Pool Boiling Heat Transfer Enhancement Through Nanostructures on Silicon Microchannels

Uniform silicon nanowires (SiNW) were successfully fabricated on the top, bottom, and sidewall surfaces of silicon microchannels by using a two-step electroless etching process. Different microchannel patterns with the channel width from 100 to 300 μm were first fabricated in a 10 mm × 10 mm silicon chip and then covered by SiNW with an average height of 10–20 μm. The effects of the microchannel geometry, micro/nano-hierarchical structures on pool boiling were studied and the bubble dynamics on different sample surfaces were compared. It was found that the combination of the micro/nanostructures promoted microbubble emission boiling under moderate heat fluxes, and yielded superior boiling heat transfer performance. At given wall superheats, the maximum heat flux of the microchannel with SiNW was improved by 120% over the microchannel-only surface, and more than 400% over a plain silicon surface. These results provide a new insight into the boiling mechanism for micro/nano-hierarchical structures and demonstrate their potential in improving pool boiling performance for microchannels. [DOI: 10.1115/1.4007425]

1 Introduction

Heat transfer with liquid–vapor phase change over microchannels has attracted great attention in thermal management due to the high thermal performance of microchannels in single-phase flow, and boiling in conventional systems. Such efficient systems are highly desirable as continuous minimization in microelectronic components requires superior heat dissipation within small and confined spaces. For instance, liquid-cooled microchannel heat sinks provide one of the most effective and promising thermal management methods due to their excellent heat transfer characteristics in single-phase flow with offset strip fins [1]. The microchannels generally consist of single or parallel channels with the height (Dh) between 10 and 200 μm, as defined by Kandlikar and Grande [2]. These channels may be rectangular, trapezoidal, or triangular in cross sections.

The microchannel designs have been continuously evolving since the pioneering research on microchannel liquid cooling led by Tuckerman and Pease [3]. Kandlikar and Upadhye [4] investigated single-phase heat transfer in plain and offset strip fins and presented performance plots for optimizing heat transfer and pressure drop. Li and Peterson [5] optimized microchannel spacing and channel dimensions by modifying the channel depth, channel width and fin width. The overall heat dissipation capacity of the microchannel was enhanced by more than 20% at a given condition. Gong et al. [6] performed a parametric numerical study of heat transfer in microchannels with wavy walls and suggested a 55% improvement in heat transfer performance compared to microchannels with straight walls. Kosar and Peles [7] employed staggered pin fin geometries in rectangular microchannel heat sinks.

On the other hand, advancement in nanotechnology provides a novel means for better thermal management. Significant enhancements in both the critical heat flux (CHF) and the heat transfer coefficient (HTC) have been obtained by introducing Copper nanowire (NW) arrays on the surfaces [8–11]; the reported CHF (220 W/cm²) for the CuNW coated Si surface is one of the highest for pool boiling heat transfer with water on silicon surface [10]. The NW structure represents a new class of materials that can be exploited to promote boiling heat transfer. The NW structures create many folders of cavities, which provide more active bubble nucleation sites and increased heat transfer area. Due to the thermal pin fin effect, the effective heat transfer area of NW structures is much larger than the plain surface [10]. In addition, the surface covered with NW structure demonstrates enhanced surface wettability due to capillary forces, which helps prevent dryout and increase CHF. Chen et al. [10] reported a CHF value of about 82 kW/cm² for water on a plain silicon surface.

With the individual advantages of using microchannel heat sinks and introducing NW on the surfaces, it is of great interest to combine the nanostructures onto the surfaces of microchannel heat sink for further enhancing the heat transfer performance. Dixit et al. [12] presented a multilayered water cooled microchannel heat sink where silicon (Si) nanopillars were grown on the bottom walls of the microchannels by utilizing the micromasking effects in deep reactive ion etching (DRIE). The thermal performance of the heat sink was evaluated by developing a simple thermal resistance model and compared with a heat sink without the nanopillars. Their analysis showed 16% improvement in the nanopillar based microchannel heat sink. Li et al. [13] fabricated SiNW arrays on the bottom of Si microchannel and tested the flow boiling performance of the microchannel heat sink. Earlier onset of nucleate boiling and delayed onset of flow oscillation, as well as enhanced HTC were observed, which suggested a significant performance enhancement. However, in these two experiments, only certain area (i.e., the bottom surface) of the microchannel was covered by the nanostructures, thus the mechanism and advantage of nanostructures on microchannel pool boiling was not fully utilized.

In the present study, a two-step etching process is developed to create uniform SiNW structures in rectangular silicon microchannel heat sinks, including the top, bottom and sidewall areas. The major motivation of this work is to understand the underlying mechanisms and influence of nanostructures on all surfaces of a microchannel chip during pool boiling. In order to find the best combination of micro/nanostructures, nine microchannel patterns...
with different widths of channel and fin were first fabricated and then coated with SiNW on all surfaces exposed to pool boiling liquid. The boiling performances of those microchannels with and without SiNW coating were compared. The channel configuration is shown in Fig. 1. The 10 x 10 mm² microchannel patterns were centered in the 20 x 20 mm² silicon chips. All microchannels possessed the same channel length (10 mm) and fin depth (150 μm). The fin pitches and channel widths range from 100 to 300 μm on different microchannel surfaces, as listed in Table 1. To the best of authors’ knowledge, this is the first investigation to evaluate the pool boiling performance of water on Si microchannels coated with SiNW structures on all surfaces, including the top, bottom and side walls.

2 Experimental Setup

To create SiNW on the microchannel walls, the process involves two steps: (1) microchannel fabrication and (2) SiNW formation. The process details are shown in Fig. 2 and are described below:

2.1 Microchannel Fabrication. The fabrication process of the microchannels is shown in Figs. 2(a)–2(b). Further details of each step were reported in an earlier publication [14]. Basically, the microchannel geometry was first defined by a photoresist mask and then etched through the DRIE process.

2.2 SiNW Fabrication on Microchannel. The SiNW was made by adapting electroless etching (EE) processes. In general, the SiNW etching process was crystalline-direction dependent; it had different SiNW formation when different etching conditions were applied [15]. Therefore, a two-step etching process becomes necessary when there are more than one crystalline direction. In the microchannel samples, (100) crystalline direction was obtained for the top and bottom of the microchannel and (110) for the sidewall of the microchannel for a p-type (100) silicon wafer. As shown in Figs. 2(c) and 2(d), the first SiNW etching step promoted the SiNW etching in the (100) direction, which was realized by immersing the samples in 5 M HF and 0.02 M AgNO₃ at room temperature. In this etching step, the deposited Ag⁺ was reduced into Ag₀ by injecting positive holes (h⁺) into the bulk silicon because of the high positive redox level of Ag/Ag⁺. Silicon was oxidized into SiO₂ and consequently dissolved by HF. The SiO₂ removal was associated with the number of its back bonds, and the density of back bonds in different crystal planes increased in the order of (100)<(110)<(111). Therefore, at the equilibrium state, the etching preferred (100) direction, with least back bonds to break, resulting in SiNW only in the (100) direction, while the sidewall surfaces of (110) were little affected in the first etching step.

To create uniform SiNW structures on the sidewalls without affecting the other areas, H₂O₂ was introduced in the second NW etching step to alter the etching direction into (110). The solution contained HF/H₂O₂ with 2:1 molar ratio. High concentration of H₂O₂ would generate large amount of holes (h⁺) and significantly speed up the removal of silicon atoms in the crystal planes, where there were more silicon back bonds than (100) plane to polarize, resulting in the SiNW at the (110) direction. Uniform SiNW structures on the sidewalls, top and bottom areas of the microchannels were successfully fabricated thereafter, as shown in Fig. 3. The SiNW branches on the sidewall surfaces were slightly different from the ones on the top and bottom areas, as they are created during different etching steps. At the top and bottom areas, cavities and openings were observed between SiNW bundles as shown in Figs. 3(b) and 3(d), providing ideal active bubble nucleation sites for pool boiling. The SiNW structures on the sidewall area increased the active heat transfer area and functioned as wicking structures to provide capillary forces. The average height of SiNW on top/bottom surfaces is about 10–20 μm with a diameter ranging from 10–50 nm. For SiNW on sidewall surface, the average height is ~10 μm with diameters in the range 80–100 nm. It is noticed that the tips of SiNW arrays tend to bundle together, which is possibly due to the surface tension of water that pulls nanowires together during the drying process [10]. The SiNW bundling also creates numerous cavities, which may function as active bubble nucleation sites during boiling.

2.3 Surface Wettability. By improving the surface hydrophilicity, SiNWs improve surface wettability and enhance the CHF due to delayed dryout. The surface wettability of the micro/nano-hierarchical structures was quantified by the static contact angle (CA) measurements of water droplets on the test surfaces.

Table 2 presents the results of measurement of the contact angles for the microchannel samples. All samples were cleaned by Piranha solution and nitrogen dried prior to measurement. Due to the geometry of the microchannels, the contact angles were examined from both X direction (referring to Fig. 1, along the channel direction) and Y direction (referring to Fig. 1, across the channel direction) for microchannel-only samples (no SiNW). Depending on the channel width and fin width, the contact angles on the
microchannel-only samples ranged from 134 deg to 156 deg in the X direction and 101 deg to 133 deg in the Y direction. For all SiNW samples, the micro/nano-hierarchical structures enhanced the surface wettability. The droplet spreads through and across the microchannels, showing a completely wetting behavior. Figure 4 shows the contact angle of the selected samples with different fin widths (left column), and a comparison with the same samples coated with the SiNW (right column).

The surface hydrophilicity may attribute to the capillary wicking induced by the micro/nano-hierarchical structures [16]. The capillary wicking supplied fresh liquid to the dry region beneath the vapor bubbles during boiling, which delayed the irreversible growth of hot spots and CHF. As the whole surface area of SiNW sample is superhydrophilic, water can easily rewet the bottom of the channel and fin areas after bubble departure, leaving neither local hot spot nor dryout area. In contrast, the bubbles that remained or grew on the microchannel-only samples may result in local hot spots on the sidewall and top of the fin area during nucleate boiling stage.

### Table 2 CA measurement results

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>X direction (deg)</th>
<th>Y direction (deg)</th>
<th>CA of microchannel with SiNW (X-directions) (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>137</td>
<td>109</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>139</td>
<td>124</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>156</td>
<td>133</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>135</td>
<td>113</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>142</td>
<td>122</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>149</td>
<td>131</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>134</td>
<td>101</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>141</td>
<td>120</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>150</td>
<td>128</td>
<td>0</td>
</tr>
</tbody>
</table>

**2.4 Pool Boiling Test Setup.** To study the pool boiling performance of the hierarchical structure, an experimental setup shown in Fig. 5 was employed [17]. The test samples were mounted on an insulated and sealed copper block. A 450 W capacity cartridge heater served as the main heating element. Three K-type thermocouples were placed along the axis of the copper block to measure the temperature gradient at the top of the heater block.

Three thermocouples were installed 8 mm apart and the first one ($T_1$) was 3 mm below the top copper surface. Fresh distilled water was used for each test as the boiling liquid. Sufficient time was given to remove dissolved air by vigorously boiling the water before commencing the test by using an auxiliary heater, which was also used to maintain the water temperature in the reservoir at saturation condition. A venting hole was provided on top of the water tank to maintain the pressure and vent vapors. The temperature of water was monitored by a K-type thermocouple ($T_4$). After water was kept in saturation temperature for 30 min, the main heater was started and the power was increased in small increments. A LabView program was created to display temperatures to assist in determining when the system reached a steady-state, and record the measurement data.

The heat flux was calculated from the following equation:

$$q'' = -k_{Cu} \frac{dT}{dx} \quad (1)$$

The temperature gradient, $dT/dx$, was calculated using a three-point backward-difference Taylor series approximation as given below

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

where $T_1$, $T_2$, and $T_3$ are the temperatures measured by thermocouples located at distances $\Delta x = 8$ mm apart. The surface temperature of the microchannel, $T_s$, was obtained by calculating the heat flux through the copper block, as well as the reading from thermocouple $T_1$, from the following equation:

$$T_s = T_1 - q'' \left(\frac{L_{Cu}}{k_{Cu}} + \frac{R_{C}^{\prime \prime}}{k_{Si}} + \frac{L_{Cu}}{k_{Si}}\right) \quad (3)$$

where $L$ and $k$ represent material thickness and thermal conductivity, respectively. $R_{C}^{\prime \prime}$ represents the thermal contact resistance of the interface, which is found to be $5 \times 10^{-6}$ m²·K/W, with an
uncertainty less than 4%, as reported in an earlier publication [18]. The wall superheat $\Delta T$ is obtained by

$$\Delta T = T_s - T_{sat}$$  \hspace{1cm} (4)

For boiling with water at atmosphere pressures, the saturation temperature $T_{sat} = 100$ °C. Corrections were applied to the saturation temperature based on the local atmospheric pressure readings.

The uncertainty analysis was conducted according to the method proposed by Kline and McClintock [19]. The major uncertainties originated from the following aspects: (1) thermocouple calibration accuracy and precision resolution; (2) thermal conductivity of materials being altered due to temperature changes, and (3) actual size of the boiling area due to gasket cover, measurement of spacing between thermocouples, and thickness of materials. Multiple parameters can lead to propagation of uncertainty. The method used to find the error propagation is through partial sums in Eq. (5), where $p$ is the calculated parameter, $a_i$ is a measured parameter, and $U$ denotes the uncertainty of the subscripted parameter.

$$U_p = \pm \sqrt{\sum_{i=1}^{n} \left( \frac{\partial p}{\partial a_i} u_{a_i} \right)^2}$$  \hspace{1cm} (5)

The uncertainties in multimeters to measure voltage and current are 0.8%. The uncertainty for the heat flux can be derived from
seen from Fig. 6, sample #9 yielded a heat flux of 150 W/cm² at a given wall superheat when the channel width is increased. Boiling on the plain Si substrate served as the primary control for comparing boiling performance. The results were consistent with experimental results reported previously [20]. Significant boiling heat transfer enhancement was observed on all SiNW samples compared to the microchannel-only surface. The enhancement ratio varies according to microchannel geometry.

For microchannel-only surface, the boiling curves suggest that for a given channel depth of 150 μm, the heat transfer is increased at a given wall superheat when the channel width is increased from 100 μm to 300 μm. In addition, reducing the fin pitch also increases the heat transfer performance from the structure. As seen from Fig. 6, sample #9 yielded a heat flux of 150 W/cm² at 27.5 K wall superheat. In contrast, the lowest performing sample #1 reached only 114 W/cm² at 35 K wall superheat, as this sample has the largest fin pitch and smallest channel width.

The physical reason for wider channels providing more heat transfer in this study seems to be related to the bubble generation and dynamics. Bubbles primarily generated at the bottom of the channel due to its proximity to the heat source. The wider channels seem to result in more bubble nucleation sites. Also, increasing channel width makes it easier for water to flow into the microchannels feeding the nucleation sites, thereby preventing dry out in the channel. This finding is also consistent with a previous study on the effect of open microchannel geometry on pool boiling performance [21].

By incorporating SiNW in the microchannel heat sink, the boiling incipient wall superheat on the surface was found to be much lower than that on the microchannel-only surface. Particularly, the boiling enhancement ratio was directly related to the overall surface area. The enhanced surface area of each sample was represented by surface area augmentation factor shown in Table 4. Samples with more active heat transfer area benefitted more from the SiNW structures. The maximum heat flux was observed in the present experiments on sample #1, which reached 194 W/cm² at 28 K superheat, and the actual CHF was beyond 200 W/cm² (not observed due to safety considerations). In order to compare the heat transfer performance in a more quantitative way, a plot of the HTC against wall superheat of all the samples, including plain Si surface, is shown in Fig. 7.

For the microchannel samples coated with SiNW surfaces, the maximum HTC was observed on sample #1, which has a surface area augmentation of 2.05. At a given wall superheat
(25 K), the heat flux of sample #1 is improved by 120% over the microchannel-only surface, and its HTC is more than 4 times higher than that of plain Si surface, as shown in Table 4 and Fig. 7. The sample with the lowest surface augmentation factor (#9) has only 27% improvement in heat flux even though it has high heat fluxes. The result suggests that the microchannels with higher surface area would benefit more from nanostructures for heat transfer enhancement. It may be noted that the chosen microchannel pattern may not be the best configuration for boiling performance; the boiling performance is expected to improve further by optimizing the microchannel configuration.

It is worth mentioning that many earlier studies have successfully applied nanowire structures on plain surfaces for the enhancement of pool boiling heat transfer. At 25 K–30 K wall superheat region, the reported maximum heat flux in those studies ranges from 100 to 150 W/cm² [10,17,22,23]. By combining the nanowire structures with microchannel structure, the maximum heat flux is pushed higher to 194 W/cm² at 28 K wall superheat as shown in Fig. 6. This finding suggests a promising application of micro/nano-hierarchical structures in enhancing pool boiling heat transfer.

3.1 Bubble Dynamics. The bubble nucleation and growth on the sample surfaces were investigated with high speed camera (24,000 frames/s, Keyence VW-6000). Figure 8 shows the bubble generation event from the samples of microchannel-only and microchannel with SiNW at 0.02 s intervals; (c) and (f) illustrate the possible mechanisms of bubble generations on microchannel-only and microchannel with SiNW surface, respectively.

Different bubble behaviors were observed on microchannel surfaces with and without SiNW. For the microchannel-only surface at low heat flux, a bubble nucleates at the bottom and moves to the fin where it attaches itself to the sidewall and then migrates to the top surface and grows. The diameter of the bubble is confined by the channel width but the bubble does not depart from the top of the fin surface until it reaches a critical departure diameter. However, when the microchannel surface is coated with SiNW, the bubble directly departs from the nucleation sites without sticking on top of the fin surface, resulting in an instantaneous microsized bubble generation and a high departure frequency. The SiNW structures create a very high bubble nucleation site density; thus at a given time, large number of small bubbles were observed on microchannels with SiNW samples than those on microchannel-only surfaces.

3.1.1 Microbubble Emission Boiling (MEB). At intermediate heat fluxes, MEB was observed on microchannels with SiNW surfaces.

The MEB phenomenon was first reported by Inada [24] in a study of highly subcooled pool boiling. Subcooled flow boiling with microbubble emission has been investigated by Kubo and Kumagai [25] and Suzuki et al. [26]. The MEB regime usually occurs in the beginning of subcooled transition boiling, when the instability of bubble interface is accelerated in the subcooled liquid and the interface collapses to form many microbubbles. Because MEB promotes liquid–solid contact and increases heat flux, it significantly enhances boiling performance by maintaining high heat flux while preventing the dryout. In the boiling test of microchannel with SiNW samples, it is found that at intermediate

<table>
<thead>
<tr>
<th>Sample# (SiNW)</th>
<th>Surface augmentation factor</th>
<th>Heat flux at 25 K with SiNW (W/cm²)</th>
<th>Heat flux at 25 K without SiNW (W/cm²)</th>
<th>Enhancement of heat flux (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.02</td>
<td>168</td>
<td>76</td>
<td>120</td>
</tr>
<tr>
<td>2</td>
<td>1.69</td>
<td>129</td>
<td>80</td>
<td>61</td>
</tr>
<tr>
<td>3</td>
<td>1.50</td>
<td>122</td>
<td>92</td>
<td>32</td>
</tr>
<tr>
<td>4</td>
<td>1.69</td>
<td>139</td>
<td>86</td>
<td>62</td>
</tr>
<tr>
<td>5</td>
<td>1.51</td>
<td>132</td>
<td>90</td>
<td>45</td>
</tr>
<tr>
<td>6</td>
<td>1.48</td>
<td>129</td>
<td>95</td>
<td>30</td>
</tr>
<tr>
<td>7</td>
<td>1.52</td>
<td>142</td>
<td>106</td>
<td>32</td>
</tr>
<tr>
<td>8</td>
<td>1.41</td>
<td>154</td>
<td>117</td>
<td>23</td>
</tr>
<tr>
<td>9</td>
<td>1.35</td>
<td>174</td>
<td>138</td>
<td>27</td>
</tr>
</tbody>
</table>

Fig. 7 Heat transfer coefficient for the SiNW samples and plain surface

Fig. 8 Successive images of bubble generation at low heat flux (10–15 W/cm²) on the samples of (a) and (b) microchannel-only and (d) and (e) microchannel with SiNW at 0.02 s intervals; (c) and (f) illustrate the possible mechanisms of bubble generations on microchannel-only and microchannel with SiNW surface, respectively.

Transactions of the ASME
heat fluxes, the coalesced bubbles generated on the heated surface were broken to many microbubbles after contacting with the surrounding liquid. The bubbles stably and continuously generated and sprayed from active nucleate sites to form jet flows in the liquid (Figs. 9(a)–9(d)). While at high heat fluxes, the single bubble size increases dramatically, as shown in Figs. 9(e)–9(h). Because the details of MEB generation is not yet fully understood, the bubble behavior at different heat flux regions may be attributed to some unique characteristics of SiNW, as MEB was not observed on microchannel-only samples. The commencement of MEB, however, may explain the superior boiling performance of microchannel with SiNW surfaces at intermediate heat fluxes.

4 Conclusions
This study demonstrates that uniform SiNW structures can be created on all microchannel heat sink surfaces by a two-step etching process. The pool boiling heat transfer performance can be significantly enhanced by the microchannel/nanowire hierarchical structures. The effect of microchannel configuration and SiNW on boiling performance was investigated. The main findings of this study are summarized below:

1. A two-step synthesis process is developed to create uniform SiNW on all of the microchannel surfaces for the first time, including top, bottom and sidewall areas. The average height of SiNW on the surfaces is around 10–20 μm.
2. The SiNW structures enhance the surface wettability, making the microchannel surface superhydrophobic.
3. The testing results suggest that for pool boiling with water on the microchannel heat sink, heat transfer can be significantly enhanced by creating micro/nano-hierarchical structures on the testing surfaces.
4. For microchannels with 150 μm depth, large channel width and small channel pitch are preferred for better boiling performance. However, when SiNW are incorporated, microchannels with more surface area would have higher enhancement ratio.
5. Microbubble emission boiling and bubble jets were observed on microchannels with SiNW surface at intermediate heat fluxes. At high heat fluxes, the single bubble size increases dramatically. Individual bubbles could not be observed at high heat fluxes due to the limited visual access during vigorous boiling.
6. The silicon microchannel sample #1 with SiNW structure yielded a heat flux of 194 W/cm² at 28 K wall superheat. This result is 400% improvement compared to a plain silicon sample at the same wall superheat. The boiling performance can be further enhanced by optimizing the microchannel configuration.

Silicon is the most commonly used material in the semiconductor industry. The micro/nano-hierarchical structures employed here are attractive for future semiconductor cooling, thermal management and high-heat-flux energy conversion applications. The study of micro/nanostructures on pool boiling provides a new insight on effectively enhancing boiling heat transfer.

Acknowledgment
The authors would like to thank Mr. P. C. Kao from National Taiwan University for the microchannel fabrication. The collaborative project has been supported by National Science Council (Taiwan) (NSC98-2218-E002-023-MY3) and National Science Foundation (USA) EPDT Grant No. (# 0802100).

Nomenclature
\[ a_i = \text{measured parameter} \]
\[ H = \text{microchannel height, m} \]
\[ h = \text{heat transfer coefficient, W/m}^2\text{K} \]
\[ k = \text{thermal conductivity, W/mK} \]
\[ L = \text{test section length along } x \text{ direction} \]
\[ L_y = \text{test section length along } y \text{ direction} \]
\[ q''_h = \text{heat flux, W/cm}^2 \]
\[ R_{ct} = \text{thermal contact resistance, m}^2\text{K/W} \]
\[ T = \text{temperature, K} \]
\[ T_s = \text{surface temperature, K} \]
\[ W_{ch} = \text{microchannel channel width, m} \]
\[ W_f = \text{microchannel fin width, m} \]

References


