ABSTRACT

This paper reports a compact nanostructure based heat sink. The system has an inlet and an outlet valve similar to a conventional heat sink. From the inlet valve, pressurized deionized-water is propelled into a rectangular channel (of dimensions 24mmx59mmx8mm). This rectangular channel houses a nanostructured plate, on which ~600 nm long copper nanorod arrays with an average nanorod diameter of 150 nm are integrated to copper thin film coated on silicon wafer surface. Forced convective heat transfer characteristics of the nanostructured plate are investigated using the experimental setup and compared to the results from a flat plate of copper thin film deposited on silicon substrate. Nanorod arrays act as fins over the plate which enhances the heat transfer from the plate.

Excess heat generating small devices are mimicked through a small heat generator placed below the nanostructured plate. Constant heat flux is applied through the heat generator. Thermocouples placed on the heater surface are utilized to gather the surface temperature data. Flow rate and constant heat flux values are varied in order to obtain the correlation between heat removal rate and input power. In this study, it was proved that nanostructured surfaces have the potential to be a useful in cooling of small and excessive heat generating devices such as MEMS (Micro Electro Mechanical Systems) and micro-processors.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Surface area of the nanostructured plate</td>
</tr>
<tr>
<td>$P$</td>
<td>Power input</td>
</tr>
<tr>
<td>$q''$</td>
<td>Heat flux</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>Pressure drop</td>
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</table>
\[ T_s \quad \text{Surface temperature} \\
T_{avg} \quad \text{Average fluid temperature} \\
h \quad \text{Heat transfer coefficient} \\
m \quad \text{Mass flow rate of water} \\
c_p \quad \text{Specific heat of water} \\
T_i \quad \text{Inlet fluid temperature} \\
T_{exit} \quad \text{Exit fluid temperature} \\

1.0 INTRODUCTION

In the design processes of many mechanical and chemical devices one of the key issues of saving energies and achieving compact designs is the enhancement of heat transfer \cite{1}. As heat transfer is enhanced, the cooling process becomes more efficient. In the design of heat exchangers for spacecrafts, automobiles, MEMS devices and micro-processors, it is crucial that the heat exchanger is kept compact and lightweight \cite{2}. For the purpose of making compact and efficient heat exchangers, heat transfer enhancement with nanostructures could be considered as a futuristic candidate.

Recently, many studies have been going on for enhancing convective heat transfer by enlarging the transfer surface using extended surfaces like fins and ribs \cite{1,3-5}. These modifications enlarge the heat transfer surface area and provide high heat transfer rates but their drawback is increased friction factor and unwanted pressure drops. Using pin-fin structures causes pressure losses which is a significant problem in many thermo-fluid applications and designs \cite{1}. Such pressure losses occur because of the additional flow resistance imposed by pin-fins.

To achieve positive effects on heat transfer coefficients with diminishing length scale and high heat transfer performance due to enhanced heat transfer area, nanostructured surfaces have been used in more recent studies \cite{6,7}. The main focus of these studies was utilizing nanostructured surfaces for improving boiling heat transfer. Different from the state of the art, this paper utilizes nanostructures in a forced convective heat transfer scheme so that their potential could be exploited from a different perspective.

For this purpose, this article proposes a nanostructured plate, which comprised of vertical copper nanorods of length \( \sim 600 \text{nm} \) and average diameter \( \sim 150 \text{nm} \) with an average gap among the nanorods ranging from \( \sim 50 \) to \( 100 \text{nm} \) are integrated to copper thin film (50 nm thick) deposited on silicon substrate with a thickness of 400 μm, to enhance heat transfer via single-phase flow in a rectangular channel. Heat transfer coefficients of the system were reduced for a constant heat flux scenario up to 6.5W/cm² and it has been shown that the nanostructured plate enhances heat transfer significantly because of the large surface area of nanorods available for heat transfer, and thus heat removal takes place more effectively. The advantage of such a system is that it does not cause any significant
extra pressure drop and thus does not raise friction factor. Pin-fin geometry imposed by nanorods on the plate (integrated to the channel wall) is on the nanoscale so that the friction forces induce minor pressure losses.

2.0 OVERVIEW ON NANOSTRUCTURED PLATES

The glancing angle deposition (GLAD) technique 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 [8-11]. 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 arrays, the DC magnetron sputter GLAD technique is employed. Cu nanorods were deposited on the native oxide p-Si (100) substrates (2 cm²) 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,

Figure 1. A schematic of the glancing angle deposition (GLAD) technique used for the fabrication of vertical nanorod arrays is shown.
the substrate was tilted so that the angle $\theta$ between the surface normal of the target and the surface normal of the substrate is 87°. The substrate was attached to a stepper motor and rotated at a speed of 2 rpm for growing vertical nanorods. The depositions were performed under a base pressure of $5 \times 10^{-7}$ Torr which was achieved by utilizing a turbo-molecular pump backed by a mechanical pump. During Cu 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 75 min. For comparison purposes, conventional smooth Cu thin film samples (i.e. “plain surface” configuration) were also prepared by normal incidence deposition ($\theta = 0°$) with a substrate rotation of 2 rpm. Deposition rate of the vertical nanorods was measured utilizing quartz crystal microbalance (Inficon- Q-pod QCM monitor, crystal: 6 MHz gold coated standard quartz) measurements and cross-sectional scanning electron microscopy (SEM) image analysis to be about 8.6 nm/min. The SEM unit (FESEM-6330F, JEOL Ltd, Tokyo, Japan) was used to study the morphology of the deposited nanorods. The top and side view SEM images of Cu nanorods are shown 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 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 had diameters as small as about 5-10 nm. As they grew longer and some of the rods stopped growing, due to the shadowing effect, their diameter grew up to about 150 nm. The average height of the individual rod was measured to be about 600 nm and the average gap among the nanorods also changed 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 nanorods has a pyramidal shape with four facets, which indicates that an individual nanorod has a single crystal structure. This observation was confirmed by previous studies [12-14] 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.

4.0 EXPERIMENTAL SETUP AND PROCEDURE

Experimental Apparatus

The experimental setup is demonstrated in Fig. 3. The cooling device is shown in Fig. 4. This heat transfer equipment has an aluminum base of dimensions 25mmx60mmx5mm. The base is made of aluminum for its high machinability and thermal conductivity. On top of the aluminum base, the nanostructured plate is placed and the top side is sealed with a plexiglas top which has poor thermal conductivity in order to minimize heat losses. Therefore, the resulting structure could be also regarded as an isolated rectangular channel heated from its lower surface. There is an inlet and an outlet port of the channel drilled into the Plexiglas top from which water could be pressurized. A miniature film-heater is placed underneath the base in order to simulate heat generated by any device like a micro-processor or a MEMS device. The heater is treated with thermal grease and sealed to the base with an Aluminum cap. The whole setup is then sealed to avoid any leakages.

The heat generated by the miniature film-heater is delivered to the nanostructured plate over which water flows in a rectangular channel for cooling. The heater provides constant heat flux to the system since constant voltage is applied from the ends of the film heater. Water is driven through a precisely controlled micro gear pump and surface temperatures are obtained along with constant heat flux applied to the system. Pressure drop across the system is also determined experimentally using a pressure gauge at the inlet and assuming outlet to be atmospheric. Flow rates are deduced using a flow meter integrated to the system. Thermocouples are placed on the surface of the heater and to the inlet for accurate measurement of the fluid and surface temperatures. Experimental data is gathered under steady state conditions and pressure drop, heat flux and surface temperatures are acquired through the data acquisition devices.
These data points are then exported to MATLAB and MS Visual Studio for further analysis. Data points for the plain surface configuration and the nanostructured plate configuration are compared in terms of heat transfer coefficients and flow velocities.

Figure 3. Experimental Setup

**Experimental Procedure**

After the experimental setup is prepared as explained, the surface and inlet temperatures are measured as a function of the input power data gathered from the readings of the power supply and this operation is carried out for various flow rates. The data collected through the above mentioned procedure is then compared to the setup with nanostructured plate instead of the plain one in order to account for the potential positive effects of the nanostructured plate. The effective areas of the heaters are tabulated in the manufacturer’s guide, from which their values are extracted. These values are used to analytically calculate the constant heat flux input to the system.
Data Reduction

Constant heat flux input, $q''$, to the system is obtained from

$$q'' = \frac{P}{A} \quad (1)$$

where $P$ is the power input and $A$ is the area of the nanostructured plate. The heat transfer coefficient, $h$, is then calculated by

$$h = \frac{q''}{T_s - T_{avg}} \quad (2)$$

where $T_s$ is the surface temperature and $T_{avg}$ is the average fluid temperature. $T_{exit}$ is determined by

$$T_{exit} = T_i + \frac{P}{\dot{m}c_p} \quad (3)$$

where $T_{exit}$ is the exit fluid temperature, $\dot{m}$ is the mass flow rate, $T_i$ is the inlet fluid temperature and $c_p$ is the specific heat of water. $T_{avg}$ is extracted from
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 [15].

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermocouple</td>
<td>± 0.27</td>
</tr>
<tr>
<td>Power</td>
<td>± 1</td>
</tr>
<tr>
<td>Surface Area</td>
<td>± 0.01</td>
</tr>
<tr>
<td>Heat Flux</td>
<td>± 0.14</td>
</tr>
<tr>
<td>Heat Transfer Coefficient</td>
<td>± 0.52</td>
</tr>
<tr>
<td>Flow Rate</td>
<td>± 1</td>
</tr>
</tbody>
</table>

Table 1. Uncertainty Figures in Data

\[ T_{avg} = \frac{T_I + T_{exit}}{2} \] (4)
5.0 RESULTS & DISCUSSION

The experimental results are obtained as explained in Section 4 above. Data points for Reynolds number values varying from 23 to 30 are shown in Fig. 5. Slightly enhanced heat transfer coefficients can be observed from the figure for the cases with the nanostructure. Flow rates (FR) are also shown in the figure. It can be noted that the reduction in the flow rate caused by the nanostructured plate is not significant. This is an advantage over pin-fin geometries where the flow rates are reduced much more significantly at constant pressure drop.

![Heat Transfer Coefficient vs Heat Flux](image)

Figure 5. Heat transfer coefficient versus heat flux is plotted with 23<Re<30.

The results for constant pressure drop 1.0 psi are quite similar to the results for the 0.5 psi case (Fig. 6). The flow rate is reduced slightly and heat transfer is enhanced. It can be observed that enhancement in the heat transfer coefficient on nanostructured plate compared to the plain surface configuration tends to decrease for high heat fluxes in all the results. In other words, cooling enhancement of nanostructured plate is clearer for lower heat fluxes.

![Heat Transfer Coefficient vs Heat Flux](image)
Figure 6. Heat transfer coefficient versus heat flux is plotted with 38<Re<46.

As the constant pressure drop is increased further to 1.5psi (Fig. 7), 2.0psi (Fig. 8) and 2.5psi (Fig. 9), the enhancement of the nanostructure becomes more significant. The reason for this phenomenon can be explained by the fact that the flow rates are higher. In the case of plain surface, the reason for lower heat transfer rate compared to nanostructured surfaces is the presence of a thin layer of fluid which acts as a heat transfer resistance, while on nanorods this layer can be easily broken especially at high fluid flow rates. Heat transfer enhancement up to %136 has been achieved with the experimental setup.

![Heat Transfer Coefficient vs Heat Flux](image)

Figure 7. Heat transfer coefficient versus heat flux is plotted with 54<Re<62.

![Heat Transfer Coefficient vs Heat Flux](image)

Figure 8. Heat transfer coefficient versus heat flux is plotted with 64<Re<76.
Figure 9. Nusselt number versus heat flux is plotted with 23<Re<30.

Figure 10. Nusselt number versus Reynolds number is plotted with 0.4<q<0.7.
Figure 11. Nusselt number versus Reynolds number is plotted with $1.7 < q^* < 2.1$.

Figure 12. Nusselt number versus Reynolds number is plotted with $3.1 < q^* < 3.6$. 
6.0 CONCLUSION

The results gathered from our experimental work indicate the advantageous effects of a nanostructured plate on heat transfer enhancement via a single-phase rectangular channel flow. The vertical nanorods integrated to the copper thin film layer on silicon wafer introduce enhanced surface area and does not cause any significant losses in terms of flow rates at a constant pressure drop scenario. With such a compact setup and integrated nanostructures, the cooling system acts more efficiently.

Using these tabulated results, further investigations and models, nanostructures of different nanorod lengths and diameters can be utilized in various cooling applications of small electronic devices, microreactors, micropropulsion, biotechnology, fuel cells and air conditioning. Further studies include expanding the available parameters further for both lower heat fluxes and higher heat fluxes. The flow rates will also be modified in order to test the nanostructures under different working conditions.
REFERENCES


