Compact nanostructure integrated pool boiler for microscale cooling applications

M. Şeşen[1], W. Khudhayer[2], T. Karabacak[3], A. Koşar[1]

[1]Mechatronics Engineering Program, Sabanci University, Istanbul, Turkey
[2]Department of Applied Science, Engineering Science and Systems, University of Arkansas at Little Rock, Little Rock, AR 72204, USA
[3]Department of Applied Science, University of Arkansas at Little Rock, Little Rock, AR 72204, USA
E-mail: kosara@sabanciuniv.edu

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An efficient cooling system without any external energy consumption that consists of a plate, on which an array of copper nanorods with an average diameter ~100 nm and length ~500 nm is integrated to a planar copper thin film coated silicon wafer surface, a heater, an aluminium base and a pool was developed. Heat is efficiently transferred from the nanostructure coated base plate to the liquid in the pool through boiling heat transfer mechanism. Phase change took place near the nanostructured plate, where the bubbles started to emerge because of the existing wall superheat. Bubble formation and bubble motion inside the pool resulted in effective heat transfer from the plate surface to the pool. Surface temperatures were measured and heat transfer coefficients were calculated for two working fluids; namely, water and ethanol. In this study, it was shown that using nanostructured surfaces can have the potential to be an effective method of device cooling for small and excessive heat generating microsystem applications, such as microelectromechanical systems, or microprocessors.

1. Introduction: With the miniaturisation of microprocessors and microchips, 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 utilised to achieve high heat transfer performance because of enhanced heat transfer area and positive effect on heat transfer coefficients with diminishing length scale [1]. Moreover, nanostructures also provide additional active nucleate sites so that they could promote nucleate heat transfer in boiling [2].

The applications of nanostructured surfaces in boiling mainly focus on pool boiling. Recent results of pool boiling on nanofluids [1, 3–8] and nanostructured surfaces [2, 9–12] 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 visualise 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). By this way, researchers were able to obtain high CHF values using pure water on nanoparticle coated surfaces. Significant increases in heat transfer coefficients and the CHF, 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]. However these studies generally lack a controlled method of nanostructured coating that limits the fundamental understanding of heat-transfer mechanisms in nanoscales as well as applications of such approaches in cooling systems. In this Letter, a unique method of nanostructured coating for micro-cooling systems is presented, with capability of producing nano-features of various shapes, dimensions and material types. The authors recently presented preliminary tests on a copper nanorod array coated pool boiler where conducted and boiling curves obtained were compared to the ones from a conventional planar copper thin film surface configuration [12]. In this Letter, the authors further extend their studies using two kinds of working fluid, namely water and ethanol. Convective heat transfer coefficients for both of these fluids having different thermo-physical properties have been calculated and plotted with the input heat flux. The potential use of such a compact nanostructured pool boiler having no pumping and moving components in microscale cooling applications was exploited (up to about 10 W/cm^2) and promising results were obtained.

2. Experimental: Glancing angle deposition (GLAD) technique [13–16] is a physical self-assembly growth technique that provides a novel capability of growing 3D nanostructured arrays with interesting material properties such as high electrical/thermal conductivity and also reduced oxidation compared to the polycrystalline films. It is a simple and single-step process that offers a cost and time efficient method to fabricate nanostructured arrays of various materials in the periodic table as well as compounds, alloys and oxides. The GLAD technique uses the 'shadowing effect', which is a physical self-assembly process through which obliquely incident atoms preferentially deposit on higher surface points of a rotating substrate (Fig. 1) leading to an isolated columnar morphology. Owing to the statistical fluctuations in the growth and effect of initial substrate surface roughness or pattern, some surface sites grow faster in the vertical direction. Owing to their higher height, they capture most of the obliquely incident particles, whereas the shorter surface points get shadowed and cannot grow anymore. Through the control of deposition parameters of GLAD such as angle of oblique incidence flux, substrate rotation speed and substrate rotation, it is possible to obtain a wide variety of nanostructured arrays with different shapes (rods, springs, zigzags etc.) and sizes (from tens to hundreds of nanometre). In addition, vertical nanorod arrays produced by GLAD have been observed to be single crystal [17–19] that increases their resistance to oxidation because of lack of grain boundaries, and therefore making them superior conductors of heat and electricity. Previously, Li *et al.* [2] demonstrated that tilted copper nanorod arrays produced by an oblique angle deposition technique (which is similar to the GLAD method but without substrate rotation) can significantly boost bubble formation and enhance boiling heat transfer. However, tilted nanorods are more prone to oxidation because of their polycrystalline property that can result in poorer stability and robustness. In addition, tilted nanorods produced by oblique angle deposition without substrate rotation cannot be easily produced with controlled diameters and separations, making systemic investigations towards fundamental understanding of heat transfer from

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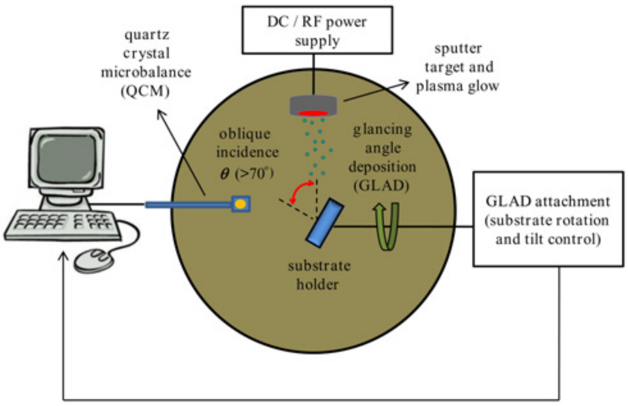

Figure 1 *Schematic of the GLAD technique used for the fabrication of vertical nanorod arrays is shown*

nanostructured surfaces and their implementations in cooling applications more difficult. Therefore it is believed that vertically aligned nanorods (with substrate rotation, i.e. by GLAD) have a potential to further improve the nucleate boiling and boiling heat transfer compared to tilted nanorods (without substrate rotation).

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 nanorods array, the DC magnetron sputter GLAD technique is employed. Cu nanorods were deposited on Cu thin film surface, which is coated on Si wafer (100) substrates (1×1 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 θ between the surface normal of the target and the surface normal of the substrate is 85°. The substrate was attached to a stepper motor and rotated at a speed of 1 rpm for growing vertical nanorods. The depositions were performed under a base pressure of 5×10^{-7} Torr, which was achieved by utilising 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 60 min. For comparison, planar Cu thin film samples (which will be also referred to as 'plain surface' in the following text) were also prepared by normal incidence deposition ($\theta = 0°$) with a substrate rotation of 1 rpm. The film thickness of the vertical columns was measured utilising 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 ~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 SEM images of Cu nanorods are shown in Fig. 2 in which an isolated columnar morphology can be seen. However, surface of the conventional Cu film deposited at normal incidence was smooth 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, because of the shadowing effect, their diameter grows up to about 100 nm. The height of an individual rod is about 500 nm and the average gap among the nanorods also changes with their length from 5–10 to 50–100 nm at later stages. As can be seen from Fig. 2*a*, the tops of vertical nanorods have pyramidal shapes with four facets, which indicate that an individual rod has a single-crystal structure. This observation was confirmed by previous studies [17–19] 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.

The experimental setup for the heat transfer characterisation is illustrated in Fig. 3. Aluminium base has air gaps on four sides to enhance heat transfer with minimum loss from the heater placed beneath the aluminium block. A container made of Plexiglas is closely fitted on top of the aluminium block to create the desired pool for the pool boiling experiments on the nanostructured plate. The heat generated by the film miniature heater is delivered to the nanostructured plate of size 1.7 cm × 1.5 cm through the base. It provides constant heat flux to the system with constant voltage applied from the electrodes of the film heater. The heat flux values are calculated with the division of the wattage readings from the power supply by the tabulated heater active surface area. Heat losses are obtained from commercial software simulation and were found to be minor compared to electrical power since the system is compact and isolated during experiments. Water/ethanol is filled to the pool separately and all the results are recorded for steady-state surface temperatures. Thermocouples are placed near the nanostructured plate at different places for the accurate measurement of the surface temperature and an almost uniform temperature profile was observed.

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 (referred to as single phase) and during boiling (referred to as two phase). The experiment is conducted first without the nanostructured plate to clearly account for the positive effects of the nanostructured plate.

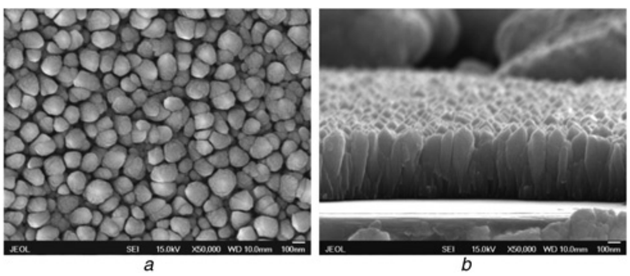

Figure 2 *Glancing angle deposited (GLAD) Cu nanorods*
a Top view
b Cross-section view

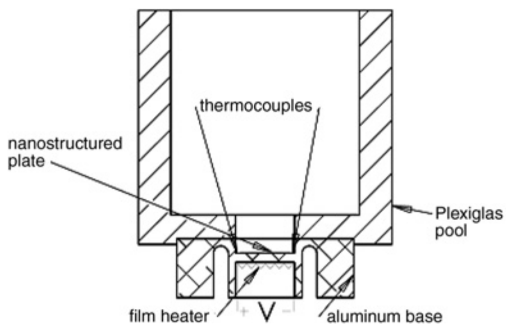

Figure 3 *Experimental setup*

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3. Results and discussion: Figs. 4 and 5 show the heat transfer results comparing plain surface to the nanostructured plate using water and ethanol as working fluids, respectively. The effect of the nanostructured plate is clearly observed from the difference in the superimposed graphs. The nanostructured plate increases heat removal rate from the system. It also decreases the boiling inception temperature by $\sim 2^{\circ}$C for both working fluids. The nanorods on the surface of the plate act effectively in the enhancement of boiling heat transfer. The data presented in Figs. 4*a* and 5*a* show the superimposed two-phase data from the experiments with and without the nanostructured plate during boiling. These results show that in the boiling region the rise in the surface temperature is suppressed

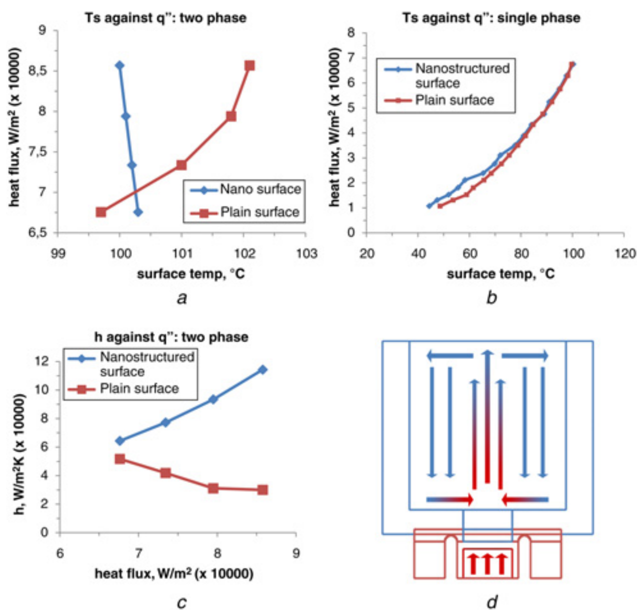

Figure 4 *Results for water*
a Superimposed two-phase heat flux plotted against surface temperature
b Superimposed single-phase heat flux plotted against surface temperature
c Heat transfer coefficient against heat flux for two-phase region
d Schematic of heat removal from the system

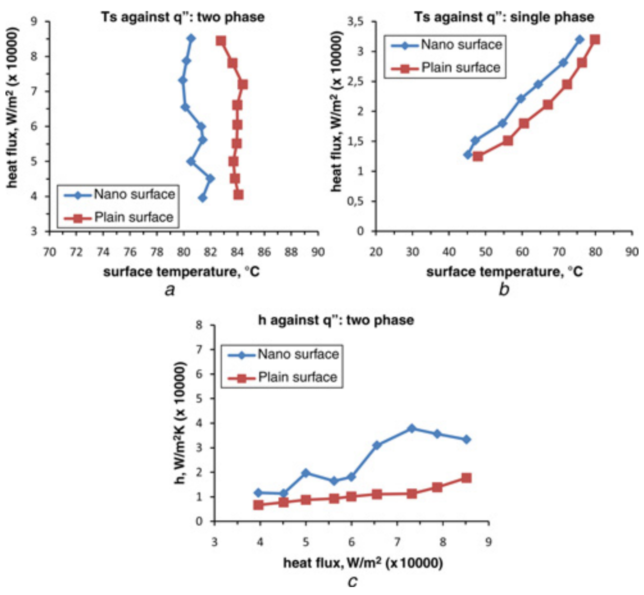

Figure 5 *Results for ethanol*
a Superimposed two-phase heat flux plotted against surface temperature
b Superimposed single-phase heat flux plotted against surface temperature
c Heat transfer coefficient against heat flux for two-phase region

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 nanostructured surface and promote nucleate boiling. Recent studies [2, 20] have shown a significant reduction in the macroscopic water contact angle of some metallic nanorods (such as Pt and Cu), implying the increased wettability because of the enhanced roughness caused by the nanorod structure which, in turn, contributes to enhanced CHF. These effects are believed to facilitate enhanced heat removal from the nanostructured surface of the plate and lead to stabilisation of the surface temperature (Fig. 4*d*).

Heat removal in the single-phase region is also promoted with the introduction of the nanostructured plate. The single-phase linear slopes are evaluated and 13% decrease in the slope is observed with the nanostructured plate for water. In the case of ethanol, the single-phase results indicate an offset introduced by the nanostructured plate, which, in turn, increases heat removal rate. Thus, even in the single phase the effect of the nanostructured plate is significant because of heat transfer area enhancement (Figs. 4*b* and 5*b*).

During boiling, heat transfer coefficients are deduced from surface temperatures and displayed along with heat flux in Figs. 4*c* and 5*c* for water and ethanol, respectively. The results indicate that the heat transfer coefficient behaviour has improved with the nanostructured surface relative to the plain surface configuration (up to 400%). This could be attributed to the reduced wall superheat for boiling inception and promotion of nucleate boiling with nanostructures.

4. Conclusion: In conclusion, these results show that glancing angle deposited nanorod arrays can significantly enhance the nucleate boiling and heat transfer properties leading to superior cooling of the underlying plate. The enhancement in heat transfer was significant especially during boiling, where nanostructured surface had heat transfer coefficient values about up to five times larger than those of planar plain surfaces. Therefore these nanorod integrated plates offer opportunities for enhanced cooling of various applications such as small electronic devices, microreactors, micropropulsion, biotechnology, fuel cells and air conditioning.

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6 References

[1] Ujereh S., Fisher T.S., Mudawar I., Amama P.B., Qu W.: ‘Enhanced pool boiling using carbon nanotube arrays on a silicon surface’. ASME Int. Mechanical Engineering Congress & Exposition, 2005

[2] Li C., Wang Z., Wang P.-I., Peles Y., Koratkar N., Peterson G.P.: ‘Nanostructured copper interfaces for enhanced boiling’, *Small*, 2008, **4**, (8), pp. 1084–1088

[3] Keblinski P., Eastman J.A., Cahill D.G.: ‘Nanofluids for thermal transport’, *Mater. Today*, 2005, **8**, (6), pp. 36–44

[4] Bang I.C., Chang S.H.: ‘Boiling heat transfer performance and phenomena of Al_2O_3–water nano-fluids from a plain surface in a pool’, *Int. J. Heat Mass Transf.*, 2005, **48**, (12), pp. 2407–2419

[5] Vassallo P., Kumar R., D’Amico S.: ‘Pool boiling heat transfer experiments in silica–water nano-fluids’, *Int. J. Heat Mass Transf.*, 2004, **47**, (2), pp. 407–411

[6] Vemuri S., Kim K.J.: ‘Pool boiling of saturated FC-72 on nano-porous surface’, *Int. Commun. Heat Mass Transf.*, 2005, **32**, (1–2), pp. 27–31

[7] Milanova D., Kumar R.: 'Role of ions in pool boiling heat transfer of pure and silica nanofluids', *Appl. Phys. Lett.*, 2005, **87**, (23), article id 233107

[8] You S.M., Kim J.H., Kim K.H.: 'Effect of nanoparticles on critical heat flux of water in pool boiling heat transfer', *Appl. Phys. Lett.*, 2003, **83**, (16), article id 3374

[9] Kim H., Kim J., Kim M.: 'Experimental study on CHF characteristics of water TiO_2 nano-fluids', *Nucl. Eng. Technol.*, 2006, **38**, (1), pp. 61–68

[10] Kim S.J., Bang I.C., Buongiorno J., Hu L.W.: 'Surface wettability change during pool boiling of nanofluids and its effect on critical heat flux', *Int. J. Heat Mass Transf.*, 2007, **50**, (19–20), pp. 4105–4116

[11] Honda H., Takamatsu H., Wei J.J.: 'Enhanced boiling of FC-72 on silicon chips with micro-pin-fins and submicron-scale roughness', *J. Heat Transf.*, 2002, **124**, (2), pp. 383–390

[12] Sesen M., Khudhayer W.J., Karabacak T., Kosar A.: 'A compact nanostructure integrated pool boiler for microscale cooling applications'. ASME Int. Mechanical Engineering Congress & Exposition, IMECE2009–11008, 2009

[13] Karabacak T., Lu T.-M.: 'Shadowing growth and physical self-assembly' in Rieth M., Schommers W. (Eds.): 'Handbook of theoretical and computational nanotechnology', (American. Scientific Publishers, Stevenson Ranch, 2005), Chap. 69, p. 729

[14] Karabacak T., Wang G.C., Lu T.-M.: 'Physical self-assembly and the nucleation of 3D nanostructures by oblique angle deposition', *J. Vac. Sci. Technol. A*, 2004, **22**, (4), pp. 1778–1784

[15] Ye D.-X., Karabacak T., Picu R.C., Wang G.-C., Lu T.-M.: 'Uniform Si nanostructures grown by oblique angle deposition with substrate swing rotation', *Nanotechnology*, 2005, **16**, (9), pp. 1717–1723

[16] Ye D.-X., Lu T.-M., Karabacak T.: 'Influence of nanotips on the hydrophilicity of metallic nanorod surfaces', *Phys. Rev. Lett.*, 2008, **100**, (25), article id 256102

[17] Karabacak T., DeLuca J.S., Ye D., Wang P.-I., Wang G.-C., Lu T.-M.: 'Low temperature melting of copper nanorod arrays', *J. Appl. Phys.*, 2006, **99**, (6), article id 064304

[18] Karabacak T., Wang P.-I., Wang G.-C., Lu T.-M.: 'Phase transformation of single crystal β-tungsten nanorods at elevated temperatures', *Thin Solid Films*, 2005, **493**, (12), pp. 293–296

[19] Karabacak T., Wang P.-I., Wang G.-C., Lu T.-M.: 'Growth of single crystal tungsten nanorods by oblique angle sputter deposition'. Mater. Res. Soc. Symp. Proc., 2004, vol. 788, p. 75

[20] Khudhayer W.J., Sharma R., Karabacak T.: 'Hydrophobic metallic nanorods with teflon nanopatches', *Nanotechnology*, 2009, **20**, (27), article id 275302 (9pp.)

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