A COMPACT NANOSTRUCTURE INTEGRATED POOL BOILER FOR MICROSCALE COOLING APPLICATIONS

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ABSTRACT

An efficient cooling system consisting of a plate, on which copper nanorods (nanorods of size ~100nm) are integrated to copper thin film (which is deposited on Silicon substrate), a heater, the Aluminum base, and a pool was developed. This high efficiency heat transfer equipment has a base of dimensions 6cmx6cm. The base is specially designed to enhance heat transfer with minimum loss from the heater placed beneath the aluminum block. The heaters produces heat flux to the nanorod integrated plate specimen placed on top of it. A container made of Plexiglas is closely fitted on top of the Aluminum block to create the desired pool for the pool boiling experiments on the nanostructured plate (made of Silicon). The heat generated by the film miniature heater is delivered to the nanostructured plate of size 1.7cmx1.5cm through the base. Heat is transferred with high efficiency to the liquid within the pool above the base through the plate by boiling heat transfer.

Near boiling temperature of the fluid, vapor bubbles started to form with the existence of wall superheat. Phase change took place near the nanostructured plate, where the bubbles emerged from. Bubble formation and bubble motion inside the pool created an effective heat transfer from the plate surface to the pool. Nucleate boiling took place on the surface of the nanostructured plate helping the heat removal from the system to the liquid above.

The heat transfer from nanostructured plate was studied using the experimental setup. The temperatures were recorded from the readings of thermocouples, which were successfully integrated to the system. The surface temperature at boiling inception was 102.1°C without the nanostructured plate while the surface temperature was successfully decreased to near 100°C with the existence of the nanostructured plate. In this study, it was proved that this device could have the potential to be an extremely useful device for small and excessive heat generating devices such as MEMS or Micro-processors. This device does not require any external energy to assist heat removal which is a great advantage compared to its counterparts.

1.0 INTRODUCTION

With the miniaturization of micro processors and micro chips an increasing trend in their power density is inevitable. As a result, there is an urgent need for micro heat sinks with low thermal resistance. Besides electronics cooling; micro heat sink technology also finds applications in microreactors, micropropulsion, biotechnology, fuel cells and air conditioning. Heat and fluid flow (both single-phase flow and flow boiling) in microscale has been rigorously studied to achieve the goal of higher heat removal capabilities. Recently, nanostructured surfaces have been utilized to achieve high heat transfer performance due to enhanced heat transfer area and positive effect on heat transfer coefficients with diminishing length scale. Moreover, nanostructures also provide additional active nucleate sites so that they could promote nucleate heat transfer in boiling.

The applications of nanostructured surfaces in boiling focus on pool boiling. Recent results of pool boiling on nanofluids [1-7] and nanostructured surfaces [8-11] have shown significant heat transfer enhancement compared to plain surface and unseeded liquids, respectively. The investigators working on pool boiling with nanofluids detected nanoparticle coating on their heater surface, which modified the surface characteristics [1-7]. They could visualize the increase in surface roughness with nanoparticle surface coating and the decrease in contact angle (thus the increase in wettability), both of which contributed to enhance critical heat flux(CHF). The authors could reproduce CHF values using pure water on nanoparticle coated surfaces. Significant increases in heat transfer coefficients and the critical heat flux, and dramatic reductions in boiling inception temperatures have been reported by independent research groups dealing with nanostructured surfaces and nanofluids in pool boiling [1-11]. Motivated by the results in the above mentioned studies, the focus of this paper is to propose a compact nanostructured based pool boiler for thermal management applications in microscale. Preliminary tests on this pool boiler were conducted and boiling curves were obtained from a nanostructured configuration and a plain surface configuration. The potential for such compact
pool boilers having no pumping and moving components in the use in microscale cooling applications was exploited (up to about 10 cm) and promising results were obtained. A brief overview of different modified surfaces is presented in Section 2. The nanostructure deposition, experimental setup description, and the experimental procedure are provided in Section 3. Section 4 presents data reduction, and uncertainty analysis. In Section 5 the discussion of the experimental results and thermal performance of the pool boiler is included. Finally, Section 6 presents the conclusions of this investigation.

**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$A_{ef}$</td>
<td>Total effective area of heaters</td>
</tr>
<tr>
<td>$V$</td>
<td>Voltage input to the system</td>
</tr>
<tr>
<td>$I$</td>
<td>Total current passing through system</td>
</tr>
<tr>
<td>$R_{eq}$</td>
<td>Equivalent resistance of heaters</td>
</tr>
<tr>
<td>$P$</td>
<td>Power input to the system</td>
</tr>
<tr>
<td>$R$</td>
<td>Result</td>
</tr>
<tr>
<td>$x_i$</td>
<td>$i^{th}$ Variable</td>
</tr>
<tr>
<td>$w_i$</td>
<td>Uncertainty of $i^{th}$ variable</td>
</tr>
<tr>
<td>$w_R$</td>
<td>Uncertainty of the result</td>
</tr>
<tr>
<td>$q$</td>
<td>Constant heat flux</td>
</tr>
</tbody>
</table>

**2.0 OVERVIEW ON NANOSTRUCTURED PLATES OF THE POOL BOILER**

The glancing angle deposition (GLAD) technique, which is also called oblique angle deposition, is a physical self-assembly growth technique that can provide a novel capability for growing 3D nanostructure arrays with interesting material properties such as high electrical/thermal conductivity and also reduced oxidation compared to the polycrystalline films [12-15]. It is a simple and single-step process that offers a cost and time efficient method to fabricate nanostructured arrays of almost any material in the periodic table as well as alloys and oxides. The GLAD technique uses the “shadowing effect,” which is a “physical self-assembly” through which some of the obliquely incident atoms may not reach certain points on the substrate due to the concurrent growth of parallel structures. Due to the statistical fluctuations in the growth and effect of initial substrate surface roughness, some rods grow faster in the vertical direction. Due to their higher height, they capture the incident particles, while the shorter rods get shadowed and cannot grow anymore. This leads to the formation of isolated nanostructures. The shadowing effect can be controlled by adjusting the deposition rate, incidence angle, substrate rotation speed, working gas pressure, substrate temperature, and the initial surface topography of the substrate.

**3.0 NANOSTRUCTURE DEPOSITION**

The schematic of the custom-made GLAD experimental setup in the present study is shown in Fig.1. For the fabrication of vertically aligned Cu nanorod array, the DC magnetron sputter GLAD technique is employed. Cu nanorods were deposited on the native oxide p-Si (100) substrates (1 x 1 cm$^2$) using a 99.9% pure Cu cathode (diameter about 7.6 cm). The substrates were mounted on the sample holder located at a distance of about 12 cm from the cathode. During the growth, the substrate was tilted so that the angle $\theta$ between the surface normal of the target and the surface normal of the substrate is 85°. The substrate was attached to a steeper motor and rotated at a speed of 1 rpm for growing vertical nanorods. The depositions were performed under a base pressure of 5 x 10$^{-7}$ Torr which was achieved by utilizing a turbo-molecular pump backed by a mechanical pump. During Teflon deposition experiments, the power was 200 W with an ultrapure Ar working gas pressure of 2.5 mTorr and the maximum temperature of the substrate during growth was below ~85 °C. The deposition time of GLAD deposited Cu nanorods was 60 min. For comparison purpose, the Cu thin film samples were also prepared by normal incidence deposition ($\theta = 0^\circ$) with a substrate rotation of 1 rpm. The film thickness of the vertical columns was measured utilizing quartz crystal microbalance (Inficon- Q-pod QCM monitor, crystal: 6 MHz gold coated standard quartz) measurements and cross-sectional SEM image analysis to 8.6 nm/min. The scanning electron microscopy (SEM) unit (FESEM-6330F, JEOL Ltd, Tokyo, Japan) was used to study the morphology of the deposited nanorods. The top and side views of Cu nanorods are illustrated in Fig. 2 in which an isolated columnar morphology can be seen. However, for the conventional Cu film deposited at normal incidence, its surface was observed to be relatively flat as indicated by the SEM images (not shown here). At early stages of GLAD growth, the number density of the nanorods was larger, and they have diameters as small as about 5-10 nm. As they grow longer and some of the rods stop growing, due to the shadowing effect, their diameter grows up to about 100 nm. The height of the individual rod is about 500 nm and the average gap among the nanorods also changes with their length from 5-10 nm up to 50-100 nm at later stages. As can be seen from Fig. 2a, the top of the vertical columns has a pyramidal shape with four facets, which indicates that an individual column has a single crystal structure. This observation was confirmed by previous studies [16-18] which reported that individual metallic nanorods fabricated by GLAD are typically single crystal. Single crystal rods do not have any interior grain boundaries and have faceted sharp tips. This property will allow reduced surface oxidation which can greatly increase the thermal conductivity, robustness, and resistance to oxidation-degradation of our nanorods in the present study.

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Fig. 1. A schematic of the glancing angle deposition (GLAD) technique used for the fabrication of nanorod arrays is shown.
4.0 EXPERIMENTAL SETUP AND PROCEDURE

Experimental Apparatus
The experimental setup is demonstrated in Fig. 3. Manufactured Aluminum Base has air gaps on four sides for minimizing heat losses from the Aluminum Base. The film heaters are located underneath the Aluminum Base and they provide constant heat flux to the system by the constant voltage applied from the ends of the film heaters. The Plexiglas pool is closely fitted on top the Aluminum Base so that water leakage is prevented. The heaters are treated with thermal grease for smooth contact with the Aluminum Base. The nanostructured plate is placed on top the Aluminum Base, which is also treated with thermal grease. Water is filled to the pool and all the results are recorded when water level is 5ml above the nanostructured plate. Thermocouples are placed on the surface of the Aluminum Base at different places for the accurate measurement of the surface temperature.

![Fig. 3. Experimental setup section view.](image)

Experimental Procedure and Uncertainties
After the experimental setup is prepared as explained, the surface temperature readings are recorded as a function of the input voltage and passing current through the heaters by the readings from the power supply. The effective areas of the heaters are tabulated within the manufacturer’s guide and their values are extracted from there. These values are used to calculate the constant heat flux input to the system. At certain values of the constant heat flux, steady state surface temperature values are recorded by the thermocouples until boiling started. The experiment is conducted first without the nanostructured plate to clearly account for the positive effects of the nanostructured plate. Gathered data points are approximated linearly for single-phase and two-phase separately using least squares regression method.

Data Reduction
A parallel resistance circuit is built up with the heaters. Resistance calculations are derived from

\[ V = I \cdot R_{eq} \]

where \( V \) is the voltage reading from the power supply and \( I \) is the current reading from the power supply. Power input to the system is calculated from

\[ P = V \cdot I \]

where \( P \) is the power input to the system, \( V \) is the voltage input and \( I \) is the total current passing through the system. Constant heat flux input to the system is obtained from

\[ q^* = \frac{P}{A_{eff}} \]

where \( P \) is the power input and \( A_{eff} \) is the total effective area of the heaters which is tabulated in the manufacturer’s datasheet.
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 [19].

Table 1. Uncertainty analysis.

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance</td>
<td>3.12</td>
</tr>
<tr>
<td>Power Supply Tracking</td>
<td>0.2</td>
</tr>
<tr>
<td>Power Supply Voltage Reading</td>
<td>0.1</td>
</tr>
<tr>
<td>Power Supply Current Reading</td>
<td>0.1</td>
</tr>
<tr>
<td>Power</td>
<td>0.2032</td>
</tr>
<tr>
<td>Thermocouple</td>
<td>±0.1°C</td>
</tr>
</tbody>
</table>

5.0 RESULTS & DISCUSSION

The results are gathered from the experiment as explained in Section 4. Data points and linear approximations are shown in Fig. 4 and Fig. 5. The effect of the nanostructured plate is clearly observed from the difference in the graphs. The nanostructured plate increases heat removal rate from the system, it also decreases the boiling inception temperature by 2°C. These results show that in the two phase region, the nanostructured plate prevents further increases in the surface temperature thereby resulting in an almost horizontal linearization of the two-phase region which is not the case for the results in the plain surface configuration. The nanorods on the surface of the plate act effectively in the enhancement of boiling heat transfer. The data presented in Fig. 6 shows the superimposed two-phase data from the experiments with and without the nanostructured plate during boiling. The rise in the surface temperature is suppressed with the application of the nanostructured plate. The reason could be explained by the increase in heat transfer area and the number of active nucleate sites so that more bubbles would emerge during boiling from the surface and promote nucleate boiling. This facilitates heat removal from the surface of the plate and stabilization of the surface temperature.
Heat removal in the single-phase region is also promoted with the introduction of the nanostructured plate. The single-phase linear approximations’ slopes are evaluated and 13% decrease in the slope is observed when the nanostructured plate is used. Thus, even in the single-phase the effect of the nanostructured plate is significant due to heat transfer area enhancement (see Fig. 7). Moreover, the nanostructures provide more mixing in natural convection mode and increase natural convection from the surface.

For all of the linear approximations the correlation factors, which quantifies the prediction ability, are calculated and tabulated (see Table 2.). The results indicate that even in the worst case a $R^2$ of 0.958 is obtained by the linear model.

<table>
<thead>
<tr>
<th>Linear Model</th>
<th>$R^2$</th>
</tr>
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<tbody>
<tr>
<td>No Sample, Single-Phase</td>
<td>0.985</td>
</tr>
<tr>
<td>No Sample, Two-Phase</td>
<td>0.958</td>
</tr>
<tr>
<td>Sample 4, Single-Phase</td>
<td>0.984</td>
</tr>
<tr>
<td>Sample 4, Two-Phase</td>
<td>0.999</td>
</tr>
</tbody>
</table>

6.0 CONCLUSION
The results gathered from the experiments properly indicate the advantageous effects of nanorod integrated thin plates on heat transfer magnification and nucleate boiling promotion. Even for such a small area 1.7cmx1.5cm, the nanorod integrated plate acts efficiently. Using these tabulated results, possible further models and experiments, nanorod integrated plates could be used in various cooling applications of small electronic devices, microreactors, micropropulsion, biotechnology, fuel cells and air conditioning. Manufacturing process of the nanorod integrated plates is costly but it is an advancing technology and advancing technologies tend to decrease manufacturing costs which enables the opportunity to use these devices more frequently.

REFERENCES