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Dynamic wetting and boiling characteristics on micro-structured and micro/nano hierarchically structured surfaces

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ABSTRACT

In this study, we conducted dynamic droplet wetting tests and saturated water pool boiling experiments on micro-structured surfaces with well-ordered micro-sized pillars (MP) and holes (MH), as well as on hierarchically structured surfaces with nano-sized wires on the pillars (MN-P) and holes (MN-H). The dynamic wetting tests revealed that surface morphology significantly affected both the wetting behaviour and state of the test surfaces. On the MP surface, a Cassie–Baxter state was formed by air trapped between the micro-pillars, and droplet rebounding occurred. However, Wenzel or mixed-state wetting occurred on the MH, MN-P, and MN-H surfaces. In addition, the nano-wires enhanced the surface energy and magnified the liquid imbibition parameter of the hierarchically structured surfaces. The dynamic wetting characteristics of the test surfaces significantly affected the boiling critical heat flux (CHF) values. However, the CHF results could not be explained only by the dynamic wetting behaviours of the test surfaces. Thus, in order to reasonably describe the CHF results, we investigated the experimental results with regard to changes in surface energy, bubble nucleation, and capillary pressure potential resulting from the different surface morphologies.

1. Introduction

Nucleate boiling heat transfer (NBHT) is a mechanism that effectively transports a large density of thermal energy from a hot surface to a cooling ambient liquid. Boiling has been used in many engineering and industrial fields that require the transfer of high heat flux, such as in nuclear and coal-fired power plants, electronic chip cooling, and power generation in marine ships. Critical heat flux (CHF) represents the upper limit of NBHT, and the accurate prediction and enhancement of this value are essential for the design of highly efficient and safe boiling systems.

Several surface modification techniques are available to enhance CHF, such as nanofluid boiling, porous layer coating, enhancement of surface wettability, and micro-/nano-structured surface fabrication (MEMS/NEMS). Recently, among these surface modification techniques, MEMS/NEMS technologies have received substantial attention for their ability to enhance boiling on surfaces by fabricating well-ordered micro-structures that can be accurately quantified [1–14]. The types of the micro-structures that can be fabricated by MEMS/NEMS techniques include micro/nano-pillars, micro-holes, nano-holes, and hierarchical structures. Micro-sized structures on a surface can significantly influence the surface roughness, wettability, liquid–solid adhesion, capillary-induced liquid flow, and triple contact line behaviour. Alterations of the CHF values of the micro-structured surfaces would occur due to the comprehensive changes in those effects. Chu et al. [14] presented a CHF correlation to quantitatively predict the CHF value on micro-structured surfaces with uniformly arranged pillars tens of micrometres in size, based on the vapour recoil mechanism for CHF described by Kandlikar [15] and Nikolaryev et al. [16,17]. In this mechanism, CHF phenomena occur when a vapour bubble irreversibly spreads on a surface due to the vapour recoil force generated by rapid evaporation at the liquid–vapour interface.

Furthermore, in other studies [18–20], micro-structure-induced capillary wicking flow has been suggested to be a mechanism critical for enhancing CHF. Other mechanisms that have been suggested to enhance CHF on micro-structured surfaces include thermal conduction on the surface [21,22], changes of Rayleigh–Taylor wavelength [22,23], and the fragmentation of non-evaporating thin films near the triple contact line [12]. However, those interpretations were qualitative, and the generalized theory had not yet been established.

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Dong et al. [13] conducted pool boiling tests on different surfaces decorated with micro-pillars, micro-cavities, nano-pillars (wires), and nano-cavities. In the tests, the CHF values of all micro-structured surfaces were greater than that of a smooth surface. The authors reported that increased bubble departure frequency and capillary wicking arising from interactions between the liquid, vapour, and surface structures contributed to enhancement of the CHF. Moreover, both Kim et al. [6] and Chu et al. [24] reported that surfaces with micro- and nano-sized hierarchical structures showed higher CHF values than surfaces with only micro-sized structures. However, their explanations for the large CHF enhancements on the hierarchical surfaces were quite different. The former [6] focussed on increased wettability and liquid spreading effects, but the latter [24] mainly considered the increased liquid–solid adhesion force arising from increased surface roughness.

In this study, we conducted dynamic droplet wetting tests and saturated water pool boiling experiments on micro-structured surfaces with well-ordered micro-sized pillars and holes, as well as on hierarchically structured surfaces with nano-sized wires on the pillars and holes. The dynamic wetting and CHF of the surfaces were quantitatively analysed, and the results were investigated with regard to changes in surface energy, bubble nucleation site density, and capillary pressure potential associated with variations in surface morphology.

2. Experiments

In order to investigate the liquid–solid interactions and measure the CHF values of the various micro/nano-structured surfaces, we performed dynamic droplet wetting and saturated water pool boiling tests. Surfaces with identical micro-/nano-structures were prepared, and each surface was utilized in both types of experiment.

2.1. Sample preparation and classification

Micro/nano-structured surfaces were fabricated using MEMS techniques. The fabrication method consisted of thin film heaters and micro-structure fabrication (Fig. 1).

First, a 4-in. silicon wafer was prepared. For electrical insulation, a silicon oxide layer (SiO_2, 5000 Å) was deposited on one side of the wafer by plasma-enhanced chemical vapour deposition (PECVD). On the other side, to fabricate the thin film heaters, heater patterns were masked with a photoresist. Thin layers of metal (platinum, 1200 Å and titanium, 120 Å) were deposited on the side with the photoresist by E-beam evaporation. The thin layer of the excluded area of the patterns was removed with acetone. In the pool boiling test, the heating area of the test section was 15 mm × 10 mm. To fabricate micro-pillars and holes, the micro-patterns were masked with a photoresist on the opposite side of the surface with the thin film heater. On the patterned silicon wafer, micro-pillars and holes were fabricated using a dry etching method, deep reactive-ion etching (DRIE). After removing the photoresist with acetone, a silicon oxide layer (SiO_2, 5000 Å) was deposited on the micro-structured surface by PECVD for electrical insulation. Finally, the nano structures on the silicon wafer were fabricated by DRIE machine with the conventional black silicon fabrication methods. The fabricated surfaces were then cleaned with O_2 plasma (600 W, 30 min) and baked at 180 °C for 24 h.

Fig. 2 shows SEM images of the test surfaces with different micro/nano-structures. The test surfaces were classified as bare, micro-hole structure (MH), micro-pillar structure (MP), micro-hole structure with nano-wires (MN-H), and micro-pillar structure with nano-wires (MN-P). The diameters and pitches (centre to centre) of the micro-pillars and holes were identical (40 μm and 80 μm, respectively). The nano-wires were arranged with a pitch of approximately 100 nm, and the height of each wire was a few micrometres.

2.2. Dynamic wetting experiments

Boiling is a complicated and comprehensive phenomenon related to liquid–vapour–solid interactions. Specifically, under high heat flux conditions near the CHF, evaporation from liquid–vapour interfaces, triple contact line movements, and rewetting of the ambient liquid on the heating surface occur rapidly and repeatedly. Thus, the dynamic wetting behaviours of a liquid on a surface might be closely related to boiling under high heat flux conditions.

In this study, we conducted dynamic wetting tests on the surfaces that were used for the pool boiling tests. Fig. 3 shows a schematic diagram of the dynamic wetting experiments. Using a micro-syringe, 0.113-mL droplets of DI water of identical height (60 mm) were placed on the centre of the test surface. For each test case, the droplet diameters were uniformly 6 mm. A support jack (*z*-direction) and *x*–*y* aligners were installed to fine-tune the droplet's impingement. A high-speed camera (Redlake) set at 5000 frames per second was used to visualize the wetting behaviour of the droplet. Sequential images of the dynamic wetting of the droplets were obtained, and the dynamic (advancing and receding) contact angle, liquid wetting length at the bottom, and the droplet height at the centre were measured and analysed. The

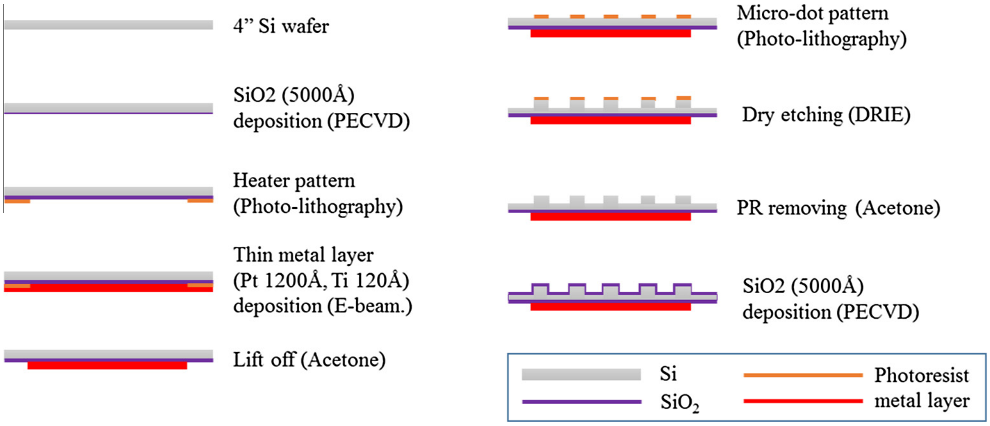

Fig. 1. Sample fabrication method.