Additive manufacturing of a compact flat-panel cryogenic gas-gap heat switch

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ABSTRACT

State-of-the-art heat switches are only rarely employed in thermal system architectures, since they are rather bulky and have a limited thermal performance (expressed as the heat transfer ratio between the “On” and “Off” state). Using selective laser melting additive manufacturing technology, also known as 3D printing, we developed a compact flat-panel gas-gap heat switch that offers superior thermal performance, is simpler and more economic to produce and assemble, contains no moving parts, and is more reliable because it lacks welded joints. A prototype measuring 5×5×1 cm^3 outer dimensions is developed with an integrated coolant heat sink to assess the feasibility of the technology. Later a second prototype measuring 3.2 mm thick, 10 cm by 10 cm frontal area panel is developed. An on-off heat conductance ratio of about 45 is measured at 100 K, and the on-conductance is 4.5 W/K. In addition to being compact, this type of heat switch has a large on-conductance compared to other types of cryogenic heat switches. This opens doors to utilize the heat switch for cryogenic temperature control applications.

Keywords: heat switch, flat-panel, additive manufacturing, gas-gap.

1. INTRODUCTION

Heat switches are devices that can change from a thermally conducting to an insulating state whenever the need arises. They enable adaptive thermal management strategies in which cooling rates are altered either spatially or temporally, leading to a substantial reduction in the energy and mass budget of a large range of systems. In cryogenic temperature range, heat switches are often used in separating the various cooler stages in a cold chain to enable fast cooling, in cryocooler redundancy applications, to control the heat flow to a sorption compressor and many other applications. The performance of a heat switch is generally expressed by the ratio of the On- to the Off- heat conductance. It is desired to have a higher value.

Several physical principles are employed to effect a change in the heat conductance state, some of them are summarized in Figure 1. The differential thermal expansion heat switch type leverages the difference in thermal expansion of two different materials with temperature to make or break a contact between two surfaces (Milanez and Mantelli (2003)). The paraffin wax heat switch uses the volumetric difference in different phases (solid and liquid) as the switching principle (Pauken *et al.* (2002)). In electrowetting type, the ability to alter the wetting characteristics of liquids with electric potential is used (McLanahan *et al.* (2011)). In liquid crystals, the thermal conductance difference of the crystals in the two polarization states is used as the switching principle (Epstein and Malloy (2009)). Our objective is to develop a heat switch with a small form-factor (slender) and a reasonably higher performance (substantially higher On/Off conductance ratio than the existing techniques).

In a gas-gap heat switch, the gas pressure in a tiny gas-gap is varied to regulate the heat flux. The manufacturing of these devices requires careful machining of the parts due to the small gaps with stringent tolerances. Heat switches often also carry a mechanical load, requiring a sturdy structure, which limits their insulating properties in the Off state. In this paper, we will present a novel design of the gas-gap heat switch, using additive manufacturing. Since this process requires no subsequent metal-joining, it allows for reliable operation and a rather short lead time to certain stringent applications such as aerospace systems. In this paper, a brief overview of the design requirements of the gas-gap heat switch is summarized, followed by possible manufacturing methods of the gas-gap heat switch. The developed hardware is presented followed with experimental results.

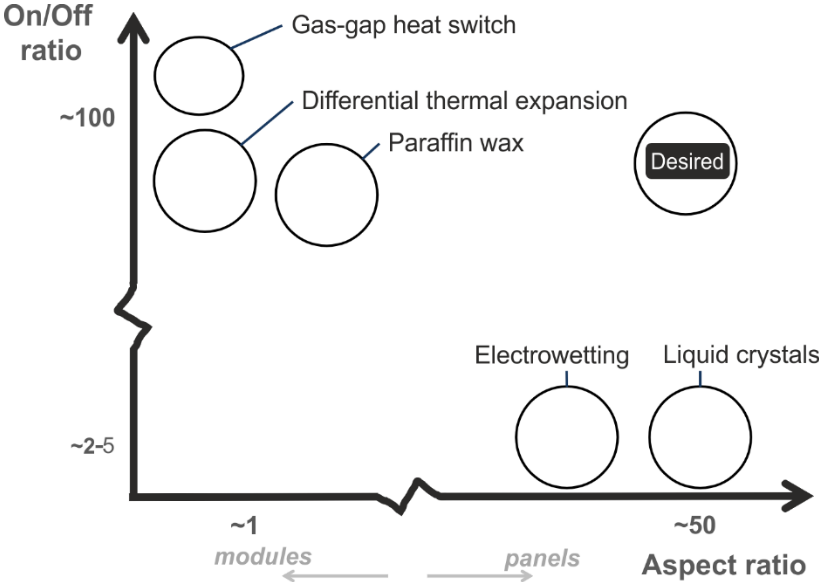

Figure 1. Overview of heat switch techniques. The aspect ratio in this graph is the ratio of the device side (frontal) major dimension to the height of the heat switch. A heat switch with an aspect ratio close to the origin of the graph resemble module and away from the origin of the graph, a panel.

2. Design constraints of the gas-gap heat switch

We selected the gas-gap technology for further investigation because of the lack of moving parts and a potential to achieve higher thermal performance. Other advantages are a relatively low mass, a high On/Off conductance ratio and the heat conductance can be varied from the Off- to the On-state and vice-versa (so a continuous variation of the conductance can be realized between the On- and the Off-state). From the kinetic theory of gases, the heat conductance of a gas in a small gap increases with pressure in the molecular regime and the heat conductance saturates to a constant value in the viscous regime. Vanapalli *et al.* (2015) discussed the details of the theory of operation of a gas-gap heatswitch. The basic functional blocks of the gas-gap heat switch are shown in figure 2 and are summarized below:

- The component represents the device whose temperature should be controlled and is attached to the device base.
- A cold heat sink is attached to the heat sink base of the gas-gap heat switch.
- Between the device base and the heat sink base is the gas-gap. The gap should be narrow (< 300 microns). The smaller the gas-gap, the larger is the On-state heat conductance. The gas-gap is usually structured to a plate fin pattern so as to increase the heat transfer area.
- A cover on the side is required to enclose the gas. The cover should be designed to reduce the parasitic heat leak between the device base and the heat sink base.
- Support pillars in the gas-gap are required to overcome the pressure difference between the gas-gap and the environment.
- A sorber material stores a large quantity of gas in a small volume. The amount of gas stored in the sorber material is a function of temperature. At higher temperature, the material stores less gas. Therefore the pressure in the gas-gap can be increased by heating the sorber material with an electrical heater. The sorber material can be connected to the gas-gap with a capillary so as to reduce the heat leak to cryogenic temperature heat sink.

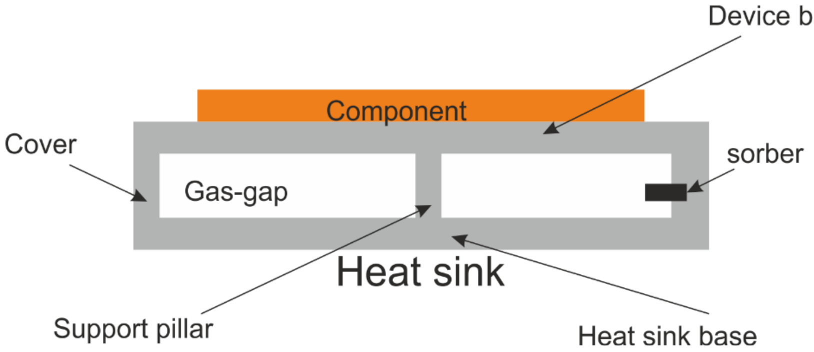

Figure 2. Schematic view of the gas-gap heat switch, showing the functional parts and the main structural parts.

3. Technology

In this section, several manufacturing technologies are explored to realize a flat-panel gas-gap heat switch.

3.1 Conventional manufacturing

As mentioned in the above section, a very small gap size of less than 300 microns is desired. Also support structures for mechanical integrity should be produced. With conventional subtracting processes, such as precision machining or wire electrical discharge machining process, small gap sizes may be realized but the supporting structures cannot be machined at the same time. Several follow up metal joining process steps are required to machine a closed system and the machining can be very complicated.

3.2 Micromachining

Micromachining is a popular microsystems technology to fabricate structures with small dimensions, mostly in silicon or glass. The gas-gap heat switch could be manufactured in glass with several lithography steps and the final bonding of two glass wafers. This process also leads to many process steps and also there is size limits on the size of the wafers used. Hence micromachining technologies are not suitable manufacturing processes of a panel-shaped gas-gap heat switch. Added to that the thermal conductivity of glass is rather low for a heat switch application.

3.3 Metal additive manufacturing

Selective Laser Melting (SLM) is a powder based additive manufacturing technique to produce mechanical structures. In this method, the design of the part is sliced into several layers of 30-100 (Song (2012)) micron thickness, which is processed by the machine. A high material density (99-100%) is desired because of the requirements of gas leak tightness of the heat switch.

With additive manufacturing, products are built up one layer at a time. Therefore, every layer needs a preceding layer to support it. Certain design rules apply when designing overhanging layers. The rule-of-thumb is that the angle made by the vertical surface with the horizontal should be less than 45 °. The smallest feature that can be printed vary depending on the type of the powder material and the particle size. Commonly used particle size vary between 50 and 100 μm. In our current facility with Titanium Grade5 alloy powder, the minimum achievable channel width is 200 microns and the minimum fin thickness is 250 micron.

4. Prototypes and discussion

Based on the review of the technologies in section 3, we chose to explore the feasibility of producing a flat-panel gas-gap heat switch with selective laser melting additive manufacturing technology.

4.1 Heat switch integrated with a coolant heat sink

Figure 3 shows several cross-sections of the gas-gap heat switch with an integrated heat sink. The outer dimensions are 56x56x9 mm without taking into account the connecting tubes. It is printed in the direction of the arrow shown in the figure. The heat switch is made from titanium alloy grade 5 because at the moment largest precision is possible with this material. The thickness of the walls and the support structures are designed so as to withstand the pressure difference between the gas-gap and the environment.

In this design the cold heat sink is integrated with the gas-gap heat switch. The inlet, outlet connecting tubes are also printed to allow flow of coolant to the heat exchanger. A third tube is realized to feed gas to the gas-gap. A cylindrical reservoir is realized to contain a sorber material for future usage. In the context of this paper the reservoir is not used.

Figure 4 shows the manufactured device and also a cut-section through the center from side to side, revealing the inner structure of the gas-gap heat switch. The device base thickness is 1.70 mm thick, the gas-gap is 0.3 mm. The aim of the fin pattern is to increase the gas-gap area. The fins are 2 mm long and increase the contact area by a factor of 4, compared to a flat plate.

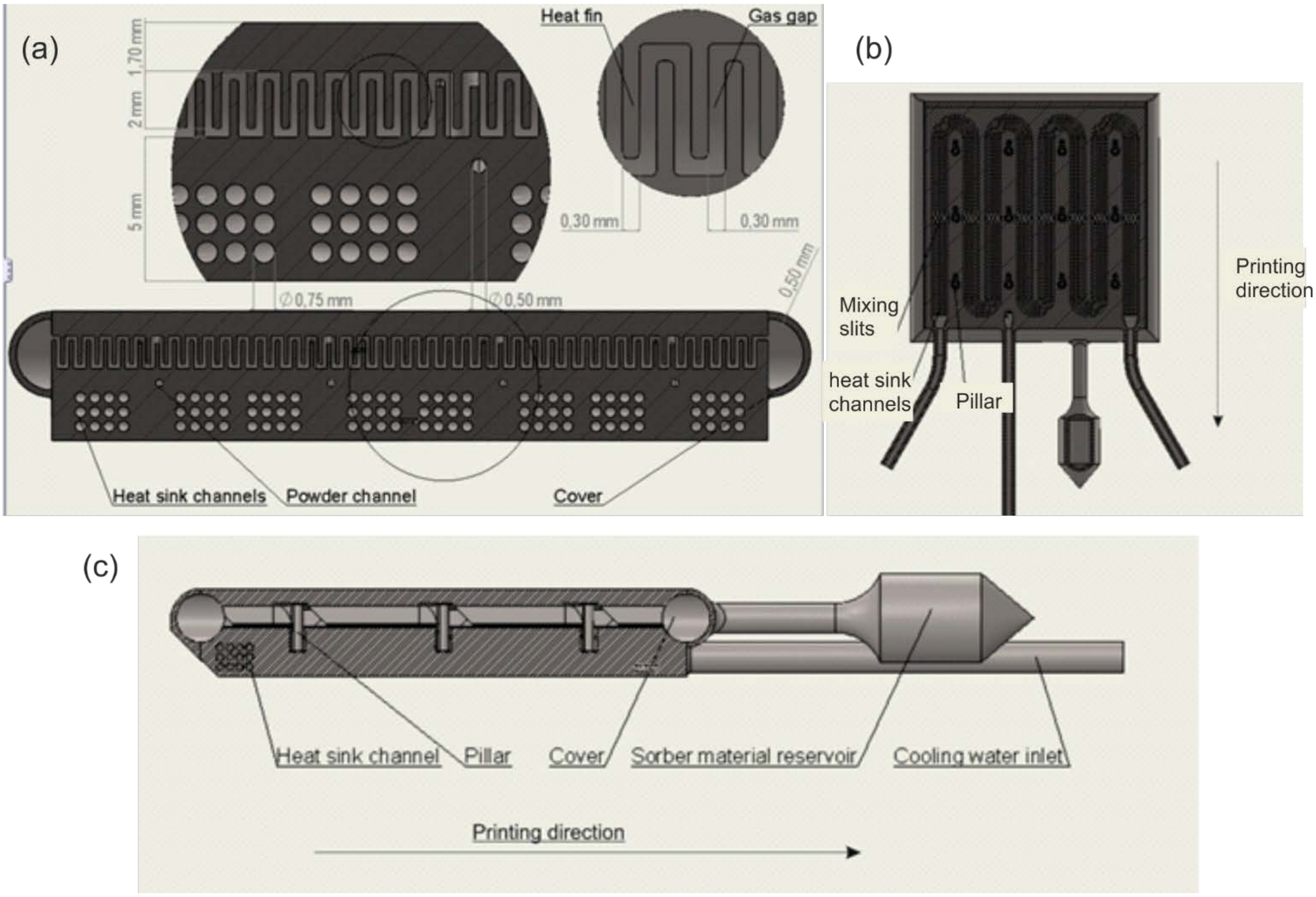

Figure 3. Cross-section and dimensions of the heat switch.

The heat switch should be able to withstand a pressure difference of at least 1 bar, as it has a near vacuum pressure inside and is subjected to normal atmospheric pressure on the outside. The heat switch can be subjected to additional loads by mounting equipment on top. The support pillars have a particular shape, as seen in Figure 3 and 4. A cylindrical pillar cannot be printed considering the direction of printing because it will have an overhanging structure. If the pillars were to have a straight wall on the right side, it would collapse since there is no support for it there. This has been solved by making one side a curved surface. This increases the contact area with the plates slightly, but it is necessary to ensure structural integrity. It would be beneficial to keep the pillars as small as possible to minimize conductance in the Off-state.

Figure 3 shows a horizontal cut through the heat switch and displays the shape of the cooling channels. The zigzag pattern allows the coolant to stay in contact with the plate for a long time, allowing more heat to be transferred. There are eight open holes in the cooling channels to allow mixing of the fluid and removal of the powder after printing. The keyhole shaped features seen next to the cooling channels are the bottom part of the support pillars.

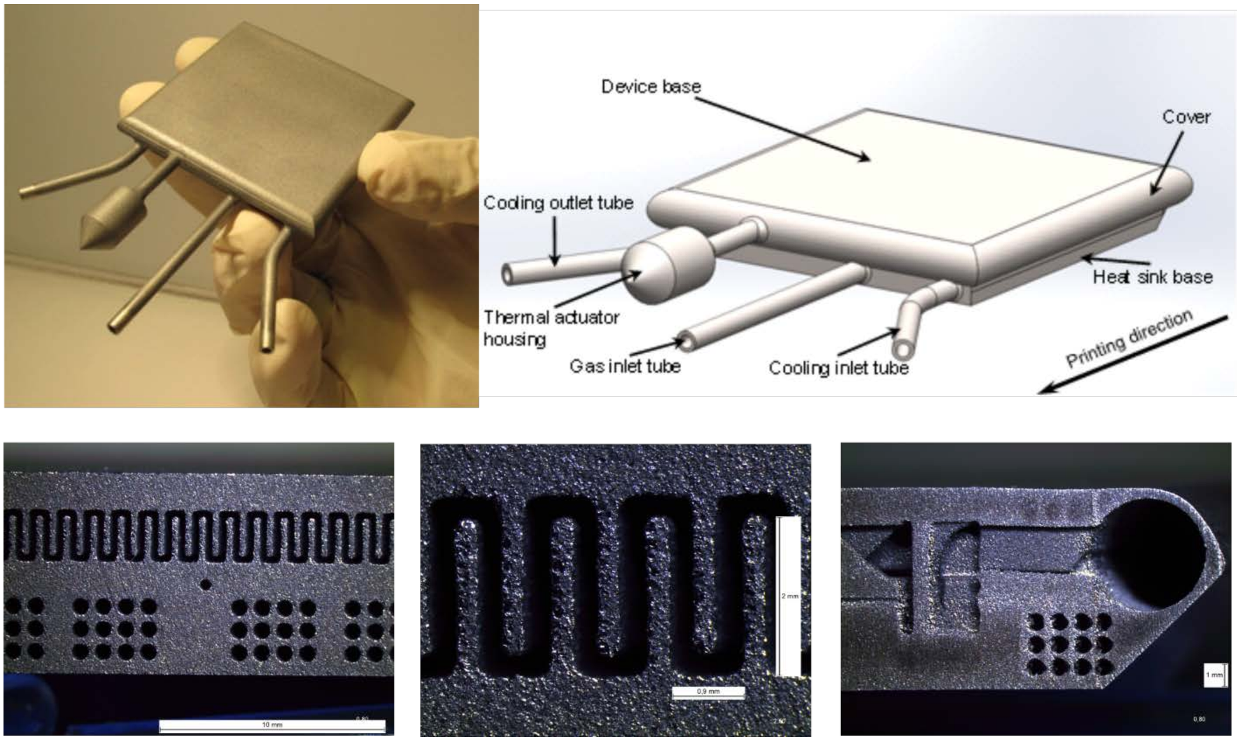

Figure 4. Pictures of the manufactured heat switch. The bottom pictures are taken with an optical microscope after the switch is cut with wire electrical discharge machining.

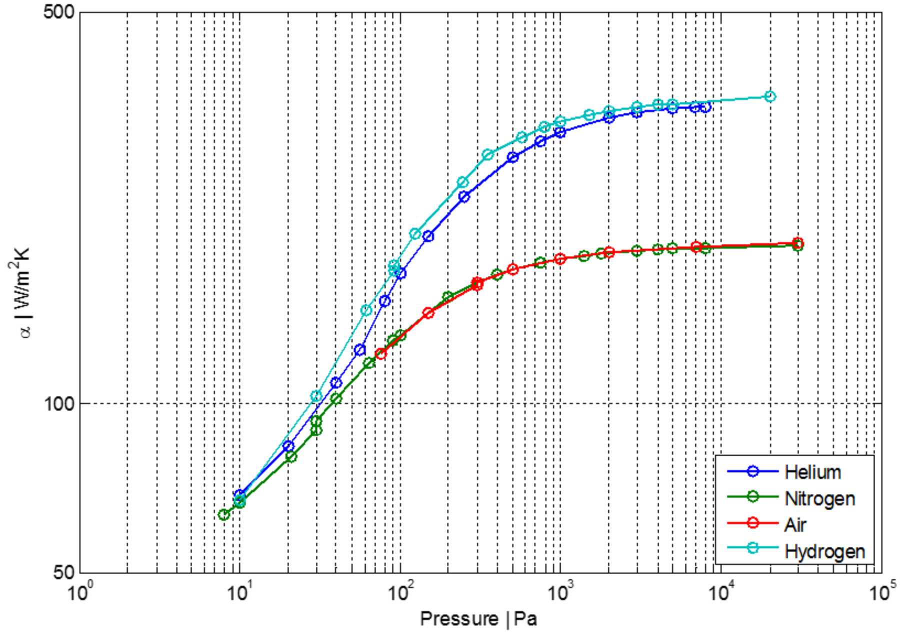

Figure 5. The measured heat conductance (the ratio of measured heat flow to the frontal area and temperature difference between the heater and the heat sink) of the heat switch for several working gases.

To evaluate the leak tightness of the manufacturing technique, the gas-gap is evaluated to a vacuum level lower than 10^{-3} mbar and the pressure of the gas-gap is monitored over a period of a week. Within the error limits of the pressure sensor, we have not measured any increase in the pressure of the gas-gap.

Figure 5 shows the measured heat conductance as a function of the pressure for several working gases at 295 K. The heat is applied with an electrical heater and water is used as a coolant. The maximum conductance of helium gas is 336.8 W/m^{2}K and of hydrogen gas is 351.1 W/m^{2}K. The maximum conductance of air and nitrogen gas is only 193.0 W/m^{2}K. The measured parasitic heat conductance at a low pressure in the gas-gap is 45.3 W/m^{2}K. This datapoint is not shown in Figure 5 because the low pressure value is out of the range of the pressure sensor. In the above conductance values the area considered is the front area of the heat switch.

Improvements

Following successful feasibility demonstration of the additive manufacturing technology to produce a heat switch a number of parameters are optimized.

Gas-gap: The gas-gap is reduced from 0.3 mm to 0.2 mm. The lower limit is due to the current limitation of the technology. In general, the smaller the gas-gap thickness the better is the performance. By lowering the gap height, the On-conductance would increase to 900 W/m^{2}K with hydrogen gas.

Fins: The topology of the fin is investigated and it is observed that the plate fin gives a larger On-conductance compared to a trapezoidal fin. The fin length is reduced from 2 mm to 1.6 mm as the contribution of the tip of the fin to the On-conductance is negligible. The fin thickness is reduced to 0.25 mm from 0.3 mm.

Cover: The shape of the cover can be changed to a serpentine pattern instead of a circular shape to increase the path length between the bases and thus reduces the parasitic conductance.

Device base and heat sink base: The thickness of the device base and the heat sink base is reduced to minimize the thermal resistance.

Material optimization:

In choosing a suitable material for the heat switch, a trade-off between the On-conductance and the Off-conductance is sought. A highly conductive material lowers thermal resistance in the bases, thus increasing the On-conductance. However, the parasitic conductance through the cover also increases. In this study, three metal alloys are studied, namely, titanium alloy (Ti-6Al-4V), aluminium alloy (Al-Si-10Mg) and Inconel 718 (a nickel based superalloy).

Table 1. Design parameters of interest evaluated for several materials.

	Mass (g)	Max. displacement(µm)	On-state (W)	Off-state (W)	On/Off ratio
Titanium alloy	31.80	25.96	69.82	1.93	36.16
Aluminium alloy	19.17	37.29	244.28	34.59	7.06
Inconel	58.80	17.25	99.51	3.29	30.28

Numerical simulations are performed with each of the material shown in table 1. Each material is evaluated based on three parameters: total mass of the heat switch, maximum displacement with pressure difference and the thermal performance. Aluminium alloy heat switch will have the least mass as expected due to low density of the alloy. Inconel alloy heat switch will have the shortest displacement because of the high strength of this alloy compared to the other alloys. Considering the On- and Off-conductance, Titanium alloy has the best characteristics.

4.2 Second prototype of the heat switch (without heat sink)

A second prototype of the heat switch is manufactured with frontal dimensions of 100 mm by 100 mm and a thickness of 3.2 mm (see Figure 6). The gas-gap is 200 microns. At 295 K as the sink temperature, the measured On/Off heat conductance ratio is about 38 (see our earlier publication, Krielaart *et al.* (2015)). The performance of the device matches very well with the thermal network model presented in the above publication.

A guarded hot-plate apparatus has been developed to measure the thermal conductance of the heat switch with the heat sink temperature in the range of 100-180 K. The apparatus is cooled with a two-stage GM cooler and the temperature is controlled with a heater and braided copper wire connections. Diode sensors are used to measure the temperature difference across the device and to monitor other temperatures. A thermal guard is mounted on the hot side of the device to confine heat flow axially through the sample. A gas handling system allows testing the device with different gas pressures in the heat switch.

A series of experiments are performed at various heat sink temperatures, gas pressure in the gas-gap and with helium, hydrogen and nitrogen gas. The measured Off-conductance with a heat sink temperature of 115 K and hot plate at 120 K is 0.134 W/K, the On-conductance with helium gas at the same temperatures is 4.797 W/K and with hydrogen gas at the same condition is 4.708 W/K. This results in an On/Off ratio of 36.8 and 35.1 for helium and hydrogen gas respectively. The experimental results matches fairly well with the predicted heat conductance at cryogenic temperature.

Possible sorber materials are investigated for closed system operation of this device. Among other materials, ZrNi is a suitable metal hydride to reversibly store hydrogen gas to enable varying the gas pressure in the gas-gap. At room temperature, the equilibrium pressure of ZrNi with hydrogen gas is lower than 0.01 mbar and at a temperature of 180 °C the equilibrium pressure is about 200 mbar. These pressure conditions fulfill the Off- and On-state pressure conditions of the heat switch.

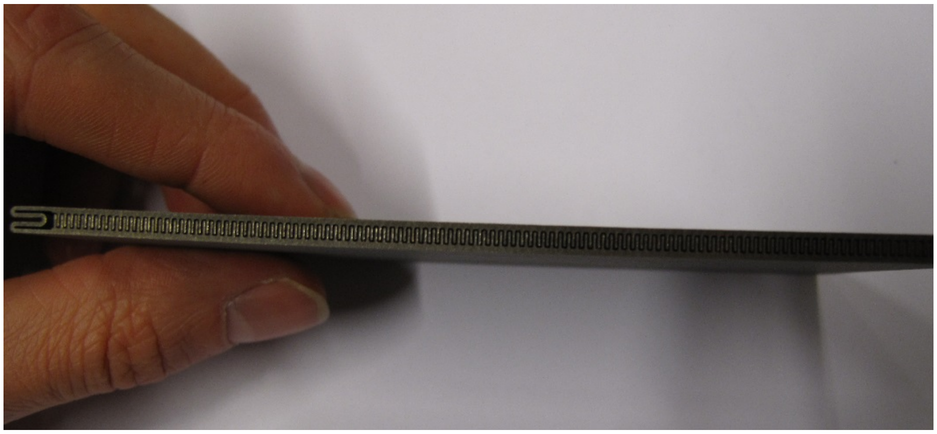

Figure 6. Picture of the section of the 10 cm by 10 cm heat switch. The side cover is serpentine in shape to reduce the parasitic heat leak.

6. Conclusion

In conclusion, we have shown the feasibility of using selective laser melting additive manufacturing process to produce a flat-panel gas-gap heat switch. The production costs are lower because it does not require any subsequent assembly steps, thereby reducing the time from concept to realization phase. With additive manufacturing it is possible to extend the functionality of the device by combining production of the components in a single run. We demonstrated this by combining the heat switch, heat sink and interconnects in a single design. Three dimensional flexibility in the design of the outer structure allows to tailor the device for any intended application (either flat, cylindrical or any other shape). It also offers the possibility for individual and fast adaption of the internal design to cope with different mechanical loads, heat loads and temperature levels. The production process has clear potential for quick adoption by stringent markets such as aerospace, because of its low footprint and mass, without moving parts or welds.

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