Development of a Gas-Gap Heat Switch for Sub-Kelvin Sorption Coolers

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ABSTRACT

Gas-gap heat switches (GGHSs) featuring no-vibration, high-reliability and high engineering adaptability and are critical components for sub-Kelvin sorption coolers (SKSCs). A GGHS which contains a miniature activated charcoal pump was designed and assembled for a SKSC. The prototype GGHS was performance tested at about 4 K. Using ^{4}He as the working medium, the ON-State thermal conductance was 0.03 W/K and the OFF-State thermal resistance was 2500 K/W, giving a switching ratio of about 75.

INTRODUCTION

Gas-gap heat switches (GGHSs), as a kind of effective thermal control devices,[1] are operated by changing the pressure in the gas gap.[2] The GGHS has no moving parts, and thus it possesses a high-reliability and can switch frequently. Furthermore, GGHSs have no field interference and can be operated in a wide operating temperature range. As a result, it has been widely applied in the space sub-Kelvin refrigerators, such as adiabatic demagnetization refrigerators and sorption coolers.[3]

A typical example of GGHS is shown in the Figure 1. It consists of a switch body and a sorption pump. For the switch body, the gas gap is built by two coaxial cylindrical copper blocks. A supporting shell restricts the blocks and seals the gap. A capillary pipe connects the switch body with the sorption pump which is used to pump the working gas from the gap or release the gas back to it. One end of the GGHS attached to the preceding cooler end is named the "base" end, and the other one thermally anchored to the heat load end is named the "top" end. There are high accuracy requirements of the machining and assembling of the GGHS, since the width of the gap of the GGHS should be narrow enough (~0.1 mm) and the two ends cannot contact each other.

The thermal resistance of a GGHS is determined by the flow state in the gas gap. In the continuum flow region, when mean free path of the gas molecules is much smaller than the gap width, collisions among molecules is dominant. Under this circumstance, the GGHS is in the ON-State. However, in the molecular flow region when the mean free path of the gas molecules is much larger than the gap width, heat is transferred relying upon ballistic scattering between molecules and gap wall. In this case, the conductance is low and the GGHS is in the OFF-State.[4]

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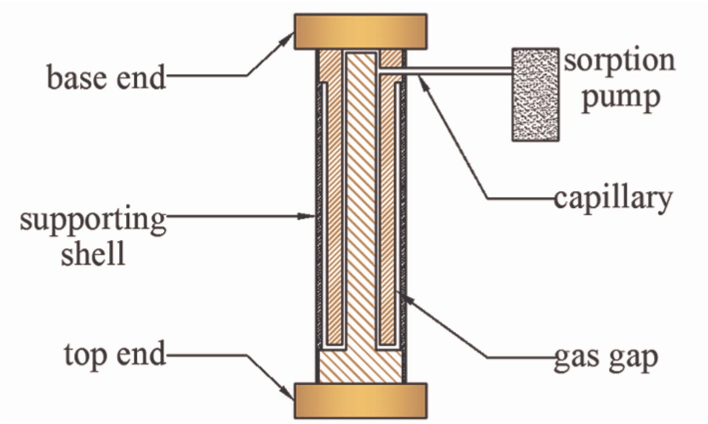


Figure 1. A diagram of the GGHS.

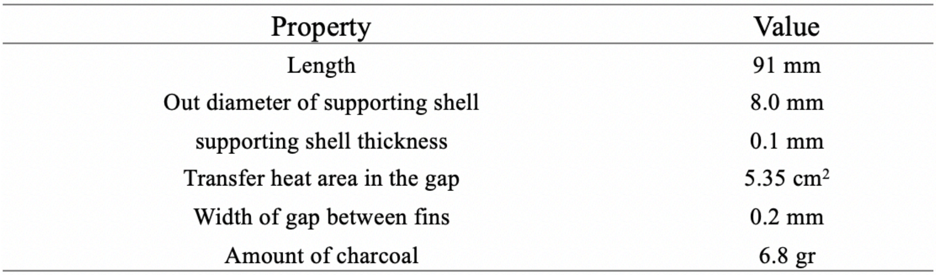
Since the first GGHS was developed,[5] numerous fundamental and practical studies have followed. The switch ratio, calculated by dividing the ON-Conductance by the OFF-Conductance, is widely regarded as one of the most significant performance parameter[6]. The ON-Conductance and the OFF-Conductance of a GGHS have many contributions, such as the size of the GGHS, the materials of the components, the gap structure, the thermal properties and the amount of the working medium. An efficient GGHS tends to have a larger surface area of the fins that contacts the gas, a narrower gas gap and a thinner supporting shell[7]. In our laboratory, a sub-Kelvin sorption cooler (SKSC) is being developed. Based on the design calculations for the SKSC, a GGHS which would be used in the SKSC was designed and its performances were measured.

DEGISN AND ASSEMBLY

The thermal performance of the GGHS is affected by its size and structure. In the ON-State, the heat conduction through the gas in the gap plays an important part. The switch tends to have a larger heat transfer area of gas gap and a narrower gap.[8] The OFF-State Conductance is limited mainly by the thermal resistance of the supporting shell. Hence, both the gas gap and the supporting shell should be considered in the design. For the goals of performances and the convenience of machining and fabrication, a GGHS with a single cylindrical gas gap was designed (as shown in Figure 1). A stainless steel supporting shell aligns and encloses two copper blocks, forming a gap of 0.2 mm and a gap surface area of 5.35 cm^2. A stainless steel tube connects the gap with a sorption pump which is used to pump the working gas from the gap or release back to it. The sorption pump has a volume of 11 cm^3 and contains 6.8 gr activated charcoal. The mechanical parameters of this GGHS are listed in Table 1.

For the switch body, there are high accuracy requirements of the machining and assembling to keep no contact between the two ends, since the gap of the GGHS is narrow and long. To avoid the thermal deformation of the fins in welding, the laser weld should be the final weld. Beyond that, the fins should be repaired and the concentricity of copper fins should be ensured by an auxiliary tool

Table 1. Design parameters of the GGHS.



Property	Value
Length	91 mm
Out diameter of supporting shell	8.0 mm
supporting shell thickness	0.1 mm
Transfer heat area in the gap	5.35 cm^2
Width of gap between fins	0.2 mm
Amount of charcoal	6.8 gr

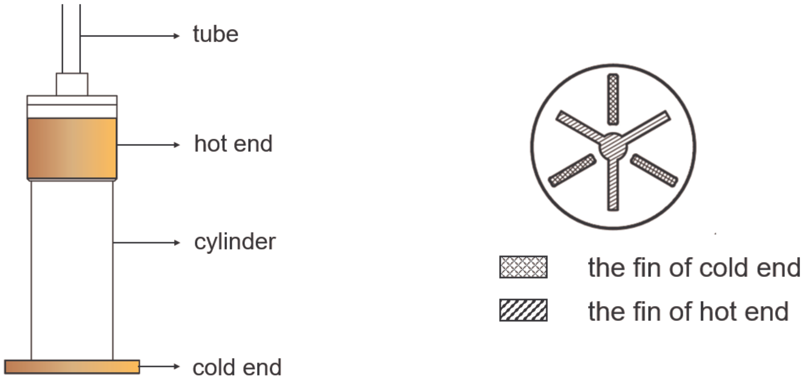


Figure 2. A diagram of the sorption pump (left) and a sectional drawing (right).

before laser weld. After assembly, the switch was testified that there is no internal contact between the two ends by X-ray inspection.

For the sorption pump, in order to enhance the heat transfer between activated carbon particles and, meanwhile, minimize the heat leakage, two sets of fins which were not contacted mutually were set in the sorption pump (as shown in Figure 2). After reaction for 24 hours at a temperature of 150 ^{0}C by vacuum pumping, 6.8 gr of charcoal particles with a diameter of 1 mm were filled into the sorption pump.

The sorption pump and the switch body were connected by a diameter of 2 mm stainless steel tube. A by-pass capillary was set on the middle of the connecting tube (as shown in Figure 3). A pressure of 70 kPa ^{4}He was filled into the GGHS through this capillary. After filling, the capillary was pinched off and then the cutting section was capped by an epoxy-filled sleeve to ensure mechanical stability.

EXPERIMENTAL RESULTS

This testing system consists of the following parts: (1) the tested GGHS; (2) a 150 Ω ceramic heater which was thermalized to the top end of the switch body, and a 20 Ω film-heater which was mounted at the hot end of sorption pump, (3) four silicon diode thermometers, one of which was mounted at each end of switch body and pump, (4) a two-stage GM cooler which can provide 1.5 W cooling capacity at 4.2 K, (5) a direct-current power supply and (6) a data acquisition system.

Figure 3. The GGHS prototype (before filling with ^{4}He).

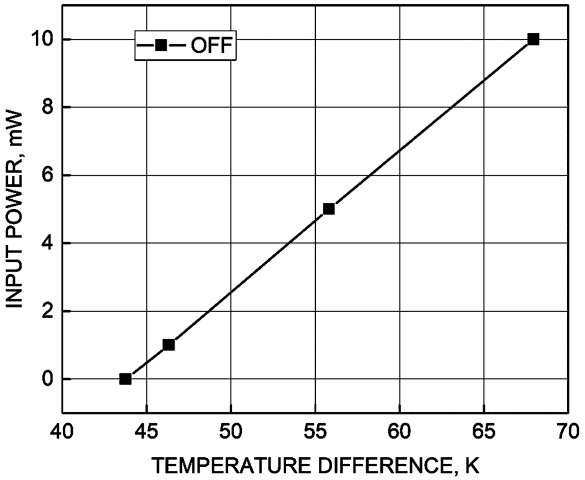


Figure 4. Input power $\dot{Q}$ vs. temperature difference ΔT in the OFF-State.

The base end of the switch was thermally jointed to the 2nd cold head of the GM refrigerator via a copper plate, which was maintained at about 4 K during experiments. The cold end of the sorption pump was thermally anchored to the heat sink by two copper wires with a length of 20 cm and a diameter of 0.8 mm. For reducing the radiation from the vacuum chamber, the switch body and the sorption pump were insulated by multi-layers super insulation.

Heater power $\dot{Q}$ was applied on the top end of the switch. The temperatures were collected and the steady-state temperature differences ΔT between two ends were calculated. This procedure was then repeated with different heater powers. During the testing, a vacuum environment of $5x10^{-5}$ Pa was maintained. Noting that the temperature of the top end of the switch T_t is higher than the base end of the switch T_b when no power is applied to the top end. This is attributed to a heat leakage on the top end. As a result, an original temperature difference ΔT_0 is subtracted. The thermal conductance is given by $\dot{Q}/(\Delta T - \Delta T_0)$.

In the OFF-State, the plot of $\dot{Q}$ versus ΔT is displayed in Figure 4. In this case, the temperature of the hot end of the sorption pump ($T_{pump\text{-}hot}$) is ~24 K and the cold end of the sorption pump ($T_{pump\text{-}cold}$) is ~11 K, giving an OFF-State resistance of 2500 K/W. As can be seen that the original steady temperature difference is up to 44 K with no power applied. This is caused by a large heat

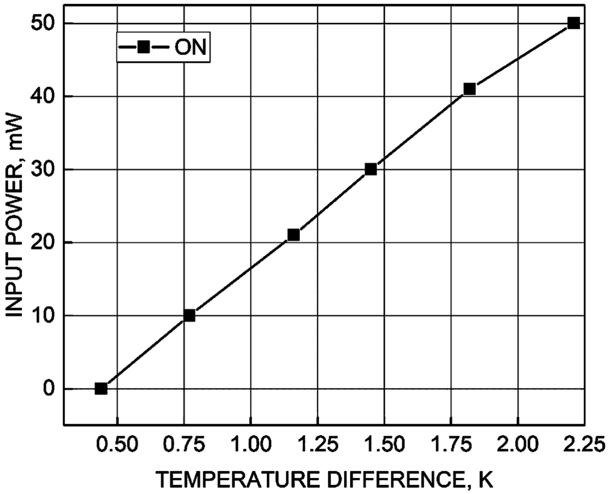


Figure 5. Input power $\dot{Q}$ vs. temperature difference ΔT in the ON-State.

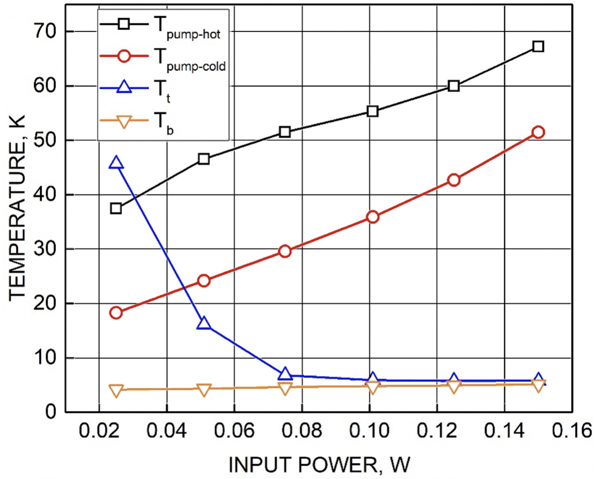


Figure 6. The OFF-ON transition.

leakage which also interferes the measured OFF-State thermal resistance. These heat leaks might derive from heat conduction through the constantan wires of the heaters and thermometers and the radiation from a thermal shield mounted on the 1st cold stage of GM refrigerator. In order to reduce the heat leakage, the constantan wires will be replaced by phosphorus bronze wires and the another thermal shield will be added on the 2nd cold stage of the GM refrigerator in later tests.

The curve of $\dot{Q}$ versus ΔT in the ON-State is shown in Figure 5. In this case, $T_{pump\text{-}hot} = 67$ K and $T_{pump\text{-}cold} = 51.5$ K. The ON-State thermal conductance is 0.03 W/K. Taking the average temperature as the calculation temperature of charcoal, the heat leakage from the sorption pump to the switch body through the stainless steel tube is ~2.2 mW. This heat leakage could be decreased effectively by increasing the mass ratio of gas to charcoal.

A graph described the process from the OFF-State to the ON-State is shown in Figure 6. The T_t drops with the heat powers applied to the hot end of the sorption pump and then the GGHS is turned ON. During the switching process, no power is provided to the top end. When the $T_{pump\text{-}hot} = 67$ K and $T_{pump\text{-}cold} = 51.5$ K, the complete ON-State is achieved and the temperature difference between the T_t and T_b is about 0.6 K. However, when the $T_{pump\text{-}hot} = 50$ K and $T_{pump\text{-}cold} = 30$ K, the T_t has already dropped by 85%. At this moment, the heat power applied to the sorption is ~0.075 W.

CONCLUSIONS

A gas-gap heat switch with an activated charcoal pump for a sub-Kelvin sorption cooler was designed and fabricated and its thermal performance was measured. An ON-State thermal conductance of 0.03 W/K and an OFF-State thermal resistance of 2500 K/W at 4 K are achieved with ^{4}He as the working medium, giving a switching ratio of 75.

The measured OFF-State thermal resistance is less than would be ideal. It may be attributed to heat leakage in the cryogenic measurements and results in the greater actual applied heat powers. Nevertheless, it is probably adequate for the intended use in SCSK. The heat leakage is probably derived from the radiation and the heat conduction through wires. It is possible that an optimum performance could be obtained after these factors are reduced.

ACKNOWLEDGMENT

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