A COMPACT POOL BOILER UTILIZING NANOSTRUCTURED PLATES FOR MICROSCALE COOLING APPLICATIONS

Turker Izci, Ebru Demir, Arif Sinan Alagoz, Tansel Karabacak, Ali Kosar*

* Mechatronics Engineering Program
Sabanci University Nanotechnology Research and Application Center
Orhanli, Istanbul, 34956, Turkey
E-mail: kosara@sabanciuniv.edu

ABSTRACT
A nanostructure based compact pool boiler cooling system consisting of an aluminum base housing the heaters, a pool and four different plates to change the surface texture of the pool is designed. Effects of nanostructured plates of different surface morphologies on boiling heat transfer performance of the system are studied. Three nanostructured plates featuring Si nanowires of diameter 850 nm and of three different lengths, 900 nm, 1800 nm and 3200 nm respectively, which are etched through single crystal p-type silicon wafers using metal assisted chemical etching (MaCE), are utilized to enhance the pool boiling heat transfer. A plain surface Si plate is used as the control sample. Constant heat flux is provided to the liquid within the pool on the surface of the aluminum base through the plate by boiling heat transfer.

Existence of wall superheat gave rise to forming of vapor bubbles near the boiling temperature of the fluid, namely DI-Water. Bubbles emerged from the nanostructured plate along with the phase change. Nucleate boiling on the surface of the plate, bubble formation and bubble motion inside the pool created an effective heat removal mechanism from the heated surface to the liquid pool.

The surface temperature at boiling inception is found to be 103 ºC for plain surface Si control sample, whereas it decreased to near 100 ºC for all the cases where a nanostructured plate was present. Along with the enhancement in both boiling and single-phase region heat transfer coefficients, this study proves the ability of nanostructured plates in improving the performance of the cooling system.

INTRODUCTION
Along with the miniaturization of individual components constructing electronic devices, functionality of such devices increased greatly due to the ability of tightly packaging these components. Recent developments in technology made it possible for electronic devices to have day to day increasing computational powers while diminishing in size. While benefitting from miniaturization process in increasing the mobility, heat dissipated per unit area by such devices increased greatly, therefore the development of more effective and equally miniaturized cooling systems became a priority in order to preserve the functionality and stability of such devices. Conventional methods such as using air and fan systems and even their improved versions with fin arrays started to fail as the heat removal problems became more demanding. Due to the superior heat removal characteristics of different liquids, a paradigm shift in cooling applications became inevitable, so using liquids as coolants became a popular trend. Most of the experiments featuring different liquids presented promising results (Mudawar, 2001). Still, some advanced electronic systems demanding removal of very high heat fluxes rendered single phase liquid cooling applications insufficient (Hendricks, Krishnan, Choi, Chang and Paul, 2010) In order to achieve higher efficiency in miniaturized cooling systems, focus of this particular research area has shifted towards cooling applications benefitting from phase-change, such as jet-impingement, flow boiling in micro-channels and pool boiling. Experiments have repeatedly shown that two-phase cooling systems yield better results than single-phase applications (Mudawar, 2001).

Though the boiling applications are not limited with pool boiling, it is one of the most popular heat removal mechanisms and is being studied by many researchers. Another hot topic is the effect of nanoparticles and nanostructured surfaces on heat transfer characteristics of cooling systems. So, it became a rising trend in heat transfer community to couple these methods that are known to be effective in heat removal (Park, Jung, 2007; Ahn, Sathyamurthi, Banerjee, 2009; Xiao, Li and Du 2011). Many experiments have proven that nanofluids (Ujereh, Fisher, Mudawar, Amama and Qu 2005; Kebinski, Eastman and Cahill, 2005; Bang and Chang 2005; Vemuri and Kim 2005; Milanova and Kumar 2005; You, Kim and Kim 2003) and nanostructured surfaces (Li, Wang, Wang, Peles, Koratkar and Peterson, 2008; Kim, Kim and Kim, 2006; Kim, Bang, Buongiorno and Hu, 2007; Honda, Takamatsu and Wei, 2002; Senes, Khudhayer, Karabacak and Kosar, 2009) are very compatible with pool boiling applications and make a significant enhancement in heat removal performance of such systems. It has been shown that the heat
transfer coefficients and CHF increase greatly when nanostructured plates and nanofluids are utilized in pool boiling applications, furthermore, dramatic reductions in boiling inception temperatures have been reported (Ujereh, Fisher, Mudawar, Amama and Qu, 2005; Keblinski, Eastman and Cahill 2005; Bang and Chang, 2005; Vassallo, Kumar and D’Amico, 2004; Vemuri and Kim, 2005; Milanova and Kumar, 2005; You, Kim and Kim 2003; Li, Wang, Wang, Peles, Koratkar and Peterson 2008; Kim, Kim and Kim 2006; Kim, Bang, Buongiorno and Hu 2007; Honda, Takamatsu and Wei, 2002). Capability of such surfaces in decreasing the contact angle and increasing wettability in boiling applications has been reported in literature (Eastman, Choi, Li, Yu and Thompson, 2001; You, Kim and Kim 2003; Vassallo, Kumar and D’Amico, 2004; Kim, Kim and Kim 2006; Kim, Bang, Buongiorno and Hu, 2007).

The novelty of this study is that it aims to contribute this popular research topic by investigating the effect of varying nanowire length on heat removal performance of pool boiler cooling systems. Three nanostructured plates, each featuring Si nanowires of different lengths and of same diameter have been experimented on and the results are compared to the measurements made using a plain surface Si plate. Surface temperatures are recorded for each of the plates in various heat fluxes starting from single-phase region and promising results are obtained as presented in this paper.

**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Total heated area</td>
</tr>
<tr>
<td>P</td>
<td>Power input to the system</td>
</tr>
<tr>
<td>q''</td>
<td>Constant heat flux</td>
</tr>
<tr>
<td>T_s</td>
<td>Surface temperature</td>
</tr>
<tr>
<td>T_i</td>
<td>Initial temperature of the liquid pool</td>
</tr>
<tr>
<td>T_{sat}</td>
<td>Saturation temperature of the liquid</td>
</tr>
<tr>
<td>R_{tot}</td>
<td>Total thermal resistance</td>
</tr>
<tr>
<td>h</td>
<td>Heat transfer coefficient</td>
</tr>
</tbody>
</table>

**NANOSTRUCTURE DEPOSITION**

Single crystal p-type (100) oriented silicon wafers at resistivity 1-100 Ω·cm were cleaned by standard RCA-I cleaning procedure. Samples were dipped into ammonium hydroxide and hydrogen peroxide solution (NH₄OH, 30% v. : H₂O₂, 30% v. : H₂O = 1 : 1 : 5) at 80°C for 15 minutes, rinsed with deionized water and dried with nitrogen gas. Following the cleaning step, single layer hexagonally close-packed polystyrene (PS) nanospheres were deposited onto samples through convectional self-assembly method (Prevo and Velev, 2004) and slightly etched in oxygen plasma. Plasma etching decreased nanosphere diameter from 1010 nm to 850 nm and formed a hexagonal pattern of isolated nanospheres. These non-closely packed nanospheres were used as shadow mask for gold film deposition of 50 nm thickness where gold atoms filled the gaps among nanospheres. This step was followed by nanosphere lift-off by ultra-sonicating samples in toluene for 1 minute, which left a honeycomb patterned gold mesh layer on the silicon substrate. After the patterning process, samples were immersed into room temperature hydrofluoric acid - hydrogen peroxide solution (HF, 50% v. : H₂O₂, 30% v. : H₂O = 4 : 1 : 5). Silicon underneath the gold layer etched and formed well-ordered single crystalline silicon nanowires. Samples were etched for 40 seconds, 80 seconds, and 160 seconds in order obtain Si wires of 900 nm, 1800nm and 3200 nm lengths, respectively. Finally, gold layer was removed by etching with potassium iodine (KI) solution for 3 minutes. In this metal-chemical assisted etching (MaCE) procedure, silicon nanowire diameter is defined by the reduced nanosphere diameter, nanowire separation by initial nanosphere diameter, and nanowire length is set by etching time. Effects of silicon wafer crystal orientation, etching solution concentration, and etching time on nanowire morphology were discussed elsewhere (Alagoz and Karabacak, in press).

![Figure 1](image-url) **Figure 1** Top-view and crosssectional view SEM images of single crystalline silicon nanowires after 40 seconds etching
EXPERIMENTAL SETUP AND PROCEDURE

Experimental Apparatus

The experimental design is demonstrated in Figure 4. An aluminum base of dimensions 6cmx6cm is designed such that it features a housing for four cartridge heaters, each of length 31.25 mm and of diameter 6.25 mm, which is surrounded with air gaps on all sides to minimize heat loss. On the surface of the aluminum base lies a pool of dimensions 2cmx2cm which has a depth of 4mm. A container made of Plexiglas is closely fitted to the aluminum base, hence the total depth of the pool increases to 8 mm. The heat generated by the cartridge heaters is delivered to the nanostructured plate of size 19mmx19mm that is placed on the bottom of the pool. Heaters provide constant heat flux to the system since constant voltage is applied to the ends of the heaters. Total resistance of the heaters is 65 ohms and each heater alone is capable of reaching powers as high as 225 W. The heaters and the nanostructured plate are treated with high quality silicone thermal grease in order to minimize thermal contact resistances and heat losses. The container is filled with 154.45 ml DI-Water and the water level is 5.8 cm above the nanostructured plate. One thermocouple is placed between the nanostructured plate and the bottom of the pool to record surface temperature, whereas another thermocouple is secured under the base in order to determine the heat loss.
Experimental Procedure

After the experimental setup is prepared as explained, the surface temperature is measured (through OMEGA thermocouples) as a function of the input power calculated using voltage and current readings on the power supply (AMETEK Sorensen XHR Series Programmable DC Power Supply). Surface temperature is recorded for various constant heat flux values. Temperature data are recorded with the aid of a computer integrated data acquisition system (NI-SCXI 1000) at a rate of 100 data points per second. These data points are exported using data acquisition software LABVIEW and then averaged using MS Visual Studio and linearized using MATLAB.

Constant voltage is applied to the ends of the cartridge heaters (Isitel Cartridge Heaters) providing constant heat flux to the surface. Heat flux values covered a range that includes both single phase and boiling heat transfer conditions. The experiment is repeated for each of the four plates, three of them featuring Si nanowires of different lengths and one being plain surface Si control sample. The results are compared to characterize the effects of nanostructures on boiling heat transfer performance of the cooling system designed.

Data Reduction

Heat flux provided to the system, \( q^* \), is obtained from

\[
q^* = \frac{P - Q_{loss}}{A} \tag{1}
\]

where \( P \) is the power input, \( Q_{loss} \) is the thermal and electrical power loss and \( A \) is the heated area of the plate. The surface temperatures are calculated by considering thermal contact resistances from the thermocouple to the surface of the nanostructured plate,

\[
T_s = T_{th} - q^* \cdot R_{tot} \tag{2}
\]

where \( T_{th} \) is the thermocouple temperature reading and \( R_{tot} \) is the total thermal resistance from the thermocouples to the surface of the nanostructured plate. The average of the surface temperatures are taken to obtain the average surface temperature \( T_{th} \). The boiling heat transfer coefficient \( h \), is then calculated by

\[
h = \frac{q^*}{T_s - T_{sat}} \tag{3}
\]

Where \( T_s \) is the surface temperature and \( T_{sat} \) is the saturation temperature of the fluid. \( T_{sat} \) is replaced with \( T_i \) while calculating single phase region heat transfer coefficient, which is the initial temperature of the liquid pool.

Uncertainty Analysis

The uncertainties of the measured values are given in Table 1 and are derived from the manufacturer’s specification sheet while the uncertainties of the derived parameters are obtained using the propagation of uncertainty method developed by Kline and McClintock (Kline and McClintock, 1953).
<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (P)</td>
<td>±7.75 %</td>
</tr>
<tr>
<td>Surface Area (A)</td>
<td>±0.08 %</td>
</tr>
<tr>
<td>Thermocouple Reading (T_{th})</td>
<td>±0.1ºC</td>
</tr>
<tr>
<td>Thermal Resistance (R_{tot})</td>
<td>5.0457 %</td>
</tr>
<tr>
<td>Heat Flux (q&quot;)</td>
<td>±7.8 %</td>
</tr>
<tr>
<td>Surface Temperature (T_s)</td>
<td>0.2636 %</td>
</tr>
<tr>
<td>Heat Transfer Coefficient (h)</td>
<td>8 %</td>
</tr>
</tbody>
</table>

Table 1 Uncertainty analysis results

RESULTS AND DISCUSSION

Experimental data is gathered as explained in the previous sections. Surface temperature data points are plotted against various constant heat flux values between 0.3 W/cm²-23 W/cm² for all four plates and presented in Figure 5. Nanostructured plate with Si nanowires of length 900 nm (referred to as Si NW 900 nm in the legends) has shown the best improvement on the surface temperature compared to the plain surface Si control sample (referred to as Plain Si in the legends). Surface temperature at the boiling inception remained very close to 100 ºC. Other two nanostructured plates with 1800 nm and 3200 nm Si nanowires respectively (referred to as Si NW 1800 nm and Si NW 3200 nm in the legends) have shown the same trend and enhanced the heat transfer compared to the plain surface Si plate, but with a slight increase in surface temperatures. As the length of the nanowires increased, an surface temperature increased, too. This behavior is attributed to the descending wettability of the surface due to the ascending nanowire length. Overall enhancement on the heat transfer characteristics is attributed to the pin-fin (Ahn, et al., 2009) effect of the nanowires. The increased heat transfer surface area available to remove heat from the surface created a more effective cooling system.

Boiling heat transfer coefficients of all four plates are plotted against various heat fluxes and presented in Figure 6. As expected after the temperature readings are analyzed, nanostructured plate with the shortest nanowires of 900 nm makes the greatest difference compared to the plain surface Si plate. Heat transfer coefficient average of the nanostructured plate with 900 nm nanowires is 3.5 times the average heat transfer coefficient of the plain surface Si plate in boiling region. Worst case observed using a nanostructured plate still yields a huge enhancement in average heat transfer coefficient. The nanostructured plate with Si nanowires of 3200 nm results in 2.2 times the average heat transfer coefficient of the plain surface Si plate. This positive effects can be attributed to the decreased contact angle of the liquid with heated surface (Hendricks, Krishnan, Choi, Chang and Paul, 2010). Decreasing contact angle increases surface wettability (Eastman, Choi, Li, Yu and Thompson, 2001; You, Kim and Kim 2003; Vassallo, Kumar and D’Amico, 2004; Kim, Kim and Kim, 2006; Kim, Bang, Buongiorno and Hu 2007) by increasing capillary surface forces, hence fluid flow to the nucleation sites is promoted (Hendricks, Krishnan, Choi, Chang and Paul, 2010). This also yields a higher bubble generation frequency. It is also widely studied and proven that such nanostructured
surfaces have the ability of increasing the nucleation site density and bubble generation frequency from the surface (McHale, John, Garimella, Suresh 2010).

**Figure 6** Boiling heat transfer coefficients vs. various constant heat flux values for all test samples

Single-phase region heat transfer coefficients of the plates are plotted against various heat flux values and are presented in Figure 7. Nanostructured plates with 900 nm and 1800 nm Si nanowires yielded better results compared to the plain surface Si plate, whereas in single-phase region, nanostructured plate with 3200 nm Si nanowires performed the worst. This behavior can be attributed to the increasing thermal resistance due to the increasing thickness of the plate. Without the superior heat removal performance of boiling conditions, nanostructured plate with such long nanowires failed to enhance the heat removal performance of the system.

**Figure 7** Single-phase region heat transfer coefficients vs. various constant heat flux values for all test samples
CONCLUSIONS

This study proves positive effects of utilizing nanostructured plates in pool boiler cooling applications. A significant enhancement in heat transfer coefficients at both single-phase and boiling regions is achieved using nanostructured plates with Si nanowires. Due to the increasing active nucleation site density, surface wettability and heat transfer area, nanostructured surfaces escalate the performance of the cooling system. Furthermore, they are assumed to increase the bubble generation frequency by decreasing the liquid-surface contact angle. It is observed that as the length of the nanowires increases, the enhancement in heat removal performance of the system decreases due to the decreased wettability of the surface.

Since there is an ongoing debate whether the decreasing contact angle would make a positive contribution to boiling heat transfer for a decrease in contact angle would also decrease the bubble diameter (Hendricks, Krishnan, Choi, Chang and Paul, 2010) authors feel the need to extend the research by providing an accurate measurement of the contact angles of the nanostructured plates used in this study. Moreover, SEM images of the plates after being experimented on will be obtained in order to determine the durability of the nanostructures under the changing operational conditions. A mathematical correlation of heat transfer characteristics of the system needs to be obtained since no existing correlation in literature completely coincides with the findings in this research.

Under the light of the presented data, it is safe to say that nanostructured plates featuring Si nanowires make a significant contribution to the heat removal performance of the pool boiling system and the enhancement in heat transfer coefficients in both single-phase and boiling regions is very promising.

Acknowledgements

This work was supported by TUBITAK (The Scientific and Technological Research Council of Turkey) Support Program for Scientific and Technological Research Projects Grant, 111M007, and Turkish Academy of Sciences. Graduate student support provided by the Faculty of Engineering and Natural Sciences of Sabanci University is greatly appreciated.

REFERENCES


