International Journal of Heat and Mass Transfer 111 (2017) 614–623

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Superhydrophobic Si nanowires for enhanced condensation heat transfer

Ming-Chang Lu *, Chien-Chang Lin, Ching-Wen Lo, Cheng-Wei Huang, Chi-Chuan Wang

Department of Mechanical Engineering, National Chiao Tung University, Hsinchu, Taiwan

ARTICLE INFO

Article history:
Received 22 November 2016
Received in revised form 7 April 2017
Accepted 7 April 2017

Keywords:
Condensation
Heat transfer
Superhydrophobic surface
Silicon nanowires

ABSTRACT

Condensation is an essential process in various industrial systems. Enhancing condensation by employing superhydrophobic (SHB) surfaces had drawn significant attention in recent years because of the emerging technology for surface engineering. However, the efficacy of SHB surfaces in condensation is controversy in the literature. The observed deteriorated heat transfer on SHB in condensation is presumably a result of highly pinned Wenzel droplets or flooding formed on the SHB surfaces. Si nanowire (SiNW) array-coated surface which can simultaneously provide a large number of nucleation sites and prevent condensate from penetrating into the nano-structure is a promising candidate for enhancing condensation. In this work, heat transfer on the SHB SiNW surface was investigated. At low subcooling, jumping of liquid droplets accompanied with a high droplet departure frequency resulted in a large heat transfer coefficient (HTC) of 88 ± 16 kW/m^2 K on the SHB surface. This value is one of the highest reported condensation HTCs in the literature. It was 155% and 87% higher than those on the plain hydrophilic and hydrophobic surfaces, respectively. Heat transfer decreased with the rise of subcooling due to an increased condensate surface coverage ratio. However, condensate can still be rapidly shed away from the SHB SiNW surface at high subcooling, which render the comparatively larger HTC of 18.6 ± 2 kW/m^2 K on the SHB SiNW surface as opposed to plain hydrophobic and hydrophilic surfaces. It was evidenced that SHB surface could have a superior heat and mass transfer performance than hydrophobic surface provided that the liquid droplets on the SHB could be shed away efficiently.

1. Introduction

Condensation which is a common phenomenon in daily life happens when water vapor in contact with a solid surface whose temperature is lower than its dew point. Condensation is an essential process in various industrial systems, for instance, steam power cycle [1], electronics cooling [2,3], thermal management [4], HVAC system [5], energy harvesting [6], water harvesting [7], desalination [8], and refrigeration cycle [9]. Condensation can be classified into two modes: dropwise condensation (DWC) and filmwise condensation (FWC). Given that liquid water is a poor thermal conductor, a liquid film covered the surface in FWC gives rise to a large thermal resistance, impeding heat and mass transfer. Thus, DWC which offers a higher heat and mass transfer rate is the preferred mode of condensation [10], and Cassie droplets [11] which lead to DWC are favorable. Superhydrophobic (SHB) surfaces with a liquid contact angle of approximately 150° or larger [12–17] can promote Cassie droplets and therefore SHB surfaces have drawn significant attention in recent years for enhancing condensation. While continuous shedding of liquid droplets in condensation was reported on some SHB surfaces [18–25], the loss of superhydrophobicity was also observed on other SHB surfaces [26–31]. Consequently, not all the SHB surfaces could efficiently shed liquid droplets away under condensation. Our previous work suggested a regime map of Bond number < 0.1 and liquid-solid fraction < 0.3 for SHB surfaces for the efficient shedding of condensate [32]. In addition, the effect of SHB surfaces in enhancing condensation is controversy in the literature. Although enhanced heat transfer was observed on some of the SHB surfaces [33–36], inefficacy in promoting heat transfer was also reported on other SHB surfaces [25,37–41]. A low droplet departure frequency and/or flooding were observed on the SHB surfaces [25,37,40], causing the inefficient heat and mass transfer. From the literature, it is reasonable to conjecture that SHB surfaces can potentially enhance heat and mass transfer in condensation provided that the liquid droplets could be efficiently shed away the SHB surfaces. Given that SHB Si nanowires have been demonstrated to have an efficient condensate shedding ability [19,32], we hypothesized that Si nanowires can promote heat transfer in condensation. To the best of our knowledge, condensation heat transfer on Si nanowire (SiNW) arrays had not been reported. Here, we reported our experimental

---

* Corresponding author.
E-mail address: mclu@mail.nctu.edu.tw (M.-C. Lu).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.04.021
0017-9310/

work on condensation on the SHB SiNW surface. A large heat transfer coefficient (HTC) of 88 ± 16 kW/m^2 K was obtained on the SiNW surface at a low subcooling of approximately 1 K, which was 155% and 87% higher than those on plain hydrophilic and hydrophobic Si surfaces, respectively (the subcooling is defined as the temperature difference between the saturation vapor temperature and the surface temperature). This value is one of the highest reported condensation HTCs. Heat transfer decreased with subcooling as a result of increased condensate surface coverage. Nevertheless, the SHB surface still could effectively shed the liquid droplets away and gave a HTC of 19 ± 2.0 kW/m^2 K at a high subcooling of approximately 15 K. This value was 100% and 42% higher than those on the plain hydrophilic and hydrophobic surfaces, respectively. With the advantages of scalable synthesis, inexpensive chemical etching, and large scale application, the enhanced heat and mass transfer observed on the SiNW could lead to practical applications in thermal management in semiconductor devices, energy and water harvesting.

2. Experimental section

2.1. Synthesis of Si nanowires

SiNW surface having microscale cavity for promoting nucleation and nanowires (with a large capillary force) for efficient condensate shedding is a promising candidate for enhancing condensation. The synthesis of the SiNW follows the same procedure as that reported in our previous works [19,32,42,43], which is briefly described here. A Si wafer was immersed in an etchant solution consisted of a 500 mL 10% hydrogen fluoride solution doped with 2 g $AgNO_3$ powder. Electroless etching of silicon nanowires spontaneously occurred on the surface of the wafer. The height of the nanowires is dependent on the etching time. The etched wafer was then cleaned by nitric acid and deionized (DI) water. Consequently, an array of the SiNW could be obtained. The method of fabrication is scalable, inexpensive, and is also compatible with the standard semiconductor manufacturing process. Fig. 1(a) and (b) shows the cross-sectional view and the top view scanning electron microscopic (SEM) pictures of nanowires, respectively. The diameter and spacing of the nanowires are both in the range of approximately 50–300 nm and the height of the nanowire is approximately 10 μm. A thin layer of Teflon of approximately 20 nm was coated on the SiNW surface and the contact angle of 144.3° ± 0.15° was obtained on the SHB SiNW surface. The Teflon layer was coated by using inductive coupled plasma reactive ion etching (ICPRIE) method. The microscale cavities on the SiNW surface are the potential nucleation sites for heterogeneous nucleation. In addition, the high aspect ratio nanowires can provide a large capillary force preventing condensate from penetrating into the nanostructures. The capillary force is inversely proportional to the spacing between the nanowires. Consequently, the condensate on the SiNW surface can be shed away efficiently. Condensations on plain hydrophobic and plain hydrophilic Si surfaces were also investigated for comparison. A layer of Teflon of approximately 20 nm was coated on the plain Si surface for rendering the surface hydrophobic with a contact angle of 102° ± 0.2°, whereas the contact angle on the plain hydrophilic Si surface was 31° ± 0.2°. The errors for the contact angles represent standard errors from five measurements conducted at different locations on

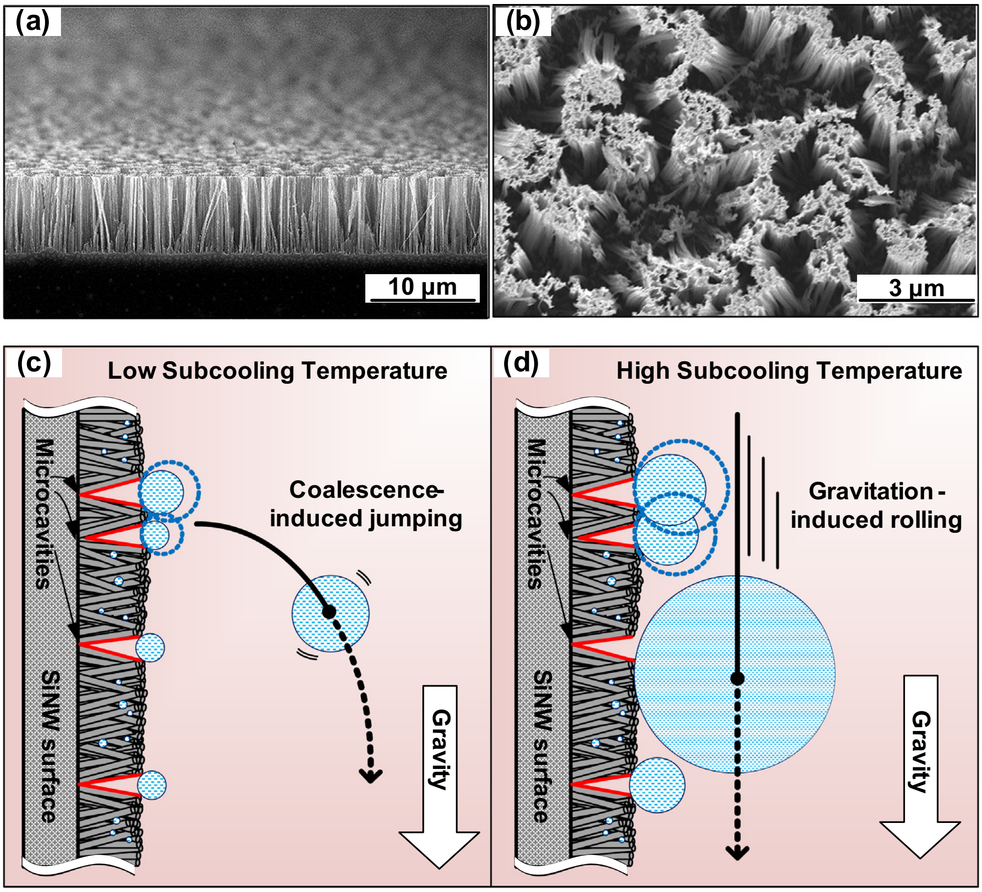

Fig. 1. SEM pictures depicting: (a) cross-sectional view of SiNW surface; (b) top view of SiNW surface; (c) and (d) Schematics of the droplet departure at low subcooling and high subcooling on the SiNW surface, respectively.