ABSTRACT

This work designs and fabricates a microchannel structure for measurement of wall temperature fields in two-phase flow. The microchannel with hydraulic diameter of 100 micrometers is etched into a suspended beam of silicon with three independently heated regions and integrated doped silicon resistors sensitive to channel temperature. Doped silicon resistors are also sensitive to strain in the silicon caused by pressure transients in the channel, so sensors are designed with two different orientations and thus two different piezoresistive coefficients to allow decoupling of pressure and temperature effects. Use of a 400 micrometer wide suspended beam reduces side-wall conduction compared to a bulk sample and provides better opportunities to measure the influence of flow regimes on heat transfer coefficients in future work. Use of the central heater reduces fluid preheating in the inlet plenum. The measured temperature distributions at flowrates up to 0.25 ml/min with heat fluxes into the silicon beam up to 78 W/cm² show initial capabilities of the structure.

KEYWORDS
Microchannel, two-phase convection, heat exchanger

INTRODUCTION

Two-phase flow of water in microchannels has attracted attention as a means of removing heat from microprocessors in computers [1]. To understand convective boiling in microchannels, single and multiple channel structures have been developed using conventional machining [2], [3] and silicon micromachining [4] – [9]. Silicon micromachining allows integration of heaters and sensors onto the test structure. Peng and Wang [2] observed an absence of partial nucleate boiling in 600 µm by 700 µm rectangular microchannels machined into a stainless steel plate with thermocouples on the backside. The same results were observed by Peng et al. [3] in V-shaped microchannels with hydraulic diameters of 200 µm to 600 µm. Jiang et al. [4] reported phase change in V-shaped microchannels with hydraulic diameters of 40 µm and 80 µm using a localized heating element with distributed polysilicon temperature sensors, and Lee et al. [5] observed phase change in parallel rectangular channels with a 24 µm hydraulic diameter. Hetroni et al. [6] used infrared imaging to determine steady-state temperature distributions in two-phase flow through parallel triangular microchannels with 103 µm to 129 µm hydraulic diameter under uniform and non-uniform heating. Peles et al. [7] studied steady flow regimes using parallel triangular microchannels with hydraulic diameters of 50 µm to 200 µm. Zhang et al. [8], [9] microfabricated suspended single channel test structures to reduce axial conduction in the silicon, using integrated aluminum heaters to achieve uniform heating and doped silicon sensors for distributed temperature measurements. Zhang et al. [9] then measured pressure transients at 30 - 40 Hz associated with bubble formation using the doped silicon sensors. They were not able to fully decouple pressure and temperature effects on a single sensor, and the heated beam led to fluid preheating in the inlet with a 2 mm separation between the heater and reservoir.

The present work develops, fabricates, and characterizes single microchannel structures that allow decoupled...
temperature and pressure measurements with optical access for flow visualization while minimizing fluid pre-heating. The structure has a single 100 µm square channel etched into a silicon beam, which is mechanically supported by means of anodic bonding with a glass substrate. Three separate aluminum heaters on the backside of the beam allow for independent uniform heating of three 10 mm long regions, with fluid pre-heating reduced when only the center heater is used. Sixteen doped single crystal silicon temperature sensors are also fabricated on the backside of the beam. The crystallographic dependence of the piezoresistive coefficient in p-type silicon [10] can be used to separate temperature and pressure effects, with sensors alternating between the <100> and <110> orientation. Initial temperature profiles at flowrates up to 0.25 ml/min and heat fluxes up to 78 W/cm² are presented.

NOMENCLATURE

\( D_h \) – hydraulic diameter [m]  
\( h \) – convective heat transfer coefficient [W/m²K]  
\( T \) – temperature [°C]

DESIGN

A single microchannel structure is fabricated for visualization of two-phase water flow under uniform heat flux with integrated temperature sensing. A schematic of the structure is shown in Fig. 1. The 400 µm wide, 525 µm thick, 32 mm long beam is suspended between two 15 mm by 15 mm pads. The beam has a single 100 µm hydraulic diameter microchannel on the top side and heaters and temperature sensors on the back side. Fluid enters and exits the channel through inlet and outlet regions which are 100 µm deep and 1 mm wide.

![Figure 1. Schematic test device showing suspended microchannel with inlet and outlet reservoirs.](image)

Three aluminum heaters are distributed along the backside of the beam for independent heat flux application. Each heater consists of a 2.3 µm thick aluminum film patterned in a 10 cm long and 12 µm wide serpentine fitting within a 1 cm by 400 µm area. The heaters have a nominal resistance of 100 Ω. At 31.6 V, each heater delivers 10 W for a heat flux into the silicon beam of 250 W/cm².

Four diffused silicon temperature sensors are located within the area of each heater serpentine, two with the current path oriented parallel to the channel and two with the current path oriented at 45° to the channel. Each sensor, formed through ion implantation of single crystal silicon, has a nominal resistance of 8 kΩ at room temperature. In addition to the 12 sensors along the beam, two sensors are located under the inlet region and two under the outlet region. The inlet sensors and a section of one heater serpentine are shown in Fig. 2.

![Figure 2. Sensor layout under inlet and a portion of the first heater serpentine. The current path in the left-most sensor is oriented in the <110> crystallographic direction, which is parallel to the wafer flat and channel. The current path in the other sensor is oriented in the <100> crystallographic direction.](image)

The temperature difference between the backside sensors and the microchannel wall depends on the convection coefficient for heat transfer between wall and fluid, the heat loss to the ambient, and the heat loss to axial conduction in the beam. To determine the effect of the convection coefficient for heat transfer between wall and fluid, a finite element simulation of the temperature profile in the cross-section of the beam is performed using FEMLAB [11]. A silicon block 400 µm wide and 525 µm thick contains a square channel with a 100 µm hydraulic diameter. The top of the channel is sealed with a 525 µm thick piece of Pyrex. In this simulation, the aluminum heater serpentine dissipates a total power of 1 W/cm, equal to 0.1 W/cm in each of the 10 legs. This total power corresponds to 25 W/cm² heat flux into the silicon beam. For the 2D simulation, all boundaries except the microchannel walls are adiabatic, with the inner surface of the microchannel having convection coefficient \( h \). The temperature profile in the 2D beam cross section for a typical single and two-phase coefficient of \( h = 50,000 \) W/m²K is shown in Fig. 3.

Based on the 2D simulation, the predicted ratio of the temperature difference between sensor and microchannel wall to the temperature difference between wall and fluid is shown in Fig. 4 for channel hydraulic diameters from 50 µm to 200 µm. With adiabatic boundary conditions and convection coefficients below 40,000 W/m²K, the temperature difference between the sensor and the microchannel wall is less than 10% of the temperature difference between the wall and the fluid mean. In this situation, the sensor temperature is a good approximation of the wall temperature. However, if the convection coefficient is greater than 40,000 W/m²K, the...
temperature difference between sensor and microchannel wall must be accounted for.

The 2D simulation neglects heat losses from natural convection on the external surfaces and axial conduction along the silicon. Experimental results for 1 W of applied power to the center heater suggest these losses to be greatest at the edge of the heated region. The magnitude of losses due to convection is at most 15%. The magnitude of losses due to axial conduction is at most 11%. These combined effects lead to at most a 26% reduction in temperature difference between wall and fluid. The ratio comparing the temperature difference between sensor and wall to the temperature difference between wall and fluid thus increases by at most 35%. If the 2D simulation underestimates this ratio by 35%, then only for convection coefficients below 25,000 W/m²K is the temperature difference between the sensor and the microchannel wall less than 10% of the temperature difference between the wall and the fluid mean.

In addition to a temperature coefficient of resistance, doped silicon resistors have a crystallographic orientation dependent piezoresistive coefficient that can be used to separate temperature and pressure effects. Fixturing or pressure differences between the channel and the ambient can cause stress in the glass and silicon. This stress will be perpendicular or parallel to the channel. The sensors with current flow parallel to the channel are oriented along the <110> crystallographic plane. In the p-type silicon, parallel or perpendicular stress causes a change in resistance. The sensors with current flow at a 45° angle to the channel are oriented along the <100> crystallographic plane and, because they are formed from p-type silicon, have piezoresistive coefficient equal to zero [10]. Using these two orientations, temperature and pressure effects on the resistive sensors can be decoupled.

FABRICATION

Fabrication begins with a 4-inch, N-type, <100> orientation, double side polished silicon wafer which is 525 µm thick and has resistivity of 5-10 ohm-cm. The fabrication process is shown in Fig. 5. The first step is formation of the resistive sensors, as shown in Fig. 5(a). The sensors are implanted with boron, then diffused and activated in a 950 °C wet oxidation that grows 225 nm of oxide on the surface. Next, the heaters and sensor contact pads are fabricated, as shown in Fig. 5(b). Vias are opened through the oxide to allow electrical contact between the resistors and the 2.3 µm film of sputtered 99% aluminum/1% silicon. Contact pads and heater serpentines are plasma etched into the aluminum, and a forming gas anneal at 400 °C completes the contact. The aluminum layer is then covered with 200 nm of LPCVD oxide, which is etched to expose the contact pads but protect the heaters.

Upon completion of the heaters and sensors, the 100 µm channel and inlet and outlet reservoirs are etched into the wafer frontside using DRIE, as shown in Fig. 5(c). After bonding the device wafer to a support wafer with photosist,
the structure is released from the wafer by a through wafer etch using DRIE from the backside, which also opens 1 mm by 1 mm holes to the inlet and outlet reservoirs, as shown in Fig. 5(d). Finally the device wafer is anodically bonded to a 525 µm thick Pyrex 7740 piece to seal the channel as shown in Fig. 5(e). An image of the final structure is shown in Fig. 6.

EXPERIMENTAL SETUP

Fluidic ports are glued to the inlet and outlet holes for connection to 1/16" Tygon tubing. A syringe pump (KD Scientific 100) is fitted with a 3 cc Monoject syringe which delivers degassed water through a 0.1 µm filter and into a flow meter (Omega FLR-1602A) which monitors flowrate, fluid inlet temperature, and line pressure. Feedback from the flow meter is used to manually adjust the pump to achieve nominal flowrates with +/- 0.02 ml/min uncertainty. An additional pressure transducer (Omega PX4100) is inline downstream of the flow meter, near the chip inlet, to verify the line pressure. The outlet tubing is open to the air. Gold-plated surfboards are attached to the back of the device and wirebonds connect the heater and sensor contact pads to the surfboard pads.

The data acquisition system consists of a PC, a 16-bit 64-analog-input DAQ card, and signal conditioning circuitry. The data acquisition is controlled through LabVIEW.

EXPERIMENTAL RESULTS

Preliminary measurements with power applied to the central heater verify the operation of this microchannel experimental structure. First, calibration is performed on each sensor to find the temperature-resistance dependence. Then, temperature profiles are obtained under flowrates up to 0.25 ml/min and heat fluxes up to 78 W/cm².

Temperature calibration of the sensors is performed in a convection oven. A single device is placed in the oven with a reference thermocouple. Applied current and voltage drop across each resistor on the sample are recorded to calculate a sensor resistance value correlated with the temperature recorded on the thermocouple. Within the measured range of 20 °C to 115 °C, the thermocouple is accurate to ± 3 °C. The temperature-resistance curves are each fitted with a second order polynomial. Fig. 7 shows typical temperature-resistance data and the fitting curves for <100> and <110> oriented sensors. The sensitivity for <100> sensors is between 1.3 Ω/°C and 8.7 Ω/°C, depending on temperature, and the sensitivity for <110> oriented sensors is between 5.8 Ω/°C and 10.0 Ω/°C. The <110> sensors have a more linear dependence of resistance on temperature than the <100> oriented sensors. Circuit noise in the voltage divider, including temporal stability of the power supply (Agilent E3631A) used to bias the sensors, dominates precision error in the measurements with uncertainty between 1 and 3%.
Figure 7. Typical temperature sensor calibration curves showing measured data and second order polynomial fits. In determining temperature fields, calibrations for each individual sensor are used to convert measured resistance into temperature.

Temperature profiles obtained under power application to the heater can be related to heat flux in two ways. The total power delivered by the heater gives rise to a heat flux into the silicon beam equal to the heating power divided by the beam area encompassed by the heater. The heat flux into the channel itself is the total power per unit length divided by the wetted perimeter of the silicon. The Pyrex wall is neglected because the low thermal conductivity of the Pyrex means most of the heat enters the channel through the silicon, as can be seen in the simulated temperature profile in Fig. 3. Because the remaining three walls of the 100 µm channel have an area 75% of the area of the backside of the beam, heat fluxes into the channel are at most 33.3% higher than the heat fluxes into the beam, with the maximum occurring at minimum axial heat conduction and environmental loss. Axial and environmental losses are expected to total 26% of the power at 1 W.

Figure 8 shows the temperature distribution along the channel at constant flowrate of 0.1 ml/min when 0.27 W to 1.09 W is dissipated by the center heater only. These heater powers correspond to a heat flux into the silicon beam of 6.8 W/cm² to 27.3 W/cm² and a maximum heat flux into the channel of 9.0 W/cm² to 36.3 W/cm². Water in the unheated entrance region of the channel is preheated by axial conduction in the silicon, leading to greater than ambient temperatures before the heated region. At higher heat flux, the pre-heating is also observed visually as boiling in the inlet plenum. The temperature rises through the heated region, then falls past the heated region due to axial conduction in the silicon. Boiling is first observed visually at 1.09 W. Visualization of slug flow during eruptive boiling is shown in Fig. 9. Comparison of <100> and <110> oriented sensor measurements illustrates the absence of measurable steady-state pressure effects at 0.1 ml/min flowrate and 0.27 W of applied power, as shown in Fig. 10.
Figure 10. Simultaneous temperature measurements using <100> oriented sensors and <110> oriented sensors at 0.1 ml/min flowrate and 0.27 W applied to center heater. Measurements indicate no measurable pressure effect at this flowrate and heat flux.

Figure 11 shows the temperature distribution along the channel at constant flowrate of 0.25 ml/min when 0.66 W to 3.12 W is dissipated by the center heater only. This applied power corresponds to a heat flux into the silicon beam of 16.5 W/cm² to 78 W/cm² and a maximum heat flux into the channel of 22 W/cm² to 104 W/cm². The onset of boiling in the channel occurs at 3.12 W, as determined from visual inspection. Due to the higher flowrate than in Fig. 8, the fall in temperature occurs farther from the heater than for a flowrate of 0.1 ml/min.

Figure 11. Temperature profile along channel at flowrate of 0.25 ml/min and input heater power between 0.66 W and 3.12 W.

The pressure response of the sensors can be measured by applying a reference pressure to a sealed channel and measuring the change in sensor resistance. No change in resistance of these sensors of either orientation is observed for static pressures between 0 and 20 psi. Zhang et al. [9] measured pressure sensitivity of -1 to -2 Ω/psi on similar sensors, but no effect is observed here. However, such an effect could be expected in future generation devices with a thinner beam or fixture clamping, both of which may induce larger strains in the sensors.

CONCLUSION

A single microchannel experimental structure has been developed for measuring temperature fields during convective boiling. The structure has three independent heaters in series along the 30 mm channel, although use of the center heater does not fully eliminate fluid pre-heating in the inlet plenum 10 mm away. Sixteen sensors, each with current flow directed in one of two crystallographic orientations, are used to measure the temperature profile. The two orientations will allow decoupling of temperature and pressure effects on the doped silicon resistors. The difference between the sensor temperature and the microchannel wall temperature is less than 10% of the temperature difference between the wall and the fluid for convection coefficients less than 25,000 W/m²K, taking into account the maximum axial and environmental losses. Under single and two-phase flow, temperature along the channel is seen to rise in the heated region, falling past the heated region due to axial conduction in the walls. Visual inspection of the flow through the Pyrex cover allows determination of the onset of boiling. Future optical measurements and pressure independent temperature measurements on these samples will provide information about transient boiling convection in microchannels and will aid with model development [12].

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