FEDSM-ICNMM2010-31147

POOL BOILING HEAT TRANSFER AND BUBBLE DYNAMICS OVER PLAIN AND ENHANCED MICROCHANNELS

Dwight Cooke*, Satish G. Kandlikar Department of Mechanical Engineering Kate Gleason College of Engineering Rochester Institute of Technology Rochester, NY, USA *DAC9669@rit.edu

ABSTRACT

Pool boiling is of interest in high heat flux applications because of its potential for removing large amount of heat resulting from the latent heat of evaporation and little pressure drop penalty for circulating coolant through the system. However, the heat transfer performance of pool boiling systems is not adequate to match the cooling ability provided by enhanced microchannels operating under single-phase conditions. The objective of this work is to evaluate the pool boiling performance of structured surface features etched on a silicon chip. The performance is normalized with respect to a plain chip. This investigation also focuses on the bubble dynamics on plain and structured microchannel surfaces under various heat fluxes in an effort to understand the underlying heat transfer mechanism. This work is expected to lead to improved enhancement features for extending the pool boiling option to meet the high heat flux removal demands in electronic cooling applications.

INTRODUCTION

During pool boiling, the latent heat involved with the phase change from liquid to vapor becomes significant in the heat removal process. The substantial increase in the heat transfer coefficient allows for pool boiling being a candidate for cooling applications in high powered electronics. It is a technique that does not require any moving parts and is highly effective from both the thermal and cost perspectives.

It is of great importance to fully understand the boiling phenomenon – failure to know the limitations of a particular surface could lead to dryout and critical heat flux (CHF) condition, which leads to a dramatic rise in wall temperature, decreased heat transfer, and possible material failure. Therefore, the mechanisms and behavior of bubble nucleation, growth, as well as the rewetting of the surface attract the interest of researchers.

Since the early scientific studies of Nukiyama [1], boiling has attracted the attention of many researchers. Early pioneers such as Rohsenow [2] and Cooper [3] have generated correlations for the heat flux and wall superheat in nucleate boiling.

Bubble nucleation has received much attention in an effort to explain how and where bubbles will nucleate. Early on, it was noticed that the wall superheat must be greater than the saturation temperature of the fluid. Hsu and Graham [4] and Hsu [5] developed the criterion for the onset of nucleation over active cavities. They found that the maximum and minimum possible active cavity sizes were functions of subcooling, pressure and the length of the thermal boundary layer. Since the heat transfer in pool boiling is intimately associated with the contact line and interface movements, microscale surface modification of the heater surface is expected to directly affect the heat transfer phenomena.

In recent years, many researchers have focused on surface enhancements to promote bubble nucleation and increased heat transfer. Mitrovic and Hartmann [6] created a micropin surface, with elements that were cylindrical in shape, some with a torospherical top. Conducting tests in a pool of R141b, they used various pin diameters $(0.8 - 23 \ \mu\text{m})$ and densities $(450 - 90,000 \ \text{pins} \ \text{per mm}^2)$. They found the microstructures effectively increased the heat transfer capabilities compared to the smooth surface. Similarly, Honda and Wei [7] used square pin fins on silicon chips immersed in subcooled FC-72 to observe the effects of pin size and height on heat transfer. The authors concluded that the fins enhanced the maximum heat flux by 4.2 times while maintaining the chip temperature below 85°C.

To evaluate the performance of various cavity and reentrant cavity geometries, Das et al. [8] used wire EDM to create tunnels in a copper block. These tunnels were inclined or normal to the heating surface, had rounded, rectangular, or circular bases and were parallel or orthogonally intersecting as well. For the nucleate pool boiling with distilled water, the authors concluded that tunnels inclined from the surface had higher heat transfer compared to ones normal to the surface. The same was true for the circular reentrant cavities, as well as for the orthogonal intersecting tunnels.

As a non-intrusive technique, high speed cameras have been employed with increasing use in recent years. Siedel et al. [9] used high speed imaging of pentane boiling to observe bubble interactions between nucleation sites. In their study, a copper plate was indented with a 180 µm diameter cavity for single bubble studies, and a second cavity was added to observe multiple bubble interactions. It was found that the bubbles produced were not spherical, so instead of bubble departure diameter, bubble departure volume was used for characterization. When bubble coalescence occurs, the microlayer under the bubbles is eliminated due to capillary forces, and is not responsible for an increase in vapor generation. The authors found the bubble frequency is proportional to the wall superheat.

Zhang and Shoji [10] conducted experiments with artificial cavities, imaging the interactions between nucleating bubbles. By changing the separation between the 10 μ m diameter cavities, the authors concluded that there are four categories for ratios of separation to bubble departure diameter. As the separation to departure diameter decreased, the departure frequency was influenced by first the hydrodynamic interaction between bubbles, the thermal interaction between sites next, and lastly by the horizontal and declining coalescences.

Using microchannel meshes created out of silicon, Ramaswamy et al. [11] conducted a parametric study, focusing on varying pore size, pitch and height. In an effort to study the bubble departure diameter, growth rate, frequency and site density from a porous layer, a 3D structure was used for boiling enhancement. The 3D structures were composed of two layers of microchannels, 0.51 mm thick, positioned 90° from one another. The authors obtained boiling curves for different pore sizes, pore pitches, and stack heights. The enhancements caused by stacking multiple structures was found to only have a significant effect at low wall superheats, diminishing at higher temperatures. It was thought that this could be because of a fin effect as height increasing the pore size, or decreasing the pore pitch increased the heat transfer.

Using a similar structure as used by Ramaswamy et al. [11] but from copper and quarts, Ghiu and Joshi [12] visualized confined pool boiling with various channel widths but with the same pitch. The 3D structure was fabricated to be 1 mm thick. By placing a quartz top cover, they were able to visualize the liquid-vapor dynamics within the microchannels. They observed a pattern of oscillations for the vapor slugs in the top and bottom channels due to the evaporation of the liquid and rewetting of the heated surface. They found that there was better performance when testing the structures without the quartz top, compared to when the surfaces were confined with the top. The authors determined that heat transfer performance only has a slight dependence on channel width.

Observing the effects of surface enhancements, Launay et al. [13], tested the heat transfer capabilities of numerous silicon surfaces. These included smooth, rough, carbon nanotube (CNT) coated surfaces, pin fin surfaces, as well as 3D structure surfaces with and without CNTs. These microchannel surfaces were of the same design as [12] with a 10mm x 10mm surface, but only 500 μ m thick. The tested the surfaces using FC-72 and deionized water. The results from the experiments were that the 3D microchannel structures performed the best, and the addition of CNTs only slightly improved the heat transfer, and this was only at the lower superheated wall temperatures.

Gorenflo et al. [14] sandblasted as well as machined 200 x 100 μ m cavities on the surface of copper horizontal tubes and tested propane and 2-propanol as the working fluids. Using high speed video, they looked at the size and number of bubbles that nucleate from active sites.

Other researchers have focused on enhancing boiling by creating cavities on the surface, through a variety of means using slurries [15, 16], emery cloth and sandblasting [17-19], and electrical discharge machining (EDM) [20]. Kandlikar and Steinke [16] studied the advancing and receding contact angles of water droplets impinging on heated surfaces of various roughness. Using a high speed camera they concluded that the contact angles have a dependence on surface roughness, and the vapor cutback phenomenon is responsible for the initiation of CHF.

Hübner and Künstler [17] investigated the heat transfer enhancement with trapezoidal, T-shaped, and Y-shaped fins. They also investigated the effects of surface roughness on these structures using sandblasting or emery paper techniques independently. It was found that trapezoidal fins only increased bubble formation because of a very rough top surface (artifact from machining). However, the T- and Y-shaped fins were responsible for increasing the heat transfer coefficient significantly.

Surface roughness on horizontal tubes has been studied extensively by Luke [18, 19]. Using emery cloth and sandblasting [18] as well as milling the surface [19], it was concluded that an increase in pressure will decrease the effects of surface roughness during boiling. The author also evaluated the 3D surface profiles of the surfaces. It was determined that large cavities are the most advantageous for bubble nucleation to begin.

The objective of the present work is to evaluate the heat transfer capabilities of different surface geometries on a silicon chip in pool boiling. Through the use of a high speed camera and quantitative data, the nature of nucleate boiling on the various surfaces will be identified.

NOMENCLATURE

k _{Cu} ,k _{Si}	thermal conductivity, W/mK
L _{Cu} , L _{Si}	length of copper, length of silicon, m
q"	heat flux, W/m^2
R" _{t,c}	thermal contact resistance, m ² K/W
T _{sat}	temperature, K
х	distance, m
ΔT_{sat}	wall superheat, K

EXPERIMENTAL SETUP

An experimental setup was designed and built to allow testing of different plain and enhanced silicon chip surfaces. Figure 1 shows an overall schematic of the test setup. To apply heat flux to the test section, a 450 W capacity cartridge heater was inserted into a copper block to serve as the heating element. The copper block was machined to have a 10 mm x 10 mm tip which was 25 mm long. Three K-type thermocouples, each spaced 8 mm apart, were used to measure the temperature gradient through the tip of the copper block. The heat flux was then calculated as:

$$q'' = -k_{Cu} \frac{dT}{dx} \tag{1}$$

The temperature gradient, $\frac{dT}{dx}$ was calculated using a threepoint backward space Taylor Series approximation:

$$\frac{dT}{dx} = \frac{3T_1 - 4T_2 + T_3}{2\Delta x}$$
(2)

At the top of the boiling pool, a 100W auxiliary heater was used to keep the water at the saturation point. A fourth thermocouple is placed in the water reservoir to measure the bulk water temperature, ensuring that the tests are conducted at saturation temperature. An NI-cDaq-9172 data acquisition system was used in conjunction with a NI-9213 card to record the temperatures during testing. A LabVIEW virtual instrument (VI) was created to display temperatures, determine when the system reached a steady-state, and record the data.

A Keyence® high speed digital camera was used to image the boiling phenomena at an angle of 15°. The camera was inclined at this angle so that nucleation at the heated surface could be clearly viewed. The high speed color camera has frame rates capable of 24,000 frames per second. In order to keep resolution satisfactory, slower frame rates of 1000 - 2000 frames per second were employed.

For the tests, a layer of conductive, polysynthetic silver thermal paste was used to decrease the contact resistance between the copper block and silicon chip. Screws with springs underneath the caps were placed on both sides of the chip, and were compressed, so the force applied between the chip and the copper block for each test was consistent. Contact resistance was quantified, as discussed in a later section.

For every test, distilled water was used to ensure it was free from contaminants. Water is chosen because of its well known fluid properties and the minimal risk associated with handling the fluid, compared to a refrigerant. Prior to each test, the water was boiled sufficiently in order to reduce the effects of any dissolved air within the fluid. Periodically between the tests, more water is added to the pool to replenish the evaporated water vapor. The water is allowed to reach steady-state before any data is collected. The pool was filled with new distilled water prior to the next test.



Figure 1. Schematic of boiling test fixture (a) cartridge heater (b) copper heating block (c) insulating block (d) silicon test chip (e) gasket (f) polycarbonate visualization tube (g) high speed camera (h) auxiliary heater (i) compression screws (j) compression screws (k) data acquisition with 4 K-type thermocouples

CONTACT RESISTANCE

Thermal contact resistance was a factor in the test setup. Due to small asperities between the copper heating block and the silicon chip, a layer of thermal paste was applied to decrease the contact resistance. To ensure that the pressure between the surfaces was constant for each test run, compression screws with springs were used to provide the same amount of force between the test chip and the heating block.

A test piece was fabricated out of copper in order to help measure the contact resistance of the setup. This block was machined to have the same outer dimensions as the rest of the test chips, but had a square channel 1 mm wide cut around the area of the heater. This was done in order to keep the heat transfer through the block one dimensional, preventing any two dimensional or fin effects from the highly conductive copper. A thermocouple hole was machined into the center of the chip to measure the temperature in the chip, so that the contact resistance could be back calculated.

Sandwiched between the copper chip and the copper block is a silicon chip of the same area as the heater. This layer helps to provide the same conditions for the contact as in actual testing: a copper-thermal paste-silicon combination. Inserting two layers of thermal paste (one on each side of the silicon) allows for a more accurate measurement of the contact resistance because it is averaged between the two sides. A schematic of the contact resistance test setup and the equivalent thermal circuit are shown in Fig. 2.



Figure 2. (a) Schematic of copper chip setup for contact resistance calculations (not to scale) (b) equivalent thermal circuit for 1-D heat conduction analysis

Tests were run, recording temperatures from thermocouples T_1 and T_4 , while also recording the heat flux. The contact resistance was then calculated:

$$R_{i,c}^{"} = \frac{1}{2} \left(\frac{T_1 - T_4}{q''} - \frac{L}{k} \Big|_{Cu,1} - \frac{L}{k} \Big|_{Si} - \frac{L}{k} \Big|_{Cu,2} \right)$$
(3)

The contact resistance was found to be repeatedly 5 x 10^{-6} m²K/W, with an uncertainty of less than 4 percent. Using this contact resistance, the surface temperature of a test chip can be calculated using the heat flux through the copper block, as well as the thermocouple T₁ from the following relation:

$$T_{s} = T_{1} - q'' \left(\frac{L_{Cu}}{k_{Cu}} + R_{t,c}^{''} + \frac{L_{Si}}{k_{Si}} \right)$$
(4)

TEST CHIPS

The purpose of this experimental study is to determine the effects of various microstructures on the pool boiling performance on a silicon chip. Table 1 describes the microstructure details of the five chips that were tested using the pool boiling test fixture. These chips were fabricated by the IBM T.J. Watson Research Center using a deep reactive ion etching method (DRIE). This technique has become a common method of micromachining silicon wafers, and is effective at

removing areas off the surface of the silicon, while retaining near vertical sidewalls.

Each silicon chip has overall dimensions of 20 mm x 20 mm with the heated micromachined area of 1 cm x 1 cm. For each of the etched chips, the area was etched to a depth of 180 μ m. In this study, 5 different categories of etched chips were used. A plain surface, three different microchannels and an offset strip fin (OSF) design were used for boiling testing and visualization. One of the microchannel designs is repeated; chip D has the same microchannel design as chip E, but with a substantially deeper etch depth. Three of the chips have a vertical notch spaced evenly along the sidewall of the channel, and is detailed in a later section. An overall schematic of the etched silicon chips are shown in Fig. 3. This selection of chip designs has been used to evaluate the effects of microchannels and fins during the boiling process, as well as evaluating the effects of cavities incorporated into the chip design.

Name	Туре	Channel	Fin	Depth	Notched
		(µm)	(µm)	(µm)	
A	Plain	N/A	N/A	0	No
В	Microchannel	200	200	208	No
С	Microchannel	200	200	192	Yes
D	Microchannel	100	100	275	Yes
E	Microchannel	100	100	182	Yes
F	OSF (fins 500 μm long)	40	60	180	No



Figure 3. Example of etched silicon chip with heated area boxed

Using a Keyence[®] laser confocal microscope, chip dimensions and parameters were quantified. The average roughness of the plain chip was determined to have a R_a value of 0.030 μ m. Chips that have been DRIE etched have an R_a value of 0.470 μ m on the bottom surface.

Figure 4 shows the detail of the chips. Figures 4(c) and 4(d) show that for chips C, D, and E, there is a rectangular notch along the walls of the microchannel spaced every 100 μ m. These are vertical notched tunnels on the sidewalls of the channels. Each of these cavities is 10 μ m wide by 20 μ m deep into the channel wall. It was postulated that providing the fluid with a location, surrounded by walls on three sides would

enhance the heat transfer by providing possible nucleation sites. This would allow for a large number of effective sites, allowing for several active sites during the boiling process. Although the chips were intended to have rectangular channels, the etching process produced channels more rectangular in shape. As part of an earlier study using similar chips, an SEM image from Steinke and Kandlikar [21] is shown in Fig. 4(f). Actual channel dimensions for each chip are listed in Table 1.



Figure 4. (a) – (e) Surface images of chips used at 20x magnification (f) example of a 250 µm deep channel cross section taken from [21]

RESULTS

Six silicon chips described in Table 1 were tested with distilled water as the working fluid. Independent power supplies provided electrical power to each of the cartridge heaters (main and auxiliary). The main cartridge heater for the copper heating block was taken up to a high heat flux, greater than 100 W/cm². Power was decremented in a stepwise fashion, until nucleate boiling ceased to occur. The power was then stepped up incrementally to higher heat fluxes, but before CHF occurred. Testing was not conducted to CHF condition to avoid damage to the setup. At each step, the system was allowed to reach steady-state, where the thermocouples did not fluctuate. Also, when the system reached steady-state, the high speed camera was used to capture images of the boiling process.

Figure 5 shows the results of the boiling tests for each chip. The heat flux is based on the projected base area. The wall temperature was calculated as the temperature at the top surface of each chip. The results shown are from the data points in which the power was increased. The data with decreasing power do not show any hysteresis effects, and follow the increasing curves very closely.

All of the chips show an increase in performance compared to the plain chip, A. The OSF chip enhances the heat transfer, but not as much as either of the 200 μ m channel chips, with the deep etched 100 μ m channel chip (chip A) performing the best. Interesting to note is the lack of any significant improvement with the introduction of the nucleation sites, which is seen with the 200 μ m channels.



Figure 5. Boiling curves for chips A-F listed in Table 1 based on projected base area

It is clear from Fig. 5 that more heat can be dissipated through the etched chips (B-F) compared to the plain (chip A) for the same wall superheat. However, there may be two reasons for this enhancement: (i) the increased surface area of the etched chips allows for more heat transfer area and (ii) the structure of the chips affects the mechanics of bubble dynamics in pool boiling through interface motion within the microstructures.

For each of the different chips, there are different boiling curves. However, it is difficult to discern whether the enhancement is due to the added amount of surface area that is produced after the surface modification. The increase in area for the etched surfaces promotes an increase in heat transfer because it allows for more convection from solid to liquid as well as providing an increase in the number of possible nucleation sites. Therefore it is beneficial to evaluate the surfaces for the heat flux applied to the chips, but normalized to reflect the area over which the fluid contacts the surface. Using this parameter, the surfaces can be compared by the surface geometries, rather than the solely the increase in area.

Figure 6 shows the boiling curve for the chips, with the heat transfer normalized with respect to the wetted surface area of the heated surface. Since there is no area enhancement in the plain chip, A, the curve remains unchanged. For the etched

chips, the curves are shifted lower by the ratio of the base area to the wetted surface area. At low superheats, all of the etched chips performances fall below the plain chip. At higher wall superheats the 200 µm wide microchannel chips B and C show improvement over the plain chip. By the nature of the curve, it appears that at higher heat fluxes, chip D would follow the same path. However, it is not clear that Chip E would perform better than the plain chip at higher values. Chip F, with the substantial increase in surface area with 1600 fins, the heat flux for a given wall superheat is always lower than the plain chip.

Comparing the data from Figs. 5 and 6, it is clear that the increase in surface area has some effect on why the etched chips show enhancement in heat transfer. For chips E and F, an increase in heat transfer is due solely to the increase in area. For chips B and C, the increase in area is responsible for the enhancement at low wall superheats. At the higher wall superheats, there is an increased heat transfer performance, despite normalizing the area. This means that there is an enhancement mechanism at work as well, with the geometry of the etch having an effect. Chip B has slightly better improvement over chip C which shows that the increase in area in the rectangular etched sites along the channel walls do not have any significant effect. Increasing channel and fin widths shows an increase in heat transfer despite increasing the area of the chip.

Comparing the data between chips D and E, with similar geometries, chip D can dissipate more heat for a given wall superheat. This is attributed to the depth of etch on each of the surfaces. Applying heat to the bottom surface of the chip, the chip with the deeper etch will have a greater temperature at the floor of the microchannel. In this way, the required superheat for bubble nucleation will be met first with chip D, allowing for a greater amount of active nucleation sites. Due to the increase in activation sites, there will be an increase in heat transfer for the chip, due to the associated latent heat flux.



Figure 6. Boiling curve for each of the chips tested with the heat flux normalized to the surface area

Figure 7 shows the boiling curve from the study of Ramaswamy et al. [22], comparing four silicon structures. The naming convention for the structures S-XX-YY-Z describes four parameters, each separated by a dash. The order is S, the material (in each case silicon) – XX, the channel width in millimeters – YY, the channel pitch in millimeters – Z, the type of etch used for micromachining (dry or wet). They used pore size as the defining geometrical parameter, which is the square through hole which results when the microchannels intersect. The pore size is equivalent to channel width.

Although several researchers have used a similar structure for enhanced boiling [11-13, 22, 23], the performance of the structures was evaluated with respect to the pore size. However, a more basic parameter is the channel width and channel pitch. Figure 7 shows that for a particular channel width, the heat transfer ability is increased when the width is increased from 150 μ m to 200 μ m. Also, reducing the channel pitch also increases the heat transfer performance from the structure.



Figure 7. Boiling curves from Ramaswamy et al. [22] for FC-72 on various surfaces



Figure 8. Boiling curves from Ramaswamy et al. [22] for FC-72 with the heat flux normalized to the surface area

Normalizing the data from Fig. 7 to the surface area of the structure, Fig. 8 shows similar trends. At low wall superheats, there is little difference between the structures. At the higher superheats, the structures start to deviate from each other, following the same pattern as from Fig. 7. The smaller the channel pitch, the greater the heat transferred. The larger the pore size, the greater the heat transferred. The structure with the poorest performance is the one with smaller pore size and larger pitch, S-0.15-1.4-D.

BUBBLE GROWTH

The bubble nucleation and growth in microchannel surface were investigated with high speed camera. Figure 9 shows a nucleation event on chip C at a low heat flux of 18 W/cm^2 , with images on the left and a representation of the image on the right. The depictions on the right show an enlarged nucleating bubble for clarity. In Figure 9(a) the white arrow points to a bright point on the bottom surface of the microchannel. This point is a small vapor bubble. After the bubble reaches the top of the channel in Fig. 9(c), it experiences rapid growth on top of the land between the two microchannels Fig. 9(d). The bubble then departs off the surface after it has grown to a considerable size.

The motion of the bubble is remarkable in that it moves from a location at the bottom of the microchannel to the top of the fin where it attaches itself to the surface and then grows. It is not known whether it moves vertically up the channel wall or up within one of the vertical notches. Since the base of the microchannel is closer to the source of the heater, there would be a greater temperature at the base than at the top, even if that difference is small. Also, the etched section of the chips has a roughness that is greater than the portions that have not been etched to provide more nucleation sites. The individual frames of the other videos show the nucleation activity similarly. Bubbles have rapid growth at the top of the microchannels. Videos show that there is water flooding the channel. If indeed all bubbles on these surfaces nucleate in this way, liquid dryout of the surface would only pertain to the tops of the walls, leaving evenly distributed dry and flooded areas. This may decrease the amount of localized hot spots, which occur under vapor bubbles on the surface. Also, this provides two different areas that are influenced by the bubble activity.

Figure 10 shows the boiling sequence of bubble growth on chips B and E at heat fluxes of 97 W/cm² and 93 W/cm², respectively. At these higher heat fluxes, much vapor is generated at the top of the fin surface leaving microchannels open to liquid supply. For the chip with microchannels etched onto the surface, the areas in which the fluid evaporates remains relatively in the same place. However, chip E has moving vapor fronts. Similar events have been noted by other researchers [20], although only for smooth surfaces. This is equivalent to periods of evaporation, followed by periods of the fluid rewetting the surface. This trend is not seen at lower heat fluxes in which the boiling regime is characterized by isolated bubbles. When there are isolated bubbles, there is a substantially longer waiting period for nucleation, and it





(a) time = 0 ms: nucleation on the bottom surface



(b) time = 2 ms: bubble movement to channel sidewall



(c) time = 5 ms: bubble movement to the top wall of channel



(d) time = 8 ms: bubble growth on the top wall of channel Figure 9. Successive images of bubble nucleation on chip C at 1 ms intervals

decreases as the heat flux is increased. At high heat fluxes, there is much more vapor generated. Chips A and E experience the vapor generation, with nucleation occurring at various active sites. For the chips with microchannels, B, C, and D, the microchannels provide efficient pathways for the water to reach the nucleation sites for evaporation, without the vapor becoming detached from the heated surface. This allows for consistent boiling, with little waiting time between successive bubbles.

Chip B



Figure 10. Successive images at 2 ms intervals of boiling at high heat fluxes for chips B (a - d) and F (e - h)

HEAT TRANSFER MECHANISM

Based on the high speed video observations from Figs. 5 and 6 as well as heat transfer data from Figs. 9 and 10, the mechanism responsible for this improvement in heat dissipation by the silicon chip can be postulated. Fig. 5 shows that an enhanced surface has the ability to augment the boiling curve from the plain chip. Etched surfaces and in particular deep etched surfaces can improve the heat transfer capabilities. A carefully chosen geometry can further improve the boiling curve, so that the enhancement is not achieved by merely the increase in area, but by a hydrodynamic mechanism.



Figure 11. Proposed mechanism of bubble dynamics on a microchannel surface (not to scale)

Figure 11 shows the schematic of the vapor generation and liquid transport mechanism on a heated surface with microchannels, with several nucleation sites. As shown in Fig. 9, the majority of bubble growth does not occur within the channel. The bubbles grow after they become attached on the top surface of the microchannel walls. Due to the structure of the microchannels beneath it, large amounts of vapor generation do not dry out the channels. Instead, the channels remain flooded, which provide pathways for the water. With water in the channels, a supply of liquid is brought to the nucleation sites and liquid is evaporated at the liquid-vapor interface. This does not allow for an excessive localized wall superheat because most of the heated area is in contact with the liquid. The liquid flow within the microchannels results in a very high heat transfer coefficient due to the small hydraulic diameter of the passages. This mechanism in reducing the wall superheat along with the efficient water pathways available in microchannel passages helps to stave off the CHF condition and serves as an efficient nucleate boiling surface. This description also explains why the offset strip fin geometry did not perform as well. Due to the configuration of the fins the movement of liquid throughout the microstructure was impeded and hindered performance.

CONCLUSION

Pool boiling of water at atmospheric pressure on silicon chips with different surface enhancements has been investigated experimentally. A total of six chips, one plain and four micromachined using a DRIE etching method, characterized in Table 1 are investigated. Each test consisted of decreasing power and then increasing power to the heater, recording data for steady state measurements of heat flux and surface temperature. No hysteresis was observed. Each chip with enhancements made to its surface performed better than the plain chip. Chips etched with microchannels prove to have the most enhancement, with the 200 μ m wide, 275 μ m deep channels being the best. After experimental testing the following conclusions have been made from the study:

- 1. Normalizing the heat flux by the surface area of the etched chips shows that the increase in heat transfer for a wall superheat is first due to the area increase. For the offset strip fin chip and 100 μ m wide channel chips, the enhancement along the entire boiling curve is due to this area increase. For the 200 μ m wide microchannel chips, however, at higher wall superheats, an increase beyond area enhancement is seen due to the benefit of the structure of the surface.
- 2. The most efficient boiling surface is one which has microchannels etched onto it, with a larger channel size, and a deep etch. These surfaces have an increased surface area and promote bubble nucleation to create an efficient boiling surface.
- 3. The introduction of 20 x 10 μ m notches in the microchannel did not provide any significant enhancement to the boiling curve. It is postulated that there may not be enough enclosure to act enough as a cavity for nucleation to occur, with nucleation occurring at smaller cavity sizes on the surfaces.
- 4. Bubbles nucleate at the bottom of the channels, before moving to the top wall of the channel where they grow. This allows for an efficient boiling process, with liquid filling the channels and vapor generated above. In the offset strip fin configuration, it seems that the liquid flow to the nucleation site is not as efficient. In fact, the geometry seems to obstruct the liquid flow to the nucleation sites in the passages.
- 5. The proposed mechanism of efficient surface rewetting facilitates the heat transfer enhancement by providing liquid to reach the nucleation sites through microchannel conduits. This allows for evaporation to take place with a method of advantageously rewetting the surface for the transient conduction from the surface to liquid. This is the reason why the surfaces with microchannels have better performance of microchannels as compared to than the offset strip fin configuration.

Future work will be undertaken to study the CHF characteristics of different chip geometries. A new experimental setup capable of withstanding higher temperatures will be

fabricated. This will give insight to the liquid flow mechanisms at the upper limits of operation near CHF condition.

ACKNOWLEDGMENTS

The authors are thankful to Drs. John Magerlein and Evan Colgan of IBM T.J. Watson Center for providing the silicon chips as part of the IBM faculty award to the second author.

REFERENCES

[1] Nukiyama, S., 1934, "Maximum and Minimum Values of Heat Transmitted from Metal to Boiling Water under Atmospheric Pressure," Society of Mechanical Engineers of Japan -- Journal, 37(206), pp. 367-374.

[2] Rohsenow, W. M., 1952, "Method of Correlating Heat-Transfer Data for Surface Boiling of Liquids," American Society of Mechanical Engineers -- Transactions, 74(6), pp. 969-975.

[3] Cooper, M. G., 1984, "Saturation Nucleate Pool Boiling, a Simple Correlation," Proc. First U.K. National Conference on Heat Transfer, 3-5 July 1984, Rugby, UK, pp. 785-93.

[4] Hsu, Y. Y., and Graham, R. W., 1961, "Analytical and Experimental Study of Thermal Boundary Layer and Ebullition Cycle in Nucleate Boiling," National Aeronautics and Space Administration -- Technical Notes, pp. 43.

[5] Hsu, Y. Y., 1961, "On Size Range of Active Nucleation Cavities on Heating Surface," Proc. ASME Meeting WA-177, Nov 26-Dec 1 1961, New York, NY, United States, pp. 7.

[6] Mitrovic, J., and Hartmann, F., "A New Microstructure for Pool Boiling," Superlattices and Microstructures, 35(3-6), pp. 617-628.

[7] Honda, H., and Wei, J. J., 2004, "Enhanced Boiling Heat Transfer from Electronic Components by Use of Surface Microstructures," Experimental Thermal and Fluid Science, 28(2-3), pp. 159-169.

[8] Das, A. K., Das, P. K., and Saha, P., 2009, "Performance of Different Structured Surfaces in Nucleate Pool Boiling," Applied Thermal Engineering, 29(17-18), pp. 3643-3653.

[9] Siedel, S., Cioulachtjian, S., and Bonjour, J., 2008, "Experimental Analysis of Bubble Growth, Departure and Interactions During Pool Boiling on Artificial Nucleation Sites," Experimental Thermal and Fluid Science, 32(8), pp. 1504-1511.

[10] Zhang, L., and Shoji, M., 2003, "Nucleation Site Interaction in Pool Boiling on the Artificial Surface," International Journal of Heat and Mass Transfer, 46(3), pp. 513-522.

[11] Ramaswamy, C., Joshi, Y., Nakayama, W., and Johnson, W. B., 2003, "Effects of Varying Geometrical Parameters on Boiling from Microfabricated Enhanced Structures," Journal of Heat Transfer, 125(Compendex), pp. 103-109.

[12] Ghiu, C.-D., and Joshi, Y. K., 2005, "Visualization Study of Pool Boiling from Thin Confined Enhanced Structures," International Journal of Heat and Mass Transfer, 48(21-22), pp. 4287-4299.

[13] Launay, S., Fedorov, A. G., Joshi, Y., Cao, A., and Ajayan, P. M., 2006, "Hybrid Micro-Nano Structured Thermal

Interfaces for Pool Boiling Heat Transfer Enhancement," Microelectronics Journal, 37(11), pp. 1158-1164.

[14] Gorenflo, D., Danger, E., Luke, A., Kotthoff, S., Chandra, U., and Ranganayakulu, C., 2004, "Bubble Formation with Pool Boiling on Tubes with or without Basic Surface Modifications for Enhancement," International Journal of Heat and Fluid Flow, 25(2), pp. 288-297.

[15] Kandlikar, S. G., 1999, Handbook of Phase Change: Boiling and Condensation, Taylor & Francis, Philadelphia, Chap. 15.

[16] Kandlikar, S. G., and Steinke, M. E., 2002, "Contact Angles and Interface Behavior During Rapid Evaporation of Liquid on a Heated Surface," International Journal of Heat and Mass Transfer, 45(Compendex), pp. 3771-3780.

[17] Hübner, P., and Künstler, W., 1997, "Pool Boiling Heat Transfer at Finned Tubes: Influence of Surface Roughness and Shape of the Fins," International Journal of Refrigeration, 20(8), pp. 575-582.

[18] Luke, A., 1997, "Pool Boiling Heat Transfer from Horizontal Tubes with Different Surface Roughness," International Journal of Refrigeration, 20(8), pp. 561-574.

[19] Luke, A., 2004, "Active and Potential Bubble Nucleation Sites on Different Structured Heated Surfaces," Chemical Engineering Research and Design, 82(4), pp. 462-470.

[20] Mchale, J. P., and Garimella, S. V., 2010, "Bubble Nucleation Characteristics in Pool Boiling of a Wetting Liquid on Smooth and Rough Surfaces," International Journal of Multiphase Flow, 36(4), pp. 249-260.

[21] Steinke, M. E., and Kandlikar, S. G., 2006, "Single-Phase Liquid Friction Factors in Microchannels," International Journal of Thermal Sciences, 45(11), pp. 1073-1083.

[22] Ramaswamy, C., Joshi, Y., Nakayama, W., and Johnson, W. B., 2003, "Semi-Analytical Model for Boiling from Enhanced Structures," International Journal of Heat and Mass Transfer, 46(22), pp. 4257-4269.

[23] Ramaswamy, C., Joshi, Y., Nakayama, W., and Johnson, W. B., 2002, "High-Speed Visualization of Boiling from an Enhanced Structure," International Journal of Heat and Mass Transfer, 45(24), pp. 4761-4771.