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Full paper

Hydrophobic copper nanowires for enhancing condensation heat transfer

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ABSTRACT

Rapid droplet removal by regulating surface topology and wettability has been exploited in nature and it is of great importance for a broad range of technological applications including water desalination and harvesting, power generation, environmental control, and thermal management. Recently there have been tremendous efforts in developing nanostructured surfaces for wettability control and enhancing phase-change heat transfer. However, the tendency of condensed droplets to form as pinned state rather than mobile mode on the nanostructured surfaces is likely to limit the applicability of such functionalized surfaces for condensation heat transfer enhancement. Here, we demonstrate enhanced condensation heat transfer on a nanowired hydrophobic copper surface where molecular permeation of water vapor into the separations between nanowires is greatly decreased, rendering spatial control on droplet nucleation and wetting dynamics. We show experimentally and theoretically that this novel strategy allows to achieve a 100% higher overall heat flux over a broadened surface subcooling range, up to 24 K, due to highly efficient droplet jumping compared to the state-of-the-art hydrophobic surfaces. These findings reveal that the droplet behaviors and condensation modes can be regulated by spatially controlling the droplet nucleation events on the nanowired surfaces, which paves the way for the design of nanostructured surfaces for enhanced phase-change heat transfer.

1. Introduction

Condensation is a ubiquitous phase-change phenomenon [1–3] and has been widely used in energy-intensive industrial applications including water desalination and harvesting [4,5], power generation [6] and environmental control [7], and thermal management of electronic systems [8–10]. Condensation heat transfer performance is highly dependent on surface property and its enhancement promises considerable savings in energy and resources [11–14]. For dropwise condensation on plain hydrophobic surfaces, the gravity-driven droplet removal helps refresh the condensing surface and allows 5–7 times better heat transfer performance when compared to the filmwise condensation [15]. There have been many efforts in promoting dropwise condensation heat transfer through the control of surface wettability [16–18]. Recent studies on nanostructured superhydrophobic surfaces demonstrated that small condensed droplets (< 100 μm) can undergo coalescence-induced droplet jumping which is independent of gravity [19–23], offering a new route to further enhance dropwise condensation heat transfer. Condensation on such functionalized surfaces undergoes four distinct stages including initial nucleation, individual droplet growth, coalescence of droplets, and droplet departure. Understanding the dynamic growth process of condensed droplets from a few nanometers in the nucleation stage to hundreds of micrometers in the shedding stage is the key to developing novel functionalized surfaces for highly efficient droplet jumping and enhanced heat transfer. Careful control of surface structure [24,25],

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nucleation density [21,26], droplet morphology [27], and departure dynamics [28,29] is of great need for the design of nanostructured surfaces for enhancing condensation heat transfer.

Despite the intensive efforts on optimizing micro/nano-structured surfaces for manipulating droplet dynamics [25,29–34], only recently enhanced condensation heat transfer utilizing the droplet jumping mechanism has been experimentally demonstrated on nanostructured superhydrophobic surfaces compared to conventional dropwise condensation on the plain hydrophobic surface, but at very small surface subcooling ($\Delta T < 5$ K) [26,35]. At larger surface subcooling, uncontrolled heterogeneous nucleation leads to a flooding condensation mode, which limits the heat transfer enhancement and thus hindering practical applications of such functionalized micro/nanostructured surfaces. Since the free energy barrier for droplet formation is strongly governed by surface wettability, delicate surface partition with wettability contrast has also been explored to spatially control droplet nucleation [4,36]. However, such surfaces exploiting wettability contrast work only at very small heat flux [37], which inevitable limits its application in pure steam, especially for large surface subcooling.

Significantly different from the above-reviewed approaches that control droplet formation by manipulating surface wettability contrast, in this work we propose a new scheme to control droplet nucleation by exploring the spatial confinement effect, which takes advantage of the reduced molecular permeability of vapor into the separations between hydrophobic nanowires on the condensing surface. By regulating the density difference of water vapor between inside and outside of the separations, droplet nucleation tends to occur at the top nanowires for larger supersaturation, which mitigates droplet formation in separations between nanowires. The novel hydrophobic nanowires allow to achieve a 100% higher heat flux over a broadened surface subcooling range, up to 24 K, due to the highly efficient droplet jumping, compared to state-of-the-art dropwise condensation at the plain hydrophobic surface.

2. Experimental section

2.1. Preparation of condensing surfaces

Due to the wide applications of copper in thermal systems, high purity copper block (99.9% purity) was used to fabricate the test samples in this work. Each test sample was polished by 2000 grit sandpaper, cleaned in an ultrasonic bath with acetone for 10 min, and then rinsed with isopropyl alcohol, ethanol, and deionized (DI) water. The samples were then dipped into a 2.0 M hydrochloric acid solution for 10 min to remove the native oxide film on the surface, then triple-rinsed with DI water, and dried with clean nitrogen gas. For comparison, both plain and nanowired hydrophobic surface has been fabricated as the condensing surfaces on the block.

Copper nanowires on the surface were fabricated by a two-step porous anodic alumina (PAA) template-assisted electro-deposition method (Supplementary Section 1). The PAA template was first bonded onto the sample surface by electrodepositing at −0.8 V for 15 min. During the deposition process, short nanorods (~1 μm) were formed to serve as the screws to connect the PAA and sample surface. In the second step, copper nanowires were fabricated by depositing copper in a three-electrode electroplating cell with the same electrolyte as that in the first step. The length of copper nanowires was controlled by the electrodeposition time. Here, the nanowires with an average height (length) of 20 μm and 30 μm were fabricated by the electro-deposition for 150 and 240 min, respectively. After immersing in 1 M NaOH solution to dissolve the PAA templates and cleaning with DI water, copper nanowired surfaces were obtained.

Hydrophobic functionalization of both the plain and nanowired surfaces was obtained by immersing the samples into a hot (70 °C) ethanol solution of 2.5 mM *n*-octadecanethiol (96% *n*-octadecyl mercaptan) for 60 min. While the self-assembled hydrophobic coating thickened the diameter of nanowires by ~3 nm due to the deposition of *n*-octadecyl mercaptan, the general morphology of nanowired surfaces was left unchanged [38].

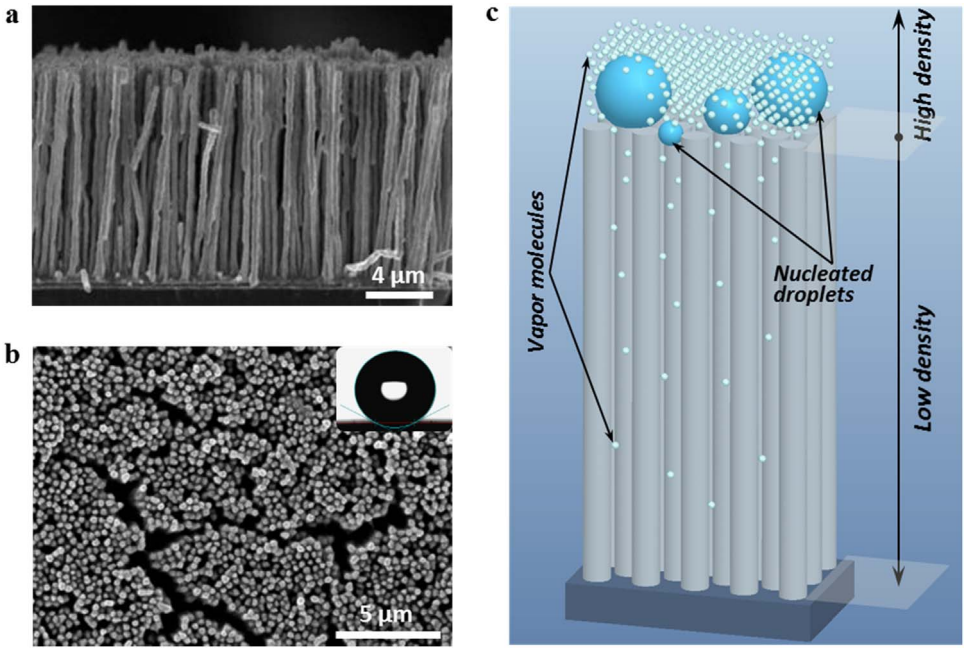

Fig. 1. Hydrophobic copper nanowires. (a–b) Scanning electron microscopy (SEM) images of the hydrophobic copper nanowires: (a) cross-sectional and (b) top view. Characteristic sizes: diameter d=200–240 nm, height h=20 μm, separation l=100–140 nm, and center-to-center spacing w=300–380 nm. Inset: a 5 μL droplet of water sitting on the nanowired hydrophobic surface with an apparent contact angle of 139.2 ± 3.5°. (c) Schematic illustrating spatial confinement effect that prohibits droplet formation in the separations between nanowires due to the reduced permeation of vapor molecules into the separations.