ACTIVE THERMAL CONTROL FOR POWER MEMS

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Abstract: Recent work devoted to the development of active MEMS thermal switches is profiled. The work has focused on two requirements for an active MEMS thermal switch: actuation and thermal contacts. First, measurements of thermal contact resistance for liquid contacts are presented. Thermal switch contacts based on liquid Hg microdroplets are shown to achieve thermal resistances less than 1 mm^2 $^oC/W$. Second, measurements of actuation via electrowetting on dielectric (EWOD) of a dielectric liquid are compared to a simple theory. Electrowetting of deionized water droplets is shown to actuate the droplets at velocities up to 2 mm/s.

Keywords: Thermal Switch, Electrowetting, MEMS

INTRODUCTION

Many proposed micropower systems require thermal control for efficient operation. In particular, waste heat rejection from heat engines and fuel cells is a prime consideration. MEMS-based thermal switches offer one possibility for the active thermal control of micropower systems. Active thermal control via a MEMS thermal switch, in turn, requires two challenges be met, the development of low thermal resistance contacts and the development of low power techniques to actuate the thermal contacts. Ideally, a thermal switch would have 1) a high off/on switch thermal resistance ratio, 2) low power consumption, and 3) quick response time.

Significant work has been done on the development of low thermal resistance contacts [1, 2, 3]. Liquid droplets, and especially liquid metal droplets sandwiched between solid substrates have been identified as demonstrating extremely low thermal contact resistance. Likewise, recent work has identified some promising actuation methods, such as electrowetting, to move those liquid droplets and actively control the thermal properties of microfabricated structures [4, 5, 6].

Previous work in our laboratory demonstrated that a thermal switch based on arrays of liquid Hg microdroplets moved into and out of contact with a Si substrate by a piezoelectric stack actuator can achieve off/on switch thermal resistance ratios of greater than 100 with switching speeds on the order of 10 milliseconds. However, this performance was achieved at the cost of high power consumption by the piezo actuator [2]. Power requirements could be dramatically reduced by replacing the stack actuator with a cantilever actuator, but this change lengthened the heat transfer path through the thermal switch itself, thus increasing the overall thermal resistance of the switch [7].

Electrowetting, particularly electrowetting on a dielectric (EWOD), appears very promising as a potential actuation method with low power consumption. EWOD has already proven to be an efficient method for moving liquid dielectric and liquid metal droplets around on the microscale. EWOD works by modifying the surface tension of a droplet by applying a localized electric field. When the electric field passes through the droplet, charges migrate to the surface of the droplet, modifying the surface tension of the droplet. This modification of surface tension causes a pressure gradient in the droplet, moving the droplet (Fig. 1). Linear speeds of up to 3.3 cm/s using EWOD actuation have been reported [6].

Combining low-power actuation via EWOD with very low thermal resistance contacts of liquid metals appears to be an attractive strategy to realize a low power, fast thermal switch with a high off/on switch thermal resistance ratio. In the present work, we document progress toward the realization of this kind of device, a MEMS-based bi-stable thermal switch based on the actuation of liquid

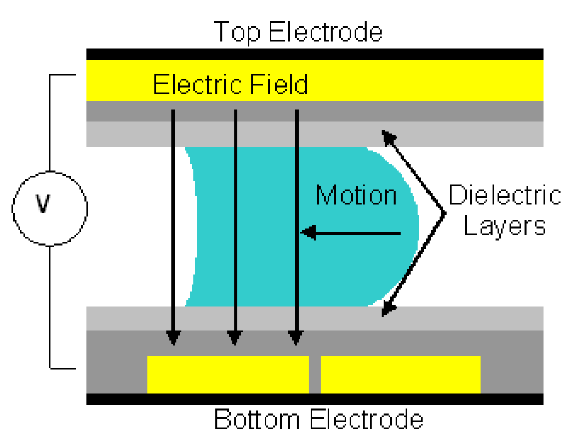

Fig. 1: Overview of electrowetting on a dielectric.

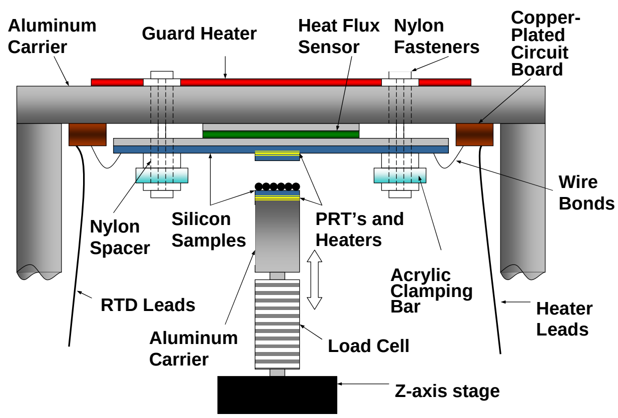

Fig. 2: Guard-heated calorimeter.

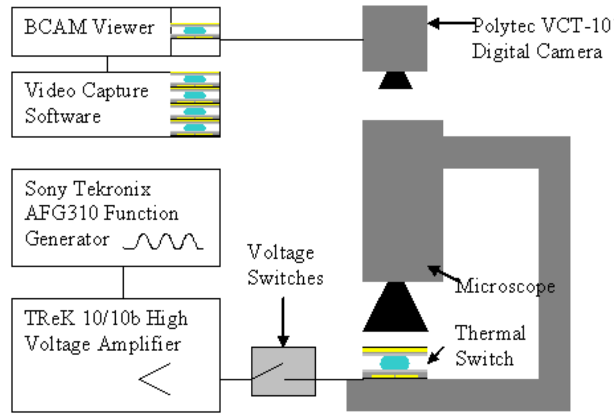

Fig. 3: Droplet actuation testing facility.

microdroplets via electrowetting. First, we present recent heat transfer measurements on liquid metal microdroplet thermal contacts. Second, we present measurements and theoretical predictions of the electrowetting actuation of liquid microdroplets.

EXPERIMENT

Thermal Contacts

Thermal resistance measurements were made across liquid metal microdroplet arrays. The microdroplet arrays were fabricated by selective physical vapor deposition of Hg on Au targets. First, the Au targets were produced by sputtering 500 nm of Au on Si wafers. Twenty-micron diameter circular targets were then defined photolithographically. Targets were produced in 20 x 20 arrays (400 targets) and 40 x 40 arrays (1600 targets). The wafers were then diced and individual arrays exposed to Hg vapor. Microdroplets of liquid Hg were condensed selectively on the Au targets, with the diameter of each microdroplet controlled by the time the die was exposed to the vapor. This process yields Hg microdroplet arrays with remarkably precise and uniform microdroplet size and positions [1, 2].

Thermal resistance across the microdroplet array contacts were measured with a custom built guard-heated calorimeter. The guard-heated calorimeter, shown in Figure 2, consists of a silicon heater die, a heat flux sensor and a guard heater, all mounted on a rigid aluminum plate. In order to make thermal resistance measurements, the heat flux sensor is zeroed by controlling power delivered to the guard heater. Under this condition, all the electrical power dissipated in the silicon heater die is transferred as heat down through the microdroplet array to the bottom contact die. The heat transfer rate across the microdroplet array is thus equal to the input power to the silicon heater die. The temperature difference across an array of microdroplets is measured with PRTs micromachined on the top silicon heater die and the bottom contact die. The thermal resistance across the microdroplet contacts is taken to be the ratio of the temperature difference across the microdroplets to the heat transfer rate across the microdroplets, normalized by the microdroplet contact area:

$$R = \frac{A(T_1 - T_2)}{q} \tag{1}$$

Details of the construction and operation of the guard heated calorimeter are given in [8].

Actuation

Electrowetting actuation experiments are conducted for dielectric liquids sandwiched between glass substrates. First, the bottom glass substrate is sputtered with 500 nm of Au. Electrodes are then defined via photolithography. Four different width electrodes were fabricated: 2.0 mm, 1.5 mm, 1.0 mm, 0.5 mm. A 12 nm Ti adhesion layer is sputtered next. A dielectric layer consisting of 500 nm of SiO_2 is then sputtered over the Au and Ti. Finally, 50 nm of Teflon is spun on top of the SiO_2 to form a hydrophobic surface on the bottom substrate.

The top glass substrate is produced by first sputtering a 25 nm layer of Ti to form a transparent electrode on a second glass slide. Next, a dielectric layer consisting of 500 nm of SiO_2 is sputtered over

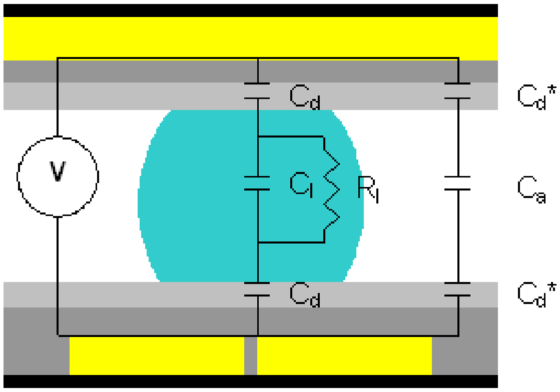

Fig. 4: Idealized circuit diagram for calculating the Maxwell stress tensor.

the Ti. A hydrophobic surface is formed on the top substrate by spinning on 50 nm of Teflon.

An experiment was conducted by depositing a droplet of deionized water on one electrode of the bottom substrate. Droplet sizes were chosen to have a radius equal to the width of electrode (2.5 mm, 2.0 mm, 1.5 mm, 1.0 mm). The top glass substrate was then put in place, squeezing the droplet of liquid, between the two glass substrates. The gap width between the substrates was fixed at 120 microns. A voltage between 35 and 65 volts was applied across the electrode adjacent to the liquid droplet using a Sony Tekronix AFG310 function generator and a TReK 10/10b high voltage amplifier. The resulting motion of each droplet was observed through the top transparent electrode, and captured using a Polytec VCT-101 digital camera (Fig. 3).

Modeling

Actuation of a liquid droplet via EWOD is modeled by applying a force balance on the droplet. We consider the effect of three forces in this model: the driving force due to electrowetting, the viscous forces at the interface between the liquid droplet and the solid substrate, and the contact line friction. The electrowetting driving force is modeled using the appropriate Maxwell stress tensor:

$$T^e_{mn} = \varepsilon E_m E_n - \delta \frac{1}{2} \varepsilon E_k E_k \qquad (2)$$

where T^e_{mn} is the stress tensor, E is the electrical field, ε is the permittivity, and δ is the Kronecker delta function. Two assumptions are made. Electrostriction effects are assumed negligible, and no free charge is assumed to be present. If the electrical field, E, is known, the electrowetting driving force can be obtained by taking a closed surface integral of T^e_{mn} around the volume of interest [4]. Obtaining an analytical solution for the electric field at the interface of the droplet is difficult. However, far away from the interface where the electric field is uniform, the integral can be found from a circuit diagram (Fig. 4). The driving force per unit length is then modeled as

$$F_e = \sum_{i=1}^{n} \frac{\varepsilon E_i^{\,2} d_i}{2} - \sum_{j=1}^{n} \frac{\varepsilon E_k^{\,2} d_k}{2} \qquad (3)$$

where E_i is the magnitude of the electric field through the droplet, E_k is the magnitude of the electric field through the surround vapor, and d is the respective thickness of the capacitive layers.

The viscous and contact line friction forces can be modeled using empirical relationships [5]. The viscous force, caused by shear stresses in the fluid, is a function of capillary number and surface tension:

$$F_d = 0.55 \left(\frac{\mu U}{\gamma_{lv}} \right)^{0.3} \gamma_{lv} \qquad (4)$$

where μ is the viscosity of the fluid, U is bulk velocity, and γ_{lv} is the surface tension between the droplet and the surrounding vapor. The force due to contact line friction, caused by molecules at the contact line sliding past each other, scales with velocity:

$$F_L = \zeta U \qquad (5)$$

Here ζ is a contact line friction coefficient, and is a function of the surface of the surface roughness.

The average velocity of a droplet is determined by setting the sum of forces on the droplet to zero.

$$F_e - F_d - F_L = 0 \qquad (6)$$

RESULTS

Results of the thermal resistance measurements for three Hg microdroplet arrays are shown in Fig. 5. Thermal resistance is plotted versus applied pressure squeezing the droplets between the

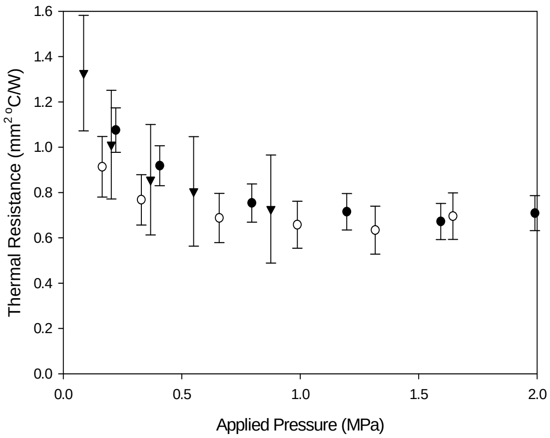

Fig. 5: Measured thermal resistance of mercury arrays as a function of contact pressure.

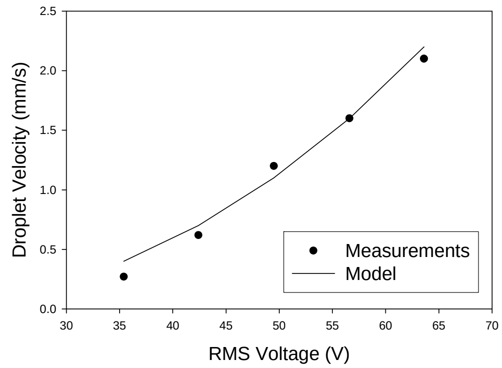

Fig. 6: Measured and predicted droplet velocity versus voltage during electrowetting actuation..

two Si substrates, where both thermal resistance and pressure are normalized by microdroplet contact area. The thermal resistance across the Hg microdroplets is seen to be remarkably low, less than 1.0 mm^2 ^{o}C/W for applied pressures of 0.5 MPa and greater.

Results for actuation of a 1.5 mm diameter droplet of deionized water are shown as solid circles in Fig. 6. Droplet velocities between 0.3 and 2.1 mm/s were obtained by varying the RMS voltage from 35.5 to 63.5 volts. Predictions of the model, assuming a contact line friction coefficient of $\zeta = 1.2$ Ns/m^2, are given by a solid line. The model is seen to be in good agreement with the measured droplet velocities.

DISCUSSION

Recent work devoted to the development of an active MEMS thermal switch has been discussed. The present work has focused on two requirements for an MEMS thermal switch: actuation and thermal contacts. First, measurements of thermal contact resistance for thermal switch contacts based on liquid Hg microdroplets have been shown to achieve thermal resistances less than 1 mm^2 ^{o}C/W. Second, electrowetting actuation of deionized water droplets at velocities up to 2 mm/s has been demonstrated. Predictions of a simple theory of electrowetting on dielectric (EWOD) of a dielectric liquid compare well with the experimental measurements.

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