A Self-Adaptive Thermal Switch Array to Stabilize the Temperature of MEMS Devices

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ABSTRACT
A self-adaptive thermal switch array (TSA) based on actuation by low-melting-point alloy droplets is reported to stabilize the temperature of a heat-generating MEMS device at a predetermined range (i.e., the optimal working temperature of the device) without any control circuit or electrical power consumption. When the temperature is below this range, the TSA stays off and works as a thermal insulator. Therefore, the MEMS device can quickly heat itself up to its optimal working temperature during startup. Once this temperature is reached, TSA is automatically turned on to increase the thermal conductance, working as an effective thermal spreader. As a result, the MEMS device tends to stay at its optimal working temperature without complex thermal management components and the associated parasitic power loss. The TSA is fabricated and characterized to confirm the proposed working mechanism.

INTRODUCTION
Keeping the temperature within the optimal range is critical for many MEMS devices, such as micro power generators [1, 2] and chip-scale atomic clocks [3]. It can be very challenging when the environmental temperature fluctuates dramatically (e.g., in space [4] or desert area). Since these devices generate heat during normal operation, cooling is usually a major issue. However, thermal insulation may become critical for quick startup (especially for micro solid oxide fuel cells) and heat conservation when the environmental temperature drops.

Several thermal switches [2-5] have been proposed to provide programmable thermal resistance. Hyeun-Su et al., [1] used gold beams as actuators to turn on and off the switch. However, under a solid-solid contact condition, the thermal conductance is limited when the object is in the on state. In order to reduce contact thermal resistance, the liquid-droplet-based technologies were employed to generate a soft intermediate layer. Towards this end, Cho and coworkers [2] reported mercury-droplet thermal switches actuated by piezoelectric actuators. In spite of the good thermal conductivity of mercury, the complexity of the device, the limited displacement and the toxicity of mercury represent significant challenges. An alternative technology was recently reported by Gong et al., [5], who directly deformed water droplets by electrowetting to achieve switching effect. It is worth noting that all of the previously-reported methods require control circuit and power consumption to actively reconfigure the thermal conductance. The associated complexity and parasitic power loss could be a significant burden for a MEMS device.

In order to eliminate the parasitic power loss and simplifying the device, we propose a novel structure named self-adaptive thermal switch array (TSA), based on actuation by low-melting-point alloys (LMA). This device can automatically change its thermal conductance according to environmental temperature without external power input and control circuit.

TSA SWITHING MECHANISM
The working mechanism of TSA is illustrated in Fig. 1. When the temperature is below the melting point of LMA, the switches are separated from the heat sink (off state). The TSA and the heat sink are thermally insulated with only minimal heat radiated through the vacuum. When the temperature increases, the LMA starts to melt and expand dramatically at the melting point. Consequently, the switches will contact the heat sink (on state) at a temperature a little above the melting point of LMA ($T_{on}$). Once the contact is made, thermal flux through the TSA increases dramatically to cool down the device and keep the temperature around $T_{on}$. In order to increase the actuation displacement, LMA droplets are filled in the cavities formed into the substrate. The exact switching temperature ($T_{on}$) can be tuned by the melting point of LMA, the gap, the size of LMA droplet and the geometry of the cavities.

LMA is chosen as the actuation material due to its good thermal conductivity, adjustable melting point, non-volatility and non-toxicity. LMA experiences large thermal expansion during phase change from solid to liquid which is necessary to provide the displacement for switching. In order to characterize thermal expansion of the material, a prototype TSA with 5mm-diameter LMA-droplet switches were
machined and illustrated in Fig. 2. The cavities were drilled into the copper substrate and manually filled with LMA with a melting point of 47°C (MCP-Group, UK). The device is polished and then covered with a copper layer of about 10 μm thick by electroplating to prevent oxidation. A small linear variable differential transformer (LVDT) (Omega, USA) is used to measure the expansion of the LMA droplet upon different temperature. A small piece of silicon wafer was placed on the top of the device to facilitate the measurement. This relatively large prototype was used to characterize the thermal expansion of LMA with an ordinary small LVDT and confirm the abrupt actuation at melting point. In Fig. 2. c, the phase change around 47°C was clearly marked by the sharp increase of the displacement curves. The maximum displacement around the melting point is measured as about 70 μm.

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The cavities were then filled with LMA droplets in an LMA bath which was heated above the melting point of LMA. Because LMA wets the surface of copper but not the photoresist, LMA droplets can be self-assembled into the copper cavities and confined by the photoresist, as Fig. 3.a shows. Because the thickness of the photoresist defined the height of LMA droplets, a thick photoresist layer can be used to mold LMA droplets with greater height and thus resulting in larger thermal expansion upon heating. In order to remove the air bubbles captured inside the cavities, samples were kept in a vacuum oven at 80°C for one hour. The uniformity of the LMA droplets is improved by using a glass slide to flatten them while they are in liquid phase, as Fig. 3. b shows. Finally, after removing the photoresist, reflowing LMA and electroplating a copper protective layer, another layer of thick PR is coated and patterned to act as a spacer to control the gap.

**FABRICATION PROCESS**

TSA with 1mm-diameter switches was fabricated by a MEMS process as shown in Fig. 3. First, the thick photoresist PR-20000p (Futerex, USA) with a thickness of 50μm was spin-coated on copper substrate and patterned by photolithography. This patterned photoresist layer was employed as a mask for the electrochemical etching of the copper substrate to form an array of 8×8 cavities. The cavities were then filled with LMA droplets in an LMA bath which was heated above the melting point of LMA. Because LMA wets the surface of copper but not the photoresist, LMA droplets can be self-assembled into the copper cavities and confined by the photoresist, as Fig. 3.a shows. Because the thickness of the photoresist defined the height of LMA droplets, a thick photoresist layer can be used to mold LMA droplets with greater height and thus resulting in larger thermal expansion upon heating. In order to remove the air bubbles captured inside the cavities, samples were kept in a vacuum oven at 80°C for one hour. The uniformity of the LMA droplets is improved by using a glass slide to flatten them while they are in liquid phase, as Fig. 3. b shows. Finally, after removing the photoresist, reflowing LMA and electroplating a copper protective layer, another layer of thick PR is coated and patterned to act as a spacer to control the gap.

**TESTINGS AND RESULTS**

The MEMS TSA was first tested as a thermally-actuated electrical switch array by a simple testing circuit sketched in Fig. 5. a. The TSA was repeatedly heated by a heater beneath it and cooled by turning the heater off. The voltage output between the TSA and a conductive plate kept about 10 μm above it was monitored to indicate the "on" and "off" states of the TSA. The response time of TSA turned out to be less than 10s for off-to-on (t\text{off-on}) and around 30s for on-to-off (t\text{on-off}). The longer t\text{on-off} is attributed to the fact that passive cooling is much slower than the active heating. The experimental results of cyclic switching shown in Fig. 5.b have therefore further confirmed the repeatable and reversible switching around the melting point of LMA.
Fig. 5 Micofabricated TSA and its performance as a thermally-actuated electrical switch: a) schematic of the testing circuit; and b) test results of cyclic switching.

The testing apparatus used to characterize the thermal performance of the TSA is schematically shown in Fig. 6.

![Schematic of the test setup](image)

A moveable 3-axis XYZ Translation stage (Thorlabs, USA) with a resolution of 0.5μm is used to control the gap between the heat sink and TSA. The heating was provided by a microheater which was fabricated by lift-off process. A thermal couple was inserted into the gap between the TSA and the microheater which was filled by thermal compound. A thick glass slide was used as thermal insulator to reduce the heat loss from the backside of the heater chip. Contact monitoring circuit as shown in Fig. 5.a is employed to monitor if the droplets on TSA contacts the heat sink or not. The whole test stand was put in a vacuum chamber. The vacuum environment serves to reduce the heat transfer through air during off state.

After installing the heater chip and TSA on the angle bracket mounted on the moveable stage, parallel alignment was performed according to the following steps: 1) loosen the screws of the angle bracket; 2) move up the angle bracket to ensure that TSA contacts the heat sink firmly; and 3) fasten the screws to fix the bracket angle. The gap between the TSA and the heat sink was adjusted by the moveable stage to an appropriate value (usually 10μm in our experiments), so that the LMA droplets can contact the heat sink when temperature is higher than the melting point (on state) and detach from the heat sink when temperature is lower than the melting point (off state).

The temperature stabilization effect of TSA was tested by measuring the temperature evolution of the TSA under different heating power and comparing the result with an insulating scheme (i.e., no heat sink) and a cooling scheme (i.e., heater contact heat sink directly). As shown in Fig. 7, with a TSA, it is found that the temperature increased rapidly to around 50°C and was maintained. This is due to the dramatically-decreased thermal resistance between the microheater and the heat sink ($R_{\Sigma}$) when the temperature reaches the melting point of LMA:

$$R_{\Sigma} = R_g + R_p$$

and

$$\frac{1}{R_g} = \frac{1}{R_p} + \frac{1}{R_c}$$

where $R_p$ is the thermal resistance of the thermal compound and the copper substrate of TSA; $R_g$ is the thermal resistance across the gap; $R_c$ is the thermal resistance of air in the gap; and $R_c$ is the contact thermal resistance between the TSA and the heat sink, which is responsive to the environment temperature. $R_c$ is infinite at the off state and drops dramatically once a contact is made between the TSA and the heat sink. If the power input is further increased, the switches can further expand to increase the contact area and thus $R_c$, to accommodate the change of power dissipation requirement (i.e., self-adaptive at on state) Since $R_p$ and $R_g$ are kept constant during the experiment, $R_{\Sigma}$ changes with $R_c$. In an idealized case (i.e, $R_g$ is infinite and $R_p$ is neglected), $R_{\Sigma} = R_c$. The heat flux between the microheater and the heat sink can therefore be expressed as:

$$q' = \frac{\Delta T}{R_{\Sigma}}$$

where $\Delta T$ is the temperature difference between the microheater and heat sink. Ideally, the temperature of the heat sink is constant. When the power input increases, $R_{\Sigma}$ decreases and $q'$ increases, which leads to faster dissipation of the heat generated by the heater.
microheater.

It is also observed that even if the heating power was further increased, the temperature still remained at roughly the same value, which supports the self-adaptive at on state. The adaptivity to various power input is attributed to the variable contact area and force between the switches and the heat sink, which automatically expands in response to the rising temperature to increase the thermal conductance accordingly.

Such an adaptive temperature stabilization effect was not observed in the other two schemes, which were conducted for comparison. When the TSA and heat sink were removed, the temperature quickly went up to 70 °C in 5 minutes, as shown by the yellow curve in Fig. 7. This represents a system without an effective cooling mechanism. Consequently, the device will be burned out quickly. When the TSA was removed and the heater was brought into direct contact with the heat sink, the temperature increases slowly with the power. This represents a system with effective constant cooling for thermal management. Although the over-heating concern is addressed, it will take tremendous time and energy to bring the device into its optimal working temperature. The comparative study confirmed that the temperature could not be stabilized without the TSA.

CONCLUSIONS

A self-adaptive thermal switch array (TSA) based on actuation by low-melting-point alloy has been demonstrated. Direct measurement of actuation in a large prototype device, cyclic thermally-actuated electrical switching and comparative study of the temperature stabilization effect has been employed to verify the working mechanism. It is therefore concluded that the self-adaptive TSA can facilitate the rapid startup and temperature stabilization of a heat-generating MEMS device at fluctuating environmental temperature or power consumption. The factors to determine the switching temperature and the maximum power that the TSA can accommodate will be the focus of further investigation.

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