THERMAL SWITCHES BASED ON COPLANAR EWOD FOR SATELLITE THERMAL CONTROL

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ABSTRACT

We propose and demonstrate a novel liquid-droplet-based thermal switch aimed for satellite thermal control by using coplanar electro-wetting-on-dielectric (EWOD) configuration. By fabricating and testing the proof-of-concept devices, we confirm the mechanism of droplet detaching and attaching for the thermal switches. Thermal tests have shown the reasonable thermal performance with water and glycerin. Further development with novel liquid with low vapor pressure and high thermal conductivity is expected to improve the performance.

1. INTRODUCTION

Thermal management of satellites in orbit requires careful balance of heat rejection to space via radiation with the internal and external heat loads. The thermal environment encountered by satellites varies greatly throughout the orbit which makes the thermal management extremely difficult. A conservative design is often employed in practice, which incorporates excess survival heater power and results in serious mass and volume penalty.

One promising technology is a thermal switch which can provide thermal control by switching between high and low heat transfer regimes around a set point. Thermal switches are an optimal solution because of the flexibility they provide, *i.e.,* application to only the areas needed and variable setting points for different components. With proper implementation of thermal switches, the thermal system design time can be reduced from years to weeks, thereby saving millions of dollars per satellite and enabling the development of novel system architectures such as operationally responsive satellites [1]. The thermal isolation requirement for the thermal switch is very strict. Parasitic heat conduction must be minimized in the "off" state, which means an absolute minimal mechanical support. When switched "on", in contrast, they need maximum contact conduction. These two opposing requirements have posed serious reliability issues.

The thermal switches have been realized by using an electrostatic radiator [2] which consists of a flexible radiator film of high emissivity separated by vacuum gap from a surface of interest. Heat transfer was controlled by electrostatically attracting the radiator film to the surface and thereby switching heat transfer mode from inefficient radiation to conduction across the solid-solid contact. An emissivity change as large as 0.6 has been demonstrated by making a very thin and flexible radiator film (< 20 μm thick polyimide) and applying strong electrostatic force to form good solid-solid contact. However, switch performance suffered from significant parasitic heat conduction along a mechanical support, which was necessary to hold the flexible radiator films from collapsing to the substrate. Furthermore, the excessive bias voltage required for actuation (> 300 V) was also unattractive for space applications.

We propose an elegantly simple system by introducing liquid droplets as the conduction element and switching them by the mechanism of electrowetting-on-dielectric (EWOD). As illustrated in Fig. 1, one plate with high emissive coating can be thermally switched on/off to the satellite surface by changing the contact angle of droplets with the coplanar EWOD actuation. The array of the droplets can be controlled individually or simultaneously to attach or detach from the top plate.

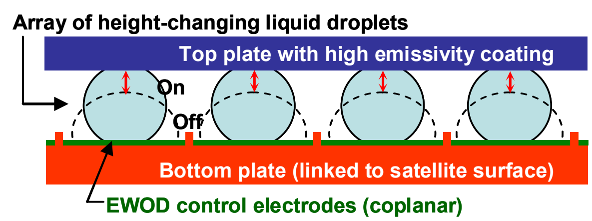


Figure 1: Conceptual design of the proposed EWOD-based thermal switch configured as a variable emittance radiator.

2. COPLANAR EWOD DEVICE

The contact angle of a liquid on a solid surface can be changed by applying an electric field between the liquid and the solid. This change becomes reversible even under a relatively high voltage if there is a thin dielectric layer separating the liquid from the solid. This configuration of electrowetting is called electrowetting-on-dielectric or EWOD. It has been demonstrated for a wide variety of conductive liquids, including aqueous solutions, glycerol, and mercury [4, 5]. A large change in contact angle can be achieved by depositing a low-surface energy material, such as Teflon®, on the control electrode to increase the contact angle at zero bias.

Recently, Yi and Kim [6] have demonstrated a switching of water droplets between beading and spreading states using a pair of coplanar electrodes where the grounding and energizing electrodes were constructed on the same electrode plate as shown in Fig. 2. The operating voltage of the device with 5000 Å SiO_2 dielectric layer was around 70 V of DC or AC (RMS) signal, which can be further reduced through the optimization of electrode geometry and the use of high-k dielectric layers. For our application (Fig. 1), the coplanar electrode design allows the electrical activities all on one plate, providing significant flexibility in optimizing the device to meet mechanical, electrical, and thermal requirements.

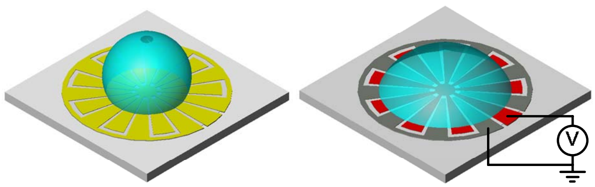


Figure 2: A water sessile droplet switching between beading and wetting on the EWOD device with coplanar electrodes [6].

3. DROPLET SWITCHING MECHANISM

We first evaluated the criteria for droplets to switch reversibly between the switching on and off states. As described in Fig. 3, a droplet attaches and detaches with a significant hysteresis due to the energy barrier associated with adhesion. To switch on, the top plate should be close enough to contact the beading droplet (EWOD-off); to switch off, the top plate should be far enough to break the liquid bridge of the spreading droplet (EWOD-on).

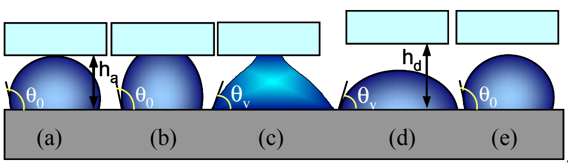


Figure 3: Hysteresis in droplet attachment-detachment. (a) EWOD off. About to touch top plate at height h_a. (b) Bridge formed. (c) EWOD on. Spreads on bottom but still bridged. (d) Detaches by elevating top to h_b. (e) EWOD off to make droplet tall but cannot connect. Need to lower top to h_a to touch it again.

The EWOD actuation should generate large enough contact angle change to enable reversible switching in a given device (i.e., h = constant). To bridge to the top plate, a droplet with a given volume and contact angle requires a small h. The critical height can be calculated through geometric analysis by assuming the droplet on the solid surface has a spherical cap and the gap between the spherical cap and the top plate is small, few nm. The critical height h^* determined by the droplet volume V^* and contact angle θ is:

$$h \le h^* = \sqrt[3]{\frac{3(1-Cos\theta_0)}{2\pi(2+Cos\theta_0)}}\sqrt[3]{V^*} \qquad (1)$$

On the other hand, for a droplet with a given volume and contact angle to detach, the height should be large enough. Typically no analytical solution exists for this criterion. Numerical simulation is used to calculate the droplet shape through the energy minimum method and determine the critical height when the liquid bridge between two plates becomes unstable. For the particular case where contact angle on top plate is 90˚, an empirical equation for the height can be determined [7] as:

$$h \ge h^* \cong \frac{1}{2}(1+0.5\theta_v)\sqrt[3]{2V^*} \qquad (2)$$

As shown in Fig. 4, these two criteria for the height are plotted with respect to contact angle on the bottom plate. At a specific height, the intersections between the horizontal line and two criteria indicate the contact angle change required to achieve both states. That determines how much EWOD actuation voltage is required to pull the droplet down to detach it from the top. The square and star dots in the graph represent static experimental data of critical detachment and attachment height with deionized (DI) water droplets tested on the Teflon® surface. The height was controlled by a step motor stage, and the contact angle on the bottom plate was changed by EWOD actuation. The critical heights were obtained by observing droplet detachment and attachment during the test. The top plate was also coated with Teflon®, on which the contact angle of DI water was around 117˚. Since this angle is larger than 90˚, the theoretical critical detachment height (equation 2) is an overestimation; experimental data show lower critical height and a steeper decrease with smaller bottom contact angle. On the other hand, the attachment data fitted very well with geometry analysis, which is accurate enough in this case. Since EWOD actuation is limited by the contact angle saturation (75˚ for DI water), the contact angle change by EWOD may not be enough for the droplet switching. Fig. 4 illustrates the full range of DI water contact angle change by EWOD, where the dot lines indicate the contact angle at the two ends of range and dash dot line shows the minimum height at zero voltage for the droplet to detach from the top. Since the maximum attachable height is smaller than the minimum detachable height at the saturation angle, these static experiments suggest we can not realize the droplet detaching and attaching by EWOD actuation for water droplet.

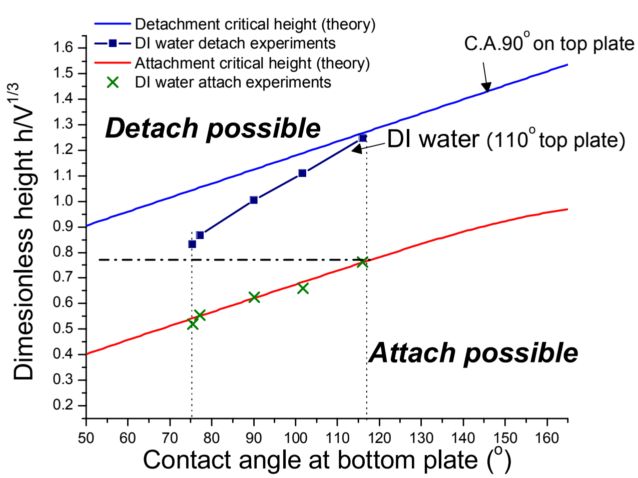
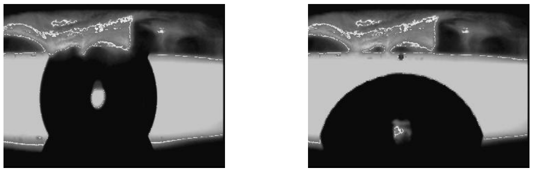


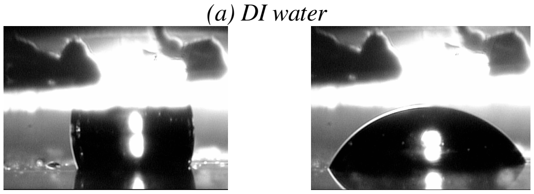
Figure 4: Static experiment for droplet detachment and attachment.

Repeatable switching has been achieved under dynamic condition for both DI water and glycerin at 70

V_{ac} by turning EWOD actuation on and off at a proper plate height near the attach-possible height as shown in Fig. 5. In the dynamic test, the inertial effect or other dynamic factors may help a droplet detach from the top plate. Better analytical analysis or numerical simulation will assist to obtain more precise droplet detachment criterion.



(a) DI water



(b) Glycerin

Figure 5: Droplets switch on/off on coplanar EWOD device with 4000Å Si_3N_4 and 2000Å Teflon driven with 1 kHz 70 V_{p-p}. The gap between top and bottom plates is approximately 1 mm.

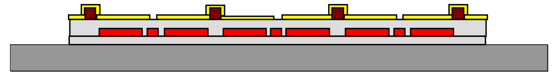
4. FABRICATION AND EXPERIMENTAL PROCEDURE

The device thermal characteristics were studied both theoretically and experimentally using a single-droplet test vehicle, which incorporated a microfabricated serpentine gold heater. Fig. 6 shows the process flow to fabricate and assemble the coplanar EWOD thermal switch devices. First, a 4x4 array of coplanar EWOD sites were fabricated on a Si substrate with 1 µm SiO_2 as an insulation layer, 2000 Å Au patterned as coplanar electrodes, 5000 Å SiO_2 as dielectric layer and 2000 Å Teflon® hydrophobic coating. The barriers were fabricated to prevent accidental droplet merging. Then, a serpentine gold strip (width = 100 µm, thickness = 1000 Å and pitch = 50 µm) with a 1.75×1.75 mm^2 footprint was patterned on a thin glass plate to serve as a planar heater and thermometer. Finally 1.1 mm-thick glass pieces were placed around the EWOD array as a spacer and adhesively bonded with top and bottom plates.

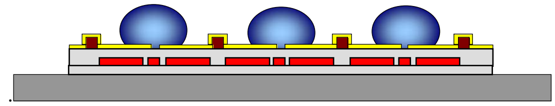
The experimental setup is schematically shown in Fig. 7. The heater was subjected to a pulsed current, and the bottom plate was placed on the temperature-controlled substrate holder. The voltage change across the heater was measured, and the temperature change was then obtained with following expression.

$$R(t) = R_0[1 + \alpha\Delta T(t)] \quad (3)$$

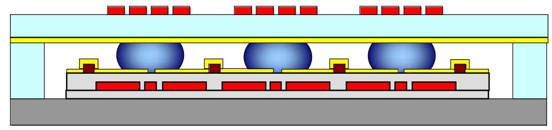
where $R(t)$ is the resistance at time t, R_0 is the resistance right before the transient,   is the temperature coefficient of resistance, and T is the temperature increase of the heater.



(a) Deposit and pattern coplanar EWOD electrode layer and insulation layer. Form barriers to prevent droplet merging. Coat and pattern hydrophobic layer



(b) Deposit droplets onto EWOD electrode



(c) Deposit and pattern heater and thermal sensor on top plate and coat hydrophobic layer on its bottom surface. Bond glass spacer around device area and assemble the top and bottom plate.

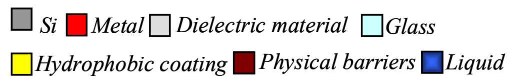


Figure 6: Process flow for EWOD-driven thermal switch testing device.

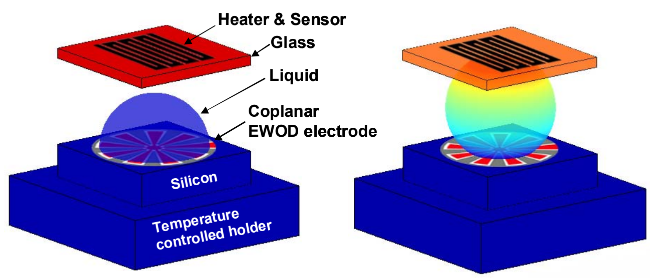


Figure 7: Schematic experimental setup, Thermal switch off (left) and switch on (right). At test, top is heated to simulate satellite surface and its temperature measured, while bottom is at constant temperature.

5. RESULTS AND DISCUSSIONS

The experimental results for water and glycerin are shown in Fig. 8 along with FEM simulation results. The switch on-off ratio as high as 2.8 was demonstrated despite significant heat conduction across the air gap between the droplet and the top plate and undesired heat spreading along the top plate. The experimental data agree well with the simulation results at short timescales for the off-state and the on-state with the glycerin droplet. The deviation at longer timescales is presumably due to the unaccounted heat loss along the bond wires and natural convection in the surrounding air.

Significant deviation was observed even at short timescales for water. This is not an experimental error but represents significant heat transfer augmentation by thermocapillary motion inside the water droplets. A finite temperature gradient along a liquid droplet creates spatial variation in the surface tension. This variation induces a tangential stress at the interface, which in turn creates bulk fluid motion inside the droplet, called thermocapillary flow. The strength of thermocapillary flows is characterized by the Marangoni number, given as

$$M = \frac{\gamma_T d\Delta T}{\rho\nu\kappa} \tag{4}$$

Here $_T$ is the first derivative of surface tension with respect to temperature, d is the characteristic length, T is the temperature difference, is the kinematic viscosity, and is the liquid density. In this experiment, the Marangoni number of water was greater than that of glycerin by a factor of 1000 because water is much less viscous than glycerin. Therefore, stronger thermocapillary effect on the enhancement of the heat transfer can be expected with water. A cyclic on-off test performed at 1 Hz (Fig. 9) also confirmed that the response of the thermal switch was much faster with water. When extrapolated to actual in-space operating conditions, the switch on-off ratio of the order of 1000 can be achieved using low-vapor-pressure liquid metals, such as non-toxic alloys of In-Ga, or low-viscosity ionic liquids with strong thermocapillary potential.

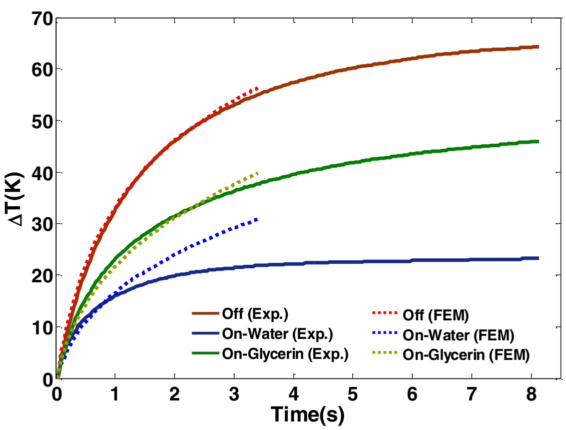


Figure 8: Measured temperatures change by switch on and off using water and glycerin. FEM results for comparison.

6. CONCLUSIONS

This report has established basic feasibility of novel liquid-droplet-based thermal switches that can overcome limitations of existing solid-conduction-based thermal switches. Different liquids with better thermal properties and low vapor pressure should be explored next for space applications.

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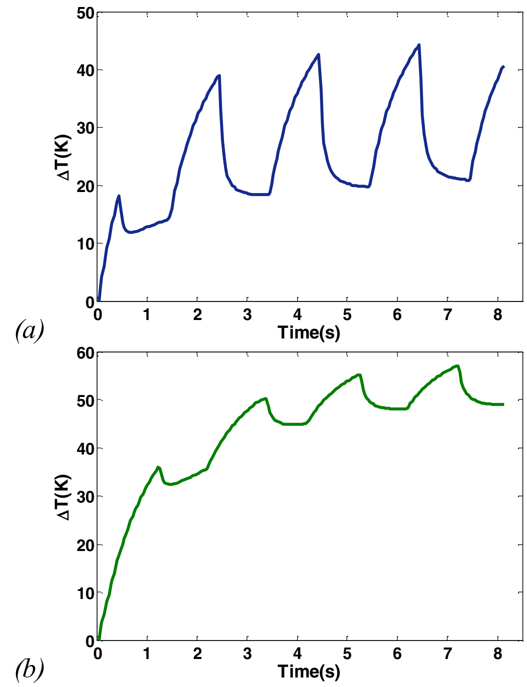

Figure 9: Experiment data of 1 Hz thermal switching test using (a) water and (b) glycerin droplets.

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