Characterization of an integrated micro heat pipe

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Abstract

The characterization of a micro heat pipe system, integrated with a local heater, temperature and capacitive microsensors is presented. Two liquid charging schemes based on a single hole, requiring vacuum environment, and a pair of holes, utilizing capillary forces are compared. Taking advantage of the great disparity between the dielectric constants of liquids and gases, capacitance sensors are used for void fraction measurements. Since it is difficult to control the phase content of a liquid–gas mixture in a micro heat pipe, a calibration technique based on a traveling water–air interface due to evaporation is introduced. The integrated sensor capacitance for pure water is found to depend on measurement frequency, temperature and ion concentration, exhibiting trends that are different from previous reports. The measured temperature and void fraction distribution along the heat pipes are consistent with the two-phase flow patterns recorded during the microsystem operation.

1. Introduction

Micro heat pipes show promise as cooling devices. The applications of micro heat pipes have expanded from the thermal control of laser diodes, photovoltaic cells and infrared (IR) detectors to the removal of heat from the leading edges of stator vanes in turbines and non-surgical treatment of cancerous tissue. Based on experimental observations, the effective thermal conductivity of micro heat pipes occupying 1.45% of the cross-sectional area was improved by 47.1%, while the surface temperature was reduced by 29%. More importantly, the temperature gradient across the chip was reduced by 41.7% [1]. Furthermore, for non-steady-state thermal performance, micro heat pipes in silicon can reduce the thermal time constant by more than 30% when compared to that obtained for plain silicon wafers [2].

The performance of the micro heat pipe is typically characterized by temperature measurements. The common methods to measure the temperature distributions employ either thermocouples or IR cameras [1–4]. Temperature measurements have indicated that the effective thermal conductivity of the heat pipes could increase by about 30%

with an increase of the volume fraction of charged liquid in the heat pipe from 10 to 50% void fraction [5]. Indeed, the charging scheme is very important for controlling the amount of working fluid, especially inside micro heat pipes, since the interior space of a micro heat pipe is extremely limited. Hence, a single charging hole is popularly utilized in conjunction with vacuum environment, for fine control of the amount of liquid charged [6].

Void fraction distribution during heat pipe operation is an important parameter. Capacitive sensors have been used in two-phase air/liquid pipe flow for void fraction measurements [7, 8]. Capacitors have also been used as humidity sensors [9]. However, no capacitance sensors have been used for the performance analysis of micro heat pipes.

In the present work, silicon-to-glass bonding technology has been utilized to fabricate a micro heat pipe system, integrated with a local heater, allowing flow visualization. We present two charging schemes, based on either a single hole or a pair of holes. In addition to distributed temperature microsensors, capacitance microsensors have also been integrated along the micro heat pipes for void fraction distribution measurement.

Figure 1. A picture of a fabricated micro heat pipe system showing four heat pipes, a local heater, charging holes, temperature and capacitor sensors (the silicon die size is $15 \times 30 \text{ mm}^2$, and the glass die size is $22 \times 26 \text{ mm}^2$).

Figure 2. A picture of a micro heat pipe with a single charging hole at the condenser region.

2. Design and fabrication

2.1. Micro heat pipe system

The micro heat pipe system was designed based on silicon-to-glass anodic bonding technology. The microsystem consists of a local heater, an array of micro heat pipes, and distributed temperature and capacitive microsensors. The heater and temperature sensors were fabricated within the silicon substrate by selective doping, using standard surface micromachining techniques. The bottom electrodes for the capacitors were defined by doping the heat-pipe grooves before bonding. Stacked Ti:W and Pt thin films were sputtered and patterned on the glass wafer for both metal interconnects and capacitor top electrodes, which were placed between the glass and Si substrate. The detailed fabrication process has been described elsewhere [10]. A picture of a fabricated device is shown in figure 1. This microsystem includes four heat pipes with triangular cross sections. Each heat pipe is $100 \mu\text{m}$ in width and 20 mm in length, with a hydraulic diameter of about $52 \mu\text{m}$. Capping the heat pipes with a glass substrate allows visualization of the two-phase flow patterns during operation.

2.2. Charging scheme

Some of the microsystems are designed with a single charging hole for each heat pipe, as shown in figure 2. In such a case, the working liquid cannot be injected into the micro pipe directly by capillary forces since the air occupying the volume inside the pipe chamber prohibits the liquid from entering and filling

Figure 3. A schematic diagram of the setup for a single-hole scheme to charge the micro heat pipes with the working liquid.

Figure 4. A picture of a micro heat pipe with a pair of charging holes; one at the condenser and one at the evaporator region.

the heat pipe. Therefore, the air inside the micro heat pipes has to be evacuated before charging the working liquid.

Figure 3 shows a schematic diagram of the setup for charging a single-hole micro heat pipe. The microdevice inside a beaker is placed in a chamber, which is connected to both a vacuum pump and a reservoir containing the working liquid. Initially, the valve between the reservoir and the chamber is closed. The charging process begins with vacuuming the chamber by the pump. After switching off the pump, the valve is opened. The working liquid in the reservoir flows into the chamber because of the pressure difference between the vacuum chamber and the ambient. The liquid then fills the entire heat pipe. In order to control the amount of liquid inside the micro heat pipe, the charging holes are not sealed immediately after charging. The liquid evaporates from the end of the heat pipe through the charging hole, and the liquid volume in the pipe decreases gradually. The charging holes are sealed when the desired amount of liquid is obtained, thus the volume fraction of liquid within the pipe can be controlled. Obviously, this charging technique is cumbersome and is prone to large non-uniformities between the various pipes.

In an alternative approach, each micro heat pipe is equipped with a pair of charging holes, as shown in figure 4. Since there are two holes, air cannot accumulate inside the micro heat pipe. When liquid comes in contact with one of the charging holes, driven by capillary forces, it flows into and fills up the heat pipe. After charging the heat pipe, one of the holes is sealed first with silicone sealant. The evaporation of water then takes place at the other unsealed charging hole. When the designated amount of liquid inside the micro heat pipe is obtained, the other charging hole is also sealed with silicone sealant. With this approach using two charging holes, there is no need for vacuum and the charging process is much more convenient.

Figure 5. A schematic diagram of the experimental setup for testing the micro heat pipe system operation.

3. Experimental setup

The experimental setup is schematically illustrated in figure 5. It comprises of the test chip, data acquisition system, inductance–capacitance–resistance (LCR) meter, power supply, temperature sink, cold chuck and video recording system. To allow testing, each microdevice has to be packaged on a printed circuit board (PCB) to provide I/O connections. The PCB is designed to minimize the contact area with the test chip to obtain maximum thermal isolation. The PCB is then mounted on acrylic holders in order to reduce thermal conductivity. Deionized (DI) water is used as the working fluid for the experiments. An adjustable voltage supply controls the power dissipated by the heater at one edge of the microdevice. The other edge is connected to a constant temperature sink kept at 16 °C to remove the heat from the microdevice. The heat sink temperature is maintained by a cold chuck, which is connected to a refrigerator. The output signals from the temperature and capacitance microsensors were collected using a computerized data acquisition system and a digital LCR meter, respectively. Simultaneously, the evolving two-phase flow patterns in the micro heat pipes during operation were recorded using a VCR through a CCD camera mounted on a microscope.

4. Microsystem calibration

4.1. Heater and temperature sensors

Device characterization started with the calibration of the temperature sensors. The microsystem was placed in an oven, and the resistance change $R - R_0$ of each sensor was recorded as a function of the controlled temperature change $T - T_0$. The resulting calibration curves of the temperature microsensors are depicted in figure 6(a), where T_0 and R_0 are the room temperature and the corresponding sensor resistance, respectively. The relative resistance change increases almost linearly with the temperature change, and the response of the various temperature sensors is very uniform with a positive temperature coefficient of resistance (TCR) of about 0.15%/°C.

Figure 6. Calibration curves of (a) the temperature sensors along a heat pipe, and (b) the local heater at the edge of a micro heat pipe system.

The performance of the heater was tested by simultaneously monitoring the voltage and current through the heater to estimate the input power, q , while recording the resistance change of the temperature sensors. The measurements are summarized in figure 6(b) for the dry device, i.e. no liquid in the heat pipes. The local temperature along the microdevice increases almost linearly with the input power, since natural convection from the device surface is the only mechanism for heat removal. Moreover, the heater is located at the edge of the device; hence, the temperature decreases with the distance x from the heater.

4.2. Capacitance sensor for void fraction measurements

The capacitance microsensor is regarded as a dielectric capacitor when the heat pipe is full of water. There is no perfect dielectric material and the loss tangent, $\tan \delta = 1/(\omega RC)$, must be recognized [11]. This loss value is a direct expression of the existence of a resistance, R , associated with the capacitance, C . Therefore, the dielectric capacitor is modeled using the parallel model, in which C_s is in parallel with R [12, 13]. In addition, a parasitic capacitance C_p , due to the overlap between the metal interconnects and the silicon substrate, is also present in parallel with the dielectric capacitance, as shown in figure 7(a). Thus, the equivalent model includes the measured capacitance C in parallel to R , and the relationship between C and R is shown in figure 7(b).

The dielectric constant of water is very different from that of air or vapor. Hence, the measured capacitance is sensitive to the air/water volume ratio of the fluid mixture between the sensor electrodes. Since the dielectric constant of vapor is almost equal to that of air, upon proper calibration, the capacitive sensor can be used for void fraction measurements

Figure 7. Physical model of the measured sensor capacitance: (a) equivalent circuit including the resistance, sensor and parasitic capacitance, and (b) corresponding phase diagram showing the dielectric capacitance with tangent loss.

Figure 8. Close-up pictures showing the water–air interface (a) before and (b) after the interface has passed through the capacitor top electrode.

of the two-phase flows inside the micro heat pipe during operation. The calibration of the capacitance sensor is very tricky. The two extreme points of single-phase air or water are clear and easy to measure. This would be sufficient to establish the entire calibration curve if the capacitance was a linear function of the air/water volume ratio. This is not the case, and the capacitance could be different even for the same air/water ratio with different phase distribution in space. Therefore, more calibration points are required, for which it is difficult to control the air/water volume ratio of the fluid between the electrodes in the micro heat pipe. Before calibration, we register the capacitance value in air medium C_a , at 1 kHz and 20 °C. One charging hole of the micro heat pipe is then connected to a syringe with a plastic tube. The syringe presses the DI water into the heat pipe and fills it up. The water inside the heat pipe gradually evaporates through the other charging hole and, consequently, the water–air interface propagates along the heat pipe. Before the interface arrives at a given sensor, as shown in figure 8(a), the capacitance value for 100% DI water, C_w , is measured. As the tip of the air–water interface passes through the capacitance sensor, the exact position of the interface cannot be observed since the sensor electrode is opaque. Still, the capacitance value for various air/water mixtures between the sensor electrodes was recorded to obtain a calibration curve. Only after the interface tip has passed through the sensor, such that it can be observed beyond the other edge of the sensor electrode as shown in

Figure 9. Calibration curves of (a) different capacitance sensors at the same time, and (b) the same capacitor at different times.

figure 8(b), can the void fraction be estimated with the corresponding capacitance measurement.

As the air–water interface travels through the pipe from one end to the other, liquid menisci remain trapped in the corners of the heat pipe. Under this condition, the volume fraction of the air underneath the sensor is estimated to be about 95%, and the corresponding measured capacitance is used as the reference value C_r . The measured capacitance C , normalized by the reference capacitance C_r , is plotted in figure 9 as a function of the estimated void fraction χ . The normalized calibration curves for sensors with different areas collapse together, as shown in figure 9(a), exhibiting an almost linear decrease of the capacitance with increasing air volume fraction from 0 to 95%. The void fraction ‘measurements’, based on the shape analysis of the gas–liquid interface by Peterson *et al* [14], are estimated to be within $\pm 2\%$ of the nominal values used in the calibration curves. Since the calibration environment is not perfectly clean, contaminating ions from the surroundings affect the ion concentration in the water. Therefore, the ion concentration within the working liquid is different and cannot be controlled during each calibration process, resulting in different capacitance measurements for the same void fraction estimates during repeated calibrations. However, as shown in figure 9(b), normalizing the measured capacitance with the reference, C_r , rather than the air value, C_a , provides similar curves at different calibration times. The resulting calibration curves are then independent of the ion concentration in the working liquid. It is interesting to note that as the menisci dry

Figure 10. Normalized sensor capacitance dependence on the measurement frequency for DI water at 20 °C.

out, the capacitance values of all sensors suddenly drop to the corresponding air values, C_a , such that no additional data point can be obtained for air volume fraction in the range 95–100%.

4.3. Parameters affecting the capacitance sensor measurements

The sensor capacitance under constant temperature is a function of the medium dielectric constant, which depends on the measurement frequency. Thus, the capacitance dependence on the measurement frequency f for various sensors is demonstrated in figure 10. The capacitance $C_a(f)$ is first measured in 100% air at a room temperature of $T_0 = 20$ °C using the LCR meter. The measurements were then repeated for 100% water, $C_w(f)$, under the same conditions. The capacitance measurements at $f = 1$ kHz for air, C_a , and water, C_w , are used as the reference values. The parasitic capacitance is modeled to be in parallel with the sensor capacitance, figure 7(a). Hence, each measured capacitance value can be viewed as the sum of two components: sensing and parasitic capacitances. Correspondingly, the sensor reference capacitances in air and water are denoted by C_{sa} and C_{sw} , while the sensor capacitances for air and water are $C_{sa}(f)$ and $C_{sw}(f)$. In order to eliminate the effect of the parasitic capacitance $C_p(f)$, taking advantage of the fact that $C_{sw}(f) \gg C_{sa}(f)$, the measured capacitance is normalized as follows:

$$\frac{C_w(f) - C_a(f)}{C_w - C_a} = \frac{[C_{sw}(f) + C_p(f)] - [C_{sa}(f) + C_p(f)]}{(C_{sw} + C_p) - (C_{sa} + C_p)} \cong \frac{C_{sw}(f)}{C_{sw}}. \quad (1)$$

The experimental results shown in figure 10 indicate that the capacitance value for 100% water decreases with an increase of frequency from 1 to 3 kHz. This means that the dielectric constant of DI water also decreases in this frequency range, although the dielectric constant of water is expected to be independent of frequency up to 100 MHz [15].

The sensor capacitance is directly proportional to the dielectric constant of the working liquid, which in turn depends on the temperature. The capacitance measurements for 100% water at a constant frequency of 1 kHz, $C_w(T)$, are summarized in figure 11 for a temperature range $T - T_0 = 0 - 50$ °C. The corresponding capacitance for 100% air, C_a , was found to

Figure 11. Normalized sensor capacitance dependence on temperature for DI water at 1 kHz measurement frequency.

Figure 12. Normalized sensor capacitance dependence on the ion concentration of NaCl in DI water at 20 °C and 1 kHz.

be independent of temperature in the same range. Again, to eliminate the parasitic capacitance effect, the measured capacitance is normalized as:

$$\frac{C_w(T) - C_a}{C_w - C_a} = \frac{[C_{sw}(T) + C_p] - (C_{sa} + C_p)}{(C_{sw} + C_p) - (C_{sa} + C_p)} \cong \frac{C_{sw}(T)}{C_{sw}}. \quad (2)$$

The measured capacitance of all sensors summarized in figure 11 increases monotonically with increasing temperature. It is known that the dielectric constant of water is inversely proportional to the temperature, $\epsilon_w(T) \propto 1/T$, where T is the absolute temperature [16]. For example, the dielectric constant of water at 70 °C is 85% of its value at 20 °C. Therefore, the dielectric constant of water and the sensor capacitance should decrease with increasing temperature. However, repeated experiments for a variety of sensors in different devices always result in the same trend of increasing sensor capacitance with increased temperature.

Different values have been obtained for repeated measurements of sensor capacitance with 100% water under seemingly identical conditions, and this was attributed to different ion concentration in the working liquid. Since this process was random, a controlled experiment was conducted to verify the dependency of the sensor capacitance on ion concentration. Sodium chloride was added to the DI water, changing its ion concentration, i_e , from nearly zero to 0.7 M. The capacitance of each sensor along the heat pipe was measured at 1 kHz and 20 °C, and the results are shown in figure 12. Evidently, the capacitance of all sensors increases

Figure 13. The flow pattern at the (a) evaporator, (b) adiabatic, and (c) condenser regions during the micro heat pipe operation; the heater is located next to the evaporator.

monotonically with increasing ion concentration for the tested range. Hence, since all other parameters are kept unchanged, the dielectric constant also increases significantly with ion concentration. This is in direct contrast with previous studies reporting that the dielectric constant of aqueous sodium chloride is constant for a concentration of sodium chloride ranging from 0.001 M to 0.7 M, at least at high measurement frequency (100 kHz) [13, 17].

The microsensor capacitance for 100% water is found to depend on the measurement frequency, temperature and ion concentration. The effects of these three parameters are different from expected trends reported in the literature. Currently, the reasons for the differences are unknown, and further research is required to study these phenomena.

5. Micro heat pipe system operation

After the microsensor calibration procedures, the heat pipes are charged with DI water and then sealed to allow testing. Flow visualizations confirm the development of the three distinct zones in the micro heat pipes, the evaporator, adiabatic and condenser regions, as shown in figure 13. The evaporator region is next to the heater, figure 13(a), having the highest temperature. A portion of the input power is converted into latent heat of phase change of the working fluid in the evaporator. Thus, the highest void fraction is observed in this region. The heat flows from the evaporator to the condenser through the adiabatic region. In this region, figure 13(b), an annular-like flow is developed. Liquid flows towards the evaporator due to the capillary force at the corners of the heat pipes, while vapor at the core flows towards the condenser due to the pressure gradient. The vapor is condensed back to liquid at the other end of the heat pipe, figure 13(c), thus transferring the latent heat of phase change from vapor to liquid to the cold sink. Since the micro heat pipe is fabricated by bonding glass to a silicon wafer, most of the heat is conducted through the silicon, leaving the glass cover relatively colder. Therefore, a fraction of the vapor condenses on the ceiling to form a thin liquid film or water droplets, as shown in figure 13.

Temperature distribution measurements along the heat pipe for different input power levels are summarized in figure 14. The temperature decreases almost linearly with the distance from the heater, and the negative temperature gradient increases as the input power increases. The increasing negative temperature gradient along the heat pipe is due to the higher rate of input heat flux in comparison with the rate of thermal conduction along the microdevice. Consequently, heat is accumulated in the evaporator region increasing its temperature. The distribution is consistent with the visualizations such that the evaporator temperature is the highest and the condenser temperature is the lowest.

Figure 14. Temperature distribution measurements along the micro heat pipe for different input-power levels.

Figure 15. Void fraction distribution measurements along the micro heat pipe for different input-power levels.

The void fraction distribution, corresponding to the liquid–vapor mixture along the heat pipe, using the capacitive sensors is plotted in figure 15. The transition from the vapor to liquid zone via the adiabatic region is clear. The vapor content in the evaporator region is highest, about 1, while in the condenser region it is about zero. The void fraction along the heat pipe increases with input power. Consequently, the extent of the condenser region decreases while the extent of the adiabatic region increases with increasing input power.

6. Conclusion

We have fabricated and characterized an integrated micro heat pipe system, consisting of a local heater, temperature and capacitive sensor arrays. The calibrated temperature sensors have a positive TCR of 0.15%/°C, while the local temperature increases linearly with the input power dissipated by the heater. The capacitance sensors are used to measure the void fraction

in the liquid–vapor mixture along the pipe. Although repeated calibrations result in different curves, the calibration curves for the same sensor collapse together when the measured capacitance is normalized properly. The capacitance decreases almost linearly with increasing void fraction up to a value of 0.95.

The sensor capacitance depends on the measurement frequency, temperature and ion concentration. The capacitance (i) decreases with increasing frequency in the range between 1–3 kHz at a constant room temperature, (ii) increases with increasing temperature at a constant frequency of 1 kHz, and (iii) increases with increasing ion concentration of NaCl in water at room temperature and 1 kHz measurement frequency. The effects of the three parameters are different from results reported in the literature, and the reasons are unknown at this stage. Further study is required to clarify these observations.

Two-phase flow patterns can be observed during the micro heat pipe operation, where the evaporator, adiabatic and condenser zones are clearly distinguishable. Void fraction and temperature distributions along the heat pipe are measured and are found to be consistent with the flow visualizations.

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