Passive Gas-Gap Heat Switches for use in Low-Temperature Cryogenic Systems

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Abstract. We present the current state of development in passive gas-gap heat switches. This type of switch does not require a separate heater to activate heat transfer but, instead, relies upon the warming of one end due to an intrinsic step in a thermodynamic cycle to raise a getter above a threshold temperature. Above this temperature sequestered gas is released to couple both sides of the switch. This enhances the thermodynamic efficiency of the system and reduces the complexity of the control system. Various gas mixtures and getter configurations will be presented.

1. Introduction

Refrigeration cycles in cryogenic coolers often need a method to control the flow of heat throughout the system. This may be done with a valve or other mechanism to make or break a thermal connection between components within the system and a heat sink. These heat sinks may be a bath of liquid cryogen, a cryocooler cold tip, or another cryogenic stage within a multistage system. In an ultra low-temperature refrigeration system such as an adiabatic demganetization refrigerator, the control of heat flow is performed via heat switches. These switches may be characterized by the physical process that changes the state of the switch: on to off or vice versa. This classification may be refined further by stating how this process is initiated. An active switch is one where the control system must explicitly initiate a change in the switch state. A passive switch changes its state in response to a change elsewhere in the system. For instance, if the temperature of a cryogenic stage is commanded to change, a passive switch may react to this temperature change. There is no explicit command to modify the switch state, it is a consequence of a temperature change within the system.

A brief survey of switch types based upon their switching mechanism is listed below. This list does not include all types that have been developed over the years but instead contains types that the authors have used or tested over the past few years.

1.1. Mechanical Switches

As the name implies, mechanical heat switches rely upon the contact of two or more conductors driven together by some mechanism to close the switch. Here, the conduction across the interface of the conductors is linearly proportional to the force applied [1]. The mechanism may be as

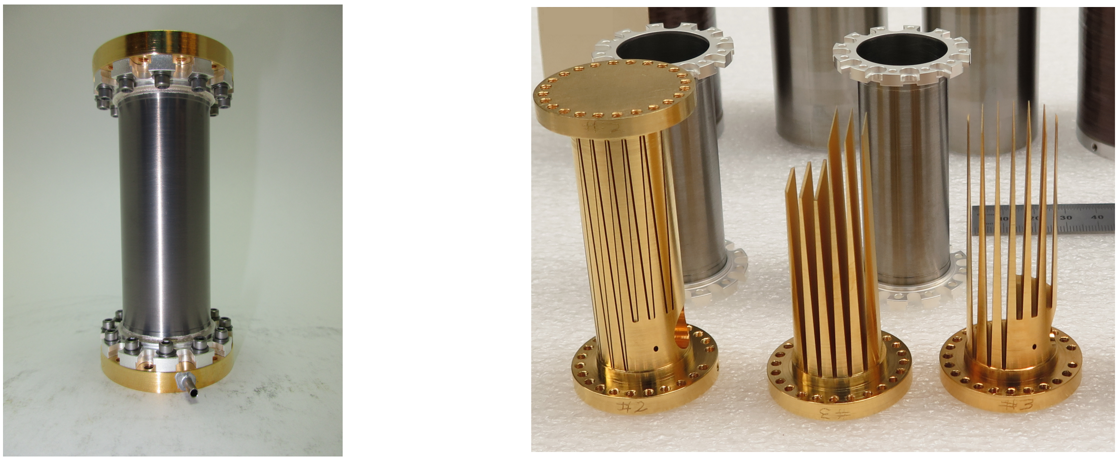

Figure 1. A complete passive gas-gap heat switch ready to be filled with gas is shown in the image on the left. The dimensions of this particular switch are ~83 mm in length and 38.1 mm in diameter at the end flanges. See text for information on the hermetic outer tube dimensions. The small open tube soldered into the lower flange accepts thin copper tubing from the fill cart. This tubing allows a known quantity of gas to be injected into the switch. It is then crimped closed and cut separating the switch from the fill cart. The image on the right shows the copper fins that are sealed onto the outer tube and flange combination using a crushed indium wire. When assembled, the gap between adjacent fins is ~0.36 mm.

simple as a vise that provides a mechanical advantage from a rotating screw connected to a room-temperature handle. Another realization may be a electrical stepper motor on the inside of a cryostat that drives the screw. A commercial example may be purchased from High Precision Devices in Boulder CO. [2].

A third method of forcing conductors together was demonstrated by Jahromi and Sullivan in 2014 [3]. Here they describe the construction and testing of a switch with one conductor held stationary and the second mounted on a piezo-electric translator. When activated, the piezo-electric stage would move its conductor into contact with the fixed conductor closing the switch. Operation of a proof-of-concept switch was demonstrated but the overall conductance was low, on the order of 1 mW/K near 4 K.

These switches may be considered active since the operator commands the switch to open or close.

1.2. Superconducting Switches

This type of switch relies upon a change in conduction when a metallic element internal to the switch transitions from the normal to superconducting state. Obviously the temperature range where this switch is used must be below the superconducting transition temperature of the particular metal chosen for the switch.

In normal metals, the thermal conduction is a combination of heat carried by electrons and phonons. Typically, the electronic contribution dominates below 10 K since most of the phonons are “frozen out”, unable to carry heat. In a switch that uses a metal that transitions into the superconducting state below some critical temperature as the switching element, when this element falls below the transition temperature, the conduction across the metal linking the two sides is proportional to the number of electrons not condensed into the quantum-mechanical ground state leaving the small phonon contribution only. This is temperature dependent and is given by

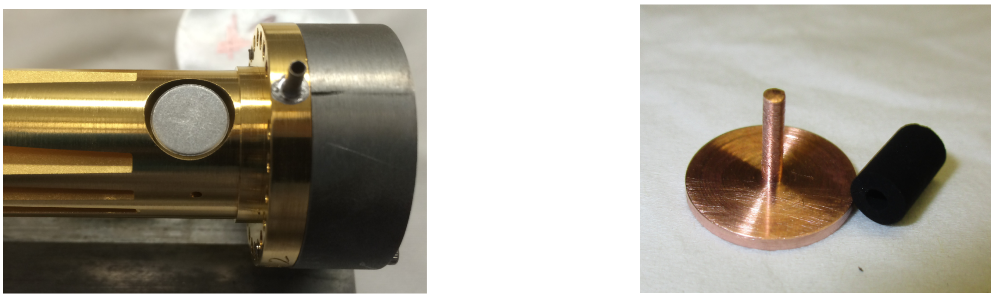

Figure 2. Examples of some of the getters used in our passive gas-gap heat switches. The image on the left shows a sintered stainless-steel getter epoxied into the switch body. This type of getter is used in our 1.2 K heat switch. The image on the right shows a charcoal getter about to be epoxied onto a copper disk and post. This whole assembly then replaces the stainless puck shown in the left image and is used in the 10 K switch. A switch intended to operate below 0.200 K may omit a large-surface area getter since even ^{3}He will bind strongly to the gold-plated copper fins in this temperature range: the fins become the getter surface.

$$\alpha T e^{-\beta T_c/T} \tag{1}$$

where α and β are constants that depend upon the material, T is the temperature of the material, and T_c is the transition temperature of the material. It is easy to see that the conduction is a strong function of the ratio of T_c/T. Therefore, to achieve low conductance in the open state, the switch must be used far below T_c.

To close this switch, one must induce a transition to the normal state. While it may be achieved by heating the switching element so it is above T_c, this introduces heat to the system, often at ultra-low temperatures where heat capacities are low and the effects are significant. A more efficient switching mechanism is to impose a magnetic field upon the switching element where the magnitude of the field is above the materials critical-field value. A Helmholtz coil is typically used to produce a uniform field transverse to the wire axis.

The benefit of this switch is it works well at ultra-low temperatures and has a rapid switching time. However, as stated before, its use is limited to a temperature range far below the transition temperature. For instance, a switch with a lead wire as the switching element is only useful below ~0.5 K while the T_c is ~9 K for lead. Like the mechanical switches discussed above, these fall into the active category.

1.3. Gas-Gap Switches

These switches—the main focus of this paper—rely upon the presence of a gas between the ends of the switch to allow heat to flow across the switch. If no gas is present, then the switch is open. The on-state conductance has many contributions such as the surface area of the ends that contact the gas, the amount of gas carrying the heat, and the conductivity of the metal switch internals. A resistance at any boundary within the switch hinders conductance. An example of this is the resistance at the boundary between helium and the internal structures. There is also a thermal boundary resistance at any metal-to-metal joint where the heat switch connects to a thermal strap or cooling stage. These effects may be large at sub-Kelvin temperatures [1].

This type of switch was proposed in 1973 by Bywaters and Griffin [4] and first put into use by Nast, Bell, and Barnes [5] and Frank and Nast [6]. A switch that transitions between the open and closed state without an explicit command to do so, was first reported by DiPirro, Shirron, Tuttle, and Canavan in 2004 [7]. This paper extends that work.

2. Contributions to Switch Conductance

2.1. Helium Gas

The choice of gas used to construct a switch for use below 10 K is limited. Here one may choose ^{3}He, ^{4}He, or hydrogen. Below about 5 K, the choice narrows to helium only. Since ^{3}He has a higher conductance than ^{4}He below 10 K, it is usually the preferred choice if the additional cost of its use is not a driving concern.

2.2. Internal Copper Fins

A large contribution to the overall switch conductance is the total area over which the helium gas within the switch contacts the structures connected to the switch ends. The more area in contact, the greater the conduction for a given gas pressure. Conductance is also inversely proportional to the gap over which the gas must transfer heat. Therefore, it is advantageous to cut the internal structures into many fins that have small gaps between adjacent surfaces. An example of a pair of switch internals, or innards as we call them, are shown in Figure 1. To create a set of fins we start with a solid rod of high-purity copper then cut it into two commensurate pieces containing large surface areas. This is performed using wire electro-discharge machining and no attempt is made to smooth the rough surface left by the process. The purity does not need to be extremely high since it is one of many factors that play a role in the overall switch conductance. Often, a purity of 99.99% is good enough to not be the limiting factor, especially at ultra-low temperatures.

2.3. Hermetic outer shells

For the switches reported here, a thin shell, ~0.13 mm in thickness, of a low-conductivity metal is used as the sidewall surrounding the internal conducting elements. Typically, they are brazed into flanges that form one side of an indium seal that mates the internal copper fins to the thin shells. The use of an indium seal eases the assembly and allows the switch to be disassembled for any reason.

The small cross-sectional area does little to aid the on-state conductance but, instead, is meant to be isolating when the switch is in the off-state. Therefore, metals known to have lower thermal conductivity below 10 K are used. These include titanium 6Al-4V, titanium 15V-3Sn-3Cr-3Al, commonly shortened to Ti 15-3-3-3, or even one of the 300-series stainless steels. The choice of a titanium alloy for an application well below its superconducting transition temperature of ~ 3.4 K is recommended due to the further reduction in conduction based upon the stronger temperature dependence of the thermal conduction of titanium in the superconducting state (see, for instance, Canavan and Tuttle [8] and Wikus et al. [9]).

3. Experimental Setup

To measure the conduction of a switch, an adiabatic demagnetization refrigerator (ADR) was mounted in a cryostat that contains a two-stage cryocooler cold head. The coldest stage acts as the heat sink for recycling the ADR. The switch is mounted to the ADR salt pill with the getter side in strongest thermal contact to the salt pill. A ruthenium oxide sensor was mounted on the ADR-side of the switch and second sensor was mounted on the “free” side. A heater was also mounted on the “free” side to allow a delta temperature to be imposed across the switch.

To measure the switch conductance, the cryostat is cooled to the base temperature provided by the cryocooler. Then the ADR stage is recycled and brought to the temperature where a conductance measurement will be made. Temperature control of the ADR stage is performed using the thermometer mounted on the ADR-side of the switch. Now heat is applied to the “free” end of the switch via the heater and the change in temperature of the “free” end is recorded. Since the ADR-side of the switch is part of the feedback loop to the ADR control, its temperature does not change with heat applied.

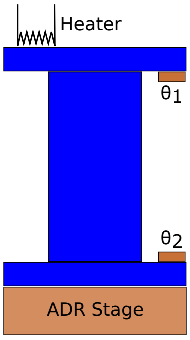

Figure 3. A simplified block diagram describing the experimental setup. The switch to be tested is mounted on an adiabatic demagnetization refrigerator stage capable of cooling the switch to sub-Kelvin temperatures. A thermometer, θ, is placed on the flange at each end of the switch to measure a delta T when heat is introduced via a heater on the "free end" of the switch. See text for more details of the setup.

It is desirable to record data for various heater powers at a fixed getter-side temperature then perform a linear fit to the power applied versus δT. The slope of this fit is the conductance. Analyzing the conductance this way eliminates first-order systematic errors such as calibration offsets in the two sensors and small heat inputs to the "free" end of the switch via heat conducted along sensor wires. Power applied to the heater is such that the temperature rise of the "free" end of the switch is no greater than a few percent of the no-power-applied value at most. Once enough data is gathered at a temperature, the ADR temperature set point is reset to another value and the same process is repeated at the new getter-side temperature.

4. Performance Data

4.1. Open-state conductance

The choice of material for the hermetic outer shell of the switch dictates the open-state, or off, conductance of the switch. One may consider thin metallic shells or even carbon fiber or other insulator material wrapped into a tube. We often choose a thin metallic shell since it is relatively easy to manufacture and nearly guaranteed to be hermetic since the diffusion constant of helium through most metals is nearly zero.

The conductance across the heat switch shell is given by the following equation:

$$\dot{Q} = \frac{A}{L} \int_{T_{\text{low}}}^{T_{\text{high}}} \lambda \, dT \tag{2}$$

where A and L are the cross-sectional area and length of the shell respectively, and T_{low} and T_{high} are the temperatures at each end of the heat switch. The conductivity λ is material specific but often follows a power low in temperature.

If one chooses a metal that will transition into a superconducting state at a temperature above where the switch will be used, then the conduction falls off more rapidly than a simple power law in temperature. The difference in the temperature dependence of the conduction between the normal and superconducting states for metals we use in our shells are shown in Table 1.

4.2. Closed-state conductance

Conduction data for a switch designed to have a switching temperature near 10 K is shown in Figure 4 for four different pressures of helium. Data for three different fill pressures is shown for a switch designed to work at 1.2 K in Figure 5. Gas was introduced at room temperature so the pressure listed was measured at ~293 K. The pressure at the operating temperature is one factor in the overall on-state conduction. This is difficult to measure directly but it may be derived from the on-state conduction values with contributions such as the outer shell conductance subtracted off. This is done in the next section.

Table 1. Table of conductivity functions and applicable temperature ranges used to calculate the conductance of the metal shells used in these heat switches.

Material, Reference	Applicable Temperature Range (K)	Conductivity Function λ (W/m/K) (see Equation 2)
304 CRES, [10]	0 - 4	$0.05\ T^{1.33}$
304 CRES, [11]	4 - 40	$2.73\text{E-}3 + 0.0651\ T + 3.11\text{E-}3\ T^2 + \text{-}4.30\text{E-}5\ T^3$
Ti 6Al-4V, [11])	4 - 280	$3.66\text{E-}3 + 5.54\text{E-}4\ T + \text{-}2.05\text{E-}6\ T^2 + 3.31\text{E-}09\ T^3$
Ti 6Al-4V, [12]	0.2 - 4	$0.0714\ T\ e^{-0.0826 \times 4.38/T}$
Ti 15-3-3-3, [9]	3.9 - 7.7	$0.0742\ T^{0.4}$
Ti 15-3-3-3, [9]	0.23 - 3.9	$0.043\ Te^{-0.27\ 3.89/T}$

The switch designed to transition near 1.2 K contained a mixture of helium and hydrogen gases. The hydrogen was added after a long-term test switch exhibited a transition temperature that was grossly different from one test to another after sitting on the shelf for months between tests. We believe this switch had a substantial quantity of hydrogen absorbed into the 6AL-4V titanium shell for a reason we have yet to identify. Over the period of time the switch sat at room temperature, the hydrogen diffused from the shell into the switch interior. When the switch was cooled below 5 K for testing, all the hydrogen condensed onto the internal surfaces and modified the binding energy of the getter. The transition temperature of that switch moved from ~1.2 K to less than 0.3 K. To prevent this from occurring again, a substantial amount of hydrogen was mixed with helium during the filling process so small amounts of hydrogen moving into or out of the switch shell did not affect the switching temperature. Obviously, since hydrogen is shown to change the binding energy of helium to the getter surfaces, the amount of helium injected to the switch at room temperature needed to be adjusted to produce the desired transition near 1.2 K for this switch. We will add hydrogen to the helium gas when using a titanium shell for

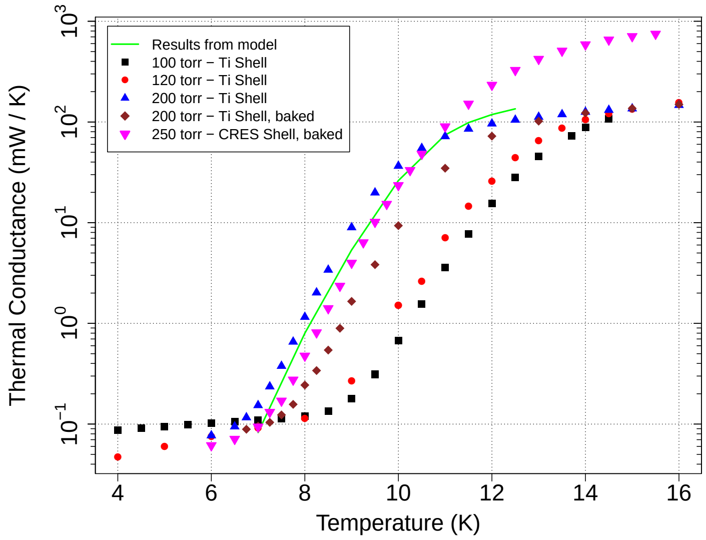

Figure 4. Conductance plotted against temperature for the passive gas-gap heat switch developed to switch near 10 K. Data is shown for many different pressures of ^{3}He measured at room temperature. The solid line is a result of a model that showed the optimal conduction as function of temperature for a particular system being developed. The fill pressure was adjusted until the conductivity was close to this line.

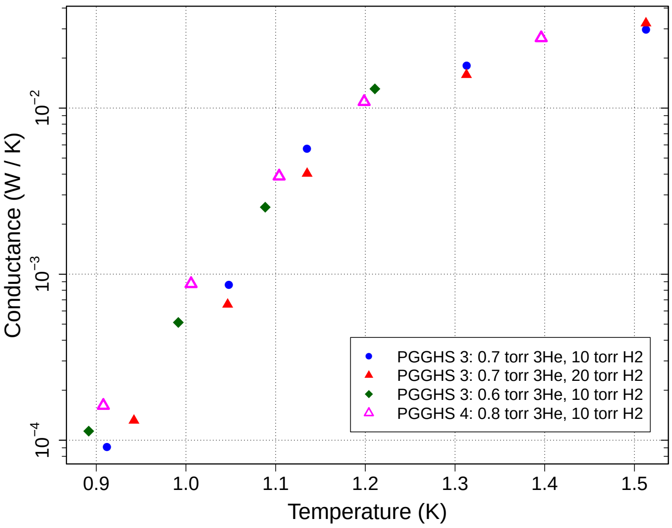

Figure 5. Conduction data for a switch designed to transition from the on to off state near 1.2 K. Data is shown for three different room-temperature ^{3}He pressures. Hydrogen gas was included in the total gas charge; the reason for using a gas mixture is discussed in the text.

future switches. We don't believe a shell made from stainless steel will exhibit this phenomenon [13].

4.3. Isosteric Heat of Adsorption

The isosteric heat of adsorption may be viewed as a binding energy of a gas particle to a cold surface at constant coverage. Over small changes in temperature, the coverage is, to first order, constant. If one plots $log_e(P)$ against $1/T$ where P is the pressure in Pascal and T is the temperature in Kelvin, then the slope of the line is the isosteric heat of adsorption. However, one must be careful to only include data in the fit where other effects do not play a role. For instance, within the heat switch itself, we don't have direct access to the gas pressure. Instead, we can calculate it based upon the on-state conductance of the switch and subtract off the minor contribution from the heat switch shell. This pressure may be calculated using a relationship between the gas-conduction and pressure given by

$$P = \frac{2\ (2\pi T_{\rm low}\kappa)^{1/2}}{A\ (k_{\rm B}T_{\rm low}/m_{\rm gas})^{1/2}\ C_{\rm accom}} \tag{3}$$

where P is the pressure in Pascal, $T_{\rm low}$ is the temperature of the coldest side of the switch in Kelvin, κ is the integrated gas conduction, A is the surface area in contact with the gas, $k_{\rm B}$ is the Boltzmann constant, $m_{\rm gas}$ is the mass of the gas participating in the conduction, and $C_{\rm accom}$ is the accommodation constant. The last term is related to the probability that a site on the conducting surfaces is empty for a gas particle to pickup or deliver heat. For the amount of gas we place into the switches at room temperature, a value of 0.5 is a good estimate. Even if this value is not accurate, it does not affect the analysis of the heat of adsorption since it is the slope of log_e(pressure) versus $1/T$ that defines the heat of adsorption, not the absolute values of the pressure.

If the mean free path of the gas is much smaller than the gap between large adjacent conducting surfaces, then the conductance calculated is independent of the gas pressure and the use of Eq. 3 is not valid to calculate the pressure of the gas. Therefore, we limit data where the calculated pressure defines a mean free path to be on the order of the gap between adjacent fins.

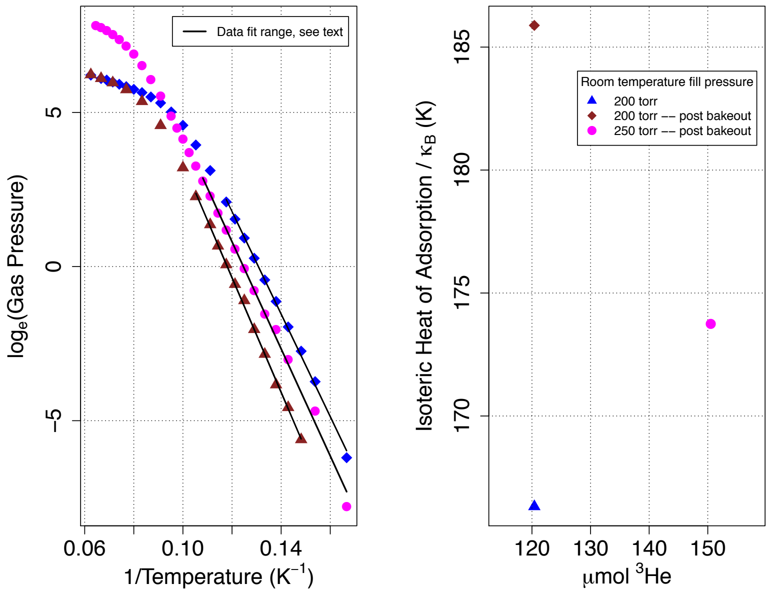

Figure 6. Data from the “10 K” heat switch. Plotting log_e(Pressure) vs. 1/T allows one to generate a fit to the data where the mean free path of the gas is on the order of the gap between the switch fins. The slope of the fit is the isosteric heat of adsorption.

A plot of $log_e(P)$ vs. $1/T$ for a heat switch meant to transition from on to off near 10 K is seen in figure 6. A linear fit to the data where the mean free path is comparable to the spacing between the sets of fins produces an estimation of the isosteric heat of adsorption. In this switch, the adsorbing surface is activated bituminous charcoal (see Figure 2) and the gas is ^{3}He. It is interesting to note that the values calculated for the heat of adsorption is comparable to ^{3}He on copper surfaces as reported by Daunt and Lerner in 1972 [14].

5. Summary

We have described recent advances made in the construction of gas-gap heat switches that turn on and off without the need to actuate them explicitly. These passive switches reduce the complexity of a control system for an ultra-low temperature cooler and are more thermodynamically efficient since the system doesn't have to lift the additional heat typically used to transition the switches from the off to on state.

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