Effect of silicon nanorod length on horizontal nanostructured plates in pool boiling heat transfer with water

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Ebru Demir [a], Turker Izci [a], Arif Sinan Alagoz [b], Tansel Karabacak [b], Ali Koşar [a],*

[a] Mechatronics Engineering Program, Sabanci University, Tuzla, 34956 Istanbul, Turkey
[b] Department of Applied Science, University of Arkansas at Little Rock, Little Rock, AR 72204, USA

A B S T R A C T

An experimental study was conducted to investigate the effect of nanorod length on pool boiling heat transfer of water from nanostructured surfaces. Three nanostructured plates featuring Si nanorods of diameter 850 nm and of three different lengths (900, 1800 and 3200 nm), which were etched through single crystal p-type silicon wafers using metal-assisted chemical etching (MaCE), were utilized to enhance pool boiling heat transfer. Nanostructured plates were placed on the bottom of a heated aluminum pool inside a Plexiglas container filled with water, and the surface temperatures of nano-structured plates were measured at increasing heat flux values to quantify boiling heat transfer enhancements, which were obtained with changing the surface morphology using nanostructured plates of different Si nanorod lengths. The experiments were repeated using a plain surface Si plate. A visualization study on bubble formation and release from individual plates was conducted using a high speed camera to bolster the experimental results. Compared to the plain Si surface, boiling heat transfer enhancements up to 254% and 120% were attained using the shortest and longest nanorod configurations, respectively.

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1. Introduction

With the miniaturization of electronic devices, the functionality of such devices greatly increased due to the improvements in their packaging. Recent developments in microsystems technology made it possible for electronic devices to have a continuous increase in their computational powers with continuous reduction in their size. While benefitting from miniaturization process, heat dissipated per unit area by such devices significantly increased. 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 cooled systems and even their improved versions with fin arrays started to fail as the heat removal problems became more demanding. As Upadhye and Kandlikar [1] stated, air is not preferred for microchannel flows due to its low heat transfer coefficient and low specific heat. Due to the superior heat removal characteristics of many fluids (water, refrigerants) compared to air, a paradigm shift in cooling applications

became inevitable so that using such fluids as coolants became a popular trend. Mudawar [2] nominated Fluorinets FC-87, PF-5052 and FC-72 as the most promising Fluorinets in electronic cooling due to their low saturation temperatures of 32.0, 50.0 and 56.6 °C respectively. Cardenas and Narayanan [3] performed jet impingement boiling on heated Cu surface using FC-72. Nguyen et al. [4] found that a heat transfer coefficient increase as much as 40% utilizing Al_2O_3 nanoparticle-water mixture could be obtained compared to the base fluid, namely water.

Still, some advanced electronic systems demanding high heat removal rates rendered single phase liquid cooling applications insufficient [5]. In order to achieve higher efficiency in miniaturized cooling systems, focus of this particular research area shifted towards cooling applications benefiting from phase-change, such as jet-impingement [3,6,7], flow boiling in micro-channels [8,9], and pool boiling [5,10,11]. Conducted experiments repeatedly showed that two-phase cooling systems yielded better results compared to their single-phase cooling counterparts. Mudawar [2] reported a reduction in device temperature rise with boiling compared to single-phase cooling. Although boiling instabilities [12,13] and high pressure losses [14,15] pose disadvantages over single-phase cooling, boiling heat transfer is considered as an effective heat removal mechanism since lower temperature rise in

* Corresponding author. Tel.: +90 216 4839621; fax: +90 216 4839550.
  E-mail address: kosara@sabanciuniv.edu (A. Koşar).

Nomenclature

A	total heated area
h	heat transfer coefficient
P	power input to the system
q''	constant heat flux
T_s	surface temperature
T_{th}	thermocouple temperature reading
T_i	initial temperature of the liquid pool
T_{sat}	saturation temperature of the liquid
Q_{loss}	heat loss
R_{Al}	thermal resistance of aluminum
R_{tg}	thermal resistance of thermal grease
R_{Si}	thermal resistance of Si Plate
R_{tot}	total thermal resistance

surface temperatures is evident with applied heat flux under boiling conditions.

Even though boiling applications are not limited to pool boiling, pool boiling is one of the most popular heat removal mechanisms and is being studied by many researchers. Another significant topic is the effect of nanoparticles and nanostructured surfaces on boiling heat transfer characteristics of cooling systems so that it became a rising trend in the heat transfer community to couple these two methods to attain better heat removal performances. You et al. [16] obtained a dramatic increase around 200% in pool boiling Critical Heat Flux (CHF) compared to pure water by employing nanofluids. Park and Jung [17] reported an increase up to 28.7% in boiling heat transfer coefficients of R22 and water when carbon nanotubes (CNTs) were employed. Ahn et al. [18] observed a 40% increase in CHF using multiwalled carbon nanotubes (CNTs). Xiao et al. [19] emphasized on reduced wall superheat for boiling inception as another advantage of using CNTs in pool boiling applications. Sesen et al. [20] reported up to 400% enhancement in pool boiling heat transfer coefficients using nanostructured plate with Cu nanorods. The abovementioned studies include just some of many experiments, which proved that nanofluids [21–25] and nanostructured surfaces [20,26–29] are very compatible with pool boiling applications and provide a significant enhancement in heat removal performance.

It was repeatedly shown that the heat transfer coefficients and CHF significantly increase when nanostructured plates are utilized in pool boiling applications. Even though the effects of nanofluids on boiling heat transfer coefficients are still controversial [4,16,30], the increase in CHF was widely reported for nanofluids.

As an advantage of nanostructured surfaces, dramatic reductions in boiling inception temperatures [16,21–30] and capability of such surfaces in decreasing the contact angle and increasing wettability in boiling applications [16,27,28,30,31] have been reported in the literature.

Boiling heat transfer performance enhancement attained using nanostructured surfaces are often attributed to 1) increased bubble release frequency [5,26,32], 2) increased nucleation site density [26,33,34], 3) enhanced surface wettability [35–38], 4) enhanced heat transfer area [38,39] introduced by nanostructures. Moreover, overall enhancement achieved through nanostructures is also dependent on many variables -such as the dimensions of the individual nanorods, porosity of the nanostructured surface, tilting angle and distribution of the nanorods on the surface (e.g. random or periodically aligned nanorods) − and these variables must be individually studied in order to have a better understanding of the enhancement mechanisms.

There are several studies in the literature reporting nanorod length effect on boiling heat transfer performance of the system. Lu et al. [39], Im et al. [40] and Yao et al. [37] conducted pool boiling experiments on Cu and Si nanorods of different lengths. However, in none of these studies, nanorod length is singled out as the only variable. Lu et al. [39] observed controversial trends in boiling curves of Si nanorods with different lengths. They reported that the shortest nanorod configuration (16 μm nanorods) yielded the lowest wall superheat at a fixed heat flux value, whereas the wall superheat increased with increasing nanorod length for other samples (122, 59 and 32 μm long nanorods). They attributed this behavior to a change in the number of large cavities resulting from the fabrication process. Similarly, in the study conducted by Im et al. [40], the authors observed a decreasing wall superheat with increasing nanorod length (1, 2, 4, and 8 μm long nanorods). The nanostructures used in the study of Yao et al. [37] were not uniform in diameter, length and array spacing, and the authors used the average nanorod height as the main parameter so that cavity size and surface roughness were left as dependent parameters.

The novelty of this study lies on its separation of the effect of varying nanorod length on heat removal performance in pool boiling. For this, three nanostructured plates, each featuring Si nanorods of different lengths and having the same diameter and spacing were tested, and the results were compared to the measurements obtained from a plain surface Si plate. Surface temperatures were recorded for each of the plates with increasing heat flux values. Furthermore, emerging bubbles from individual plates were visualized with a high speed camera system, and the bubble release frequency from the plates could be obtained.

2. Nanostructure fabrication

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 (NH_4OH, 30% v. : H_2O_2, 30% v. : H_2O = 1 : 1 : 5) at 80 °C for 15 min, 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 [41] 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 ultrasonicating samples in toluene for 1 min, 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.: H_2O_2, 30% v. : H_2O = 4 : 1 : 5). Silicon underneath the gold layer etched and formed well-ordered single crystalline silicon nanorods. Samples were etched for 40 s, 80 s and 160 s in order obtain Si rods of 900, 1800 and 3200 nm lengths, respectively. Finally, gold layer was removed by etching with potassium iodine (KI) solution for 3 min (Fig. 1). In this metal-assisted chemical etching (MaCE) procedure, silicon nanorod diameter is defined by the reduced nanosphere diameter and nanorod separation by initial nanosphere diameter, while nanorod length is set by etching time. The effects of silicon wafer crystal orientation, etching solution concentration, and etching time on nanorod morphology were discussed elsewhere [42].

In determining the length of Si nanorods, the aim was doubling them to produce samples of different length scales (e.g.