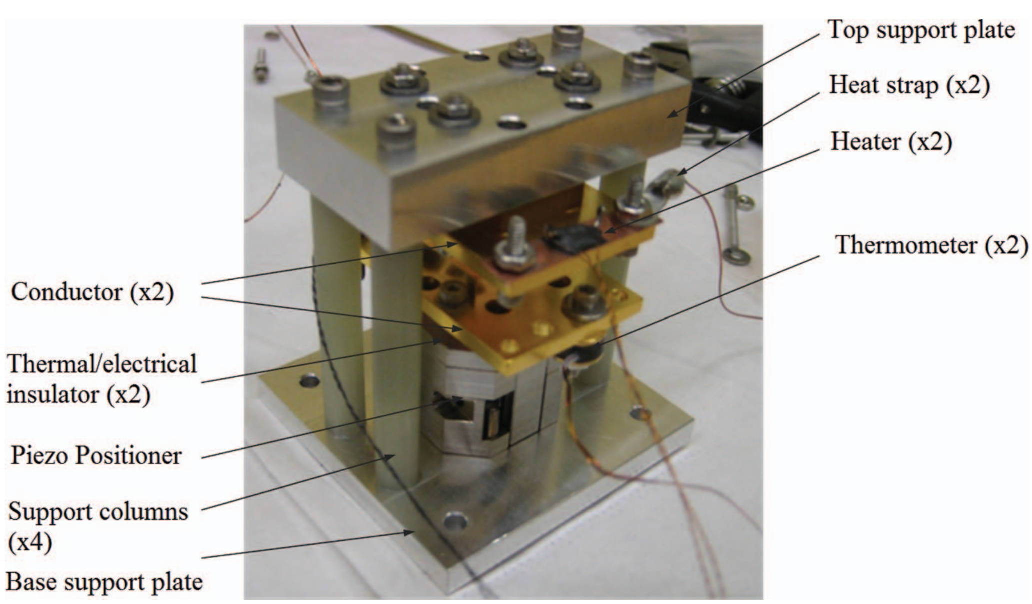

FIG. 3. PZHS test assembly. The assembly was tested in a cryostat with base temperature $\sim$3 K.

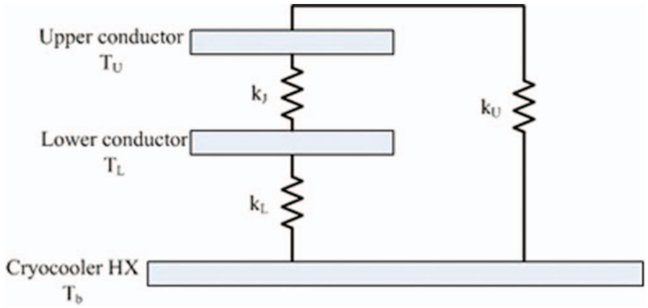

FIG. 4. A simplified conductance network of the PZHS test apparatus.

and T_L equal:

$$if\ T_U = T_L \begin{cases} \dot{q}_U = k_U\ (T_U - T_b) \\ \dot{q}_L = k_L\ (T_L - T_b) \end{cases}. \qquad (2)$$

We observed that both k_U and k_L were linearly dependent on reservoir temperature, with best-fit results (in mW/K) of $k_U = 3.2 \times 10^{-6} + (6.4 \times 10^{-6}) \times T_U$ and $k_L = 5.4 \times 10^{-6} + (4.3 \times 10^{-6}) \times T_L$. After measuring the conductance from the reservoirs to the cold plate, the joint conductance k_c was determined by closing the switch, independently controlling the temperature of each plate, and applying the following equations:

$$if\ T_U = T_L + \delta T \begin{cases} \dot{q}_U = k_U\ (T_U - T_b) + k_J\ (T_U - T_L) \\ \dot{q}_L = k_L\ (T_L - T_b) \end{cases},$$
$$if\ T_U + \delta T = T_L \begin{cases} \dot{q}_U = k_U\ (T_U - T_b) \\ \dot{q}_L = k_L\ (T_L - T_b) + k_J\ (T_L - T_U) \end{cases}. \qquad (3)$$

Solving the set of equations in Eq. (3) yields the conductance of the mechanical joint, k_c. We plot the results of our experiments in Fig. 5 for temperatures from 4 K to 10 K. It is to be noted that the performance of the heat switch (the switching ratio) did not degrade by repeating the open/close cycle indicative of its suitability for use in systems where repeated cycling is desired.

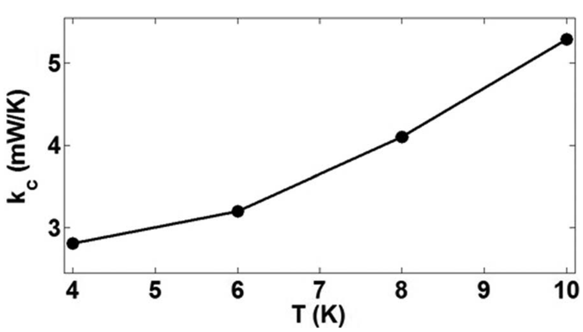

FIG. 5. Thermal conductance of the PZHS vs. temperature.

A conservative estimate of the PZHS switching ratio at 4 K can be obtained by setting $k_o = k_U \sim 0.028$ mW/K (nearly independent from temperature), determined experimentally through the method described above, which yields S ∼ 100 at the lowest temperature of 4K and ∼200 at the highest measured temperature of 10 K. We note that the thermal conductance for a solid piece of copper at 4 K with the same dimensions as our switch plates is 62 W/K, which represents the theoretical upper limit or ideal performance for the PZHS. This value can be used as a figure of merit for heat switches, ignoring any joint resistance or other loss mechanisms in the heat transfer process. A more realistic estimate, based on studies of bolted mechanical joints,[8] suggests a limit of ∼10 W/K. Thus, as anticipated, the PZHS conductance is limited by k_c, and future work should focus on methods to improve this parameter.

IV. CONCLUSIONS

We have demonstrated a proof of concept, mechanical heat switch, the PZHS, actuated by piezoelectric elements for use in cryogenic applications, with a switching ratio S ∼ 100 at 4 K and 200 at 10 K. In principle, such a heat switch would be sufficiently versatile to operate at all cryogenic temperatures of interest to NASA. The PZHS has the potential for significant improvement by using piezoelectric positioners with larger clamping forces, in addition to spring loading on a thermal reservoir. We hope to incorporate these and other improvements in a subsequent version of the PZHS. We also hope to characterize the switching ratio as a function of clamping force in future measurements.

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