POOL BOILING HEAT FLUX ENHANCEMENT USING BIOTEMPLATED NANOSTRUCTURES

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Abstract: Using the *Tobacco mosaic virus* (TMV) as a nanoscale template, superhydrophilic surfaces have been fabricated and characterized showing significant increases in heat transfer during nucleate pool boiling. We have shown that with the addition of TMV nanostructures to flat, as well as microstructured surfaces, substantial increase in critical heat flux (CHF) and heat transfer coefficient (HTC) have been achieved. Hierarchical structures comprised of deep etched silicon posts conformally coated with TMV nanostructures have demonstrated a CHF of 220 W/cm^2 and a HTC of 41 kW/m^{2}K, comparable to the largest recorded value of CHF to date (~ 230 W/cm^2).

Keywords: Pool boiling, Nanostructures, Biotemplating.

INTRODUCTION

Tobacco mosaic virus incubated micro/nano-structured surfaces, with augmented surface roughness and nanoporosity, exhibit enhanced thermofluidic properties on thermal management schemes. Such properties are ideal for increasing the maximum cooling efficiency point and extend the safe and efficient operation region for industrial thermal cooling systems [1].

Significant efforts have been reported on moderating the heat exchange surface properties to enhance critical heat flux for the past few decades including oblique angle deposition of copper nanorods [2], alumina template based electroplating of copper nanowires on copper, electroless etching of silicon nanowires [3], microreactor assisted ZnO nanoparticle deposition on copper and aluminum substrates [4], chemical vapor deposition (CVD) of multiwalled carbon nanotubes on silicon [5].

Kim et al. [1] showed one of the highest CHF values (~ 230 W/cm^2) reported in the literature for wet chemical etched silicon microposts covered with ZnO nanorods. In addition to nanostructure based hierarchical surfaces for CHF enhancement, researchers also used hydrophilic-hydrophobic mixed surfaces in order to accumulate the benefits of CHF enhancement by hydrophilicity and offsetting the onset of nucleate boiling by hydrophobicity [6].

In this paper, we report the fabrication and characterization of biotemplated nanostructured and micro-nano hierarchical surfaces for pool nucleate boiling. This work uses self-assembled and mineralized *Tobacco mosaic virus* (TMV) as the nanotemplating fabrication process reported in the literature [7] to create superhydrophilic surfaces to manipulate surface heat transfer characteristics for enhanced pool nucleate boiling.

FABRICATION

The *Tobacco Mosaic Virus*

The *Tobacco mosaic virus* (TMV) is a single strand RNA, shown in Fig. 1, exhibits several properties very rare in most of the biomolecules such as high aspect ratio, extraordinary resilience , stability up to 90 ºC with a wide pH range of 2-9 [7]. This cylindrical shaped benign plant virus measures exactly 18 nm outside diameter, 4 nm inside diameter with 300 nm length [7]. The top-down self-assembling property of this virus makes the TMV a promising candidate for building templated nanostructures [7].

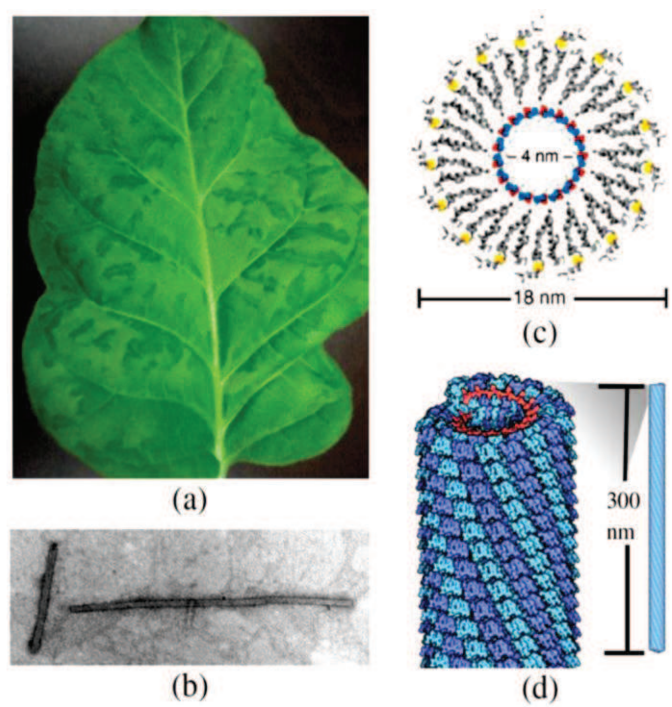

Fig. 1: Image of (a) infected tobacco plant (b) wild type virus along the axial direction [8] (c) disc shaped top [9], and (d) virus protein structure [10]

TMV Incubated Surface Fabrication

For the current work, TMV coated nanostructured and hierarchical superhydrophilic surfaces (~ 0° contact angle) have been fabricated. The TMVs were incubated and metallized on surfaces through a simple room temperature solution based three step processes.

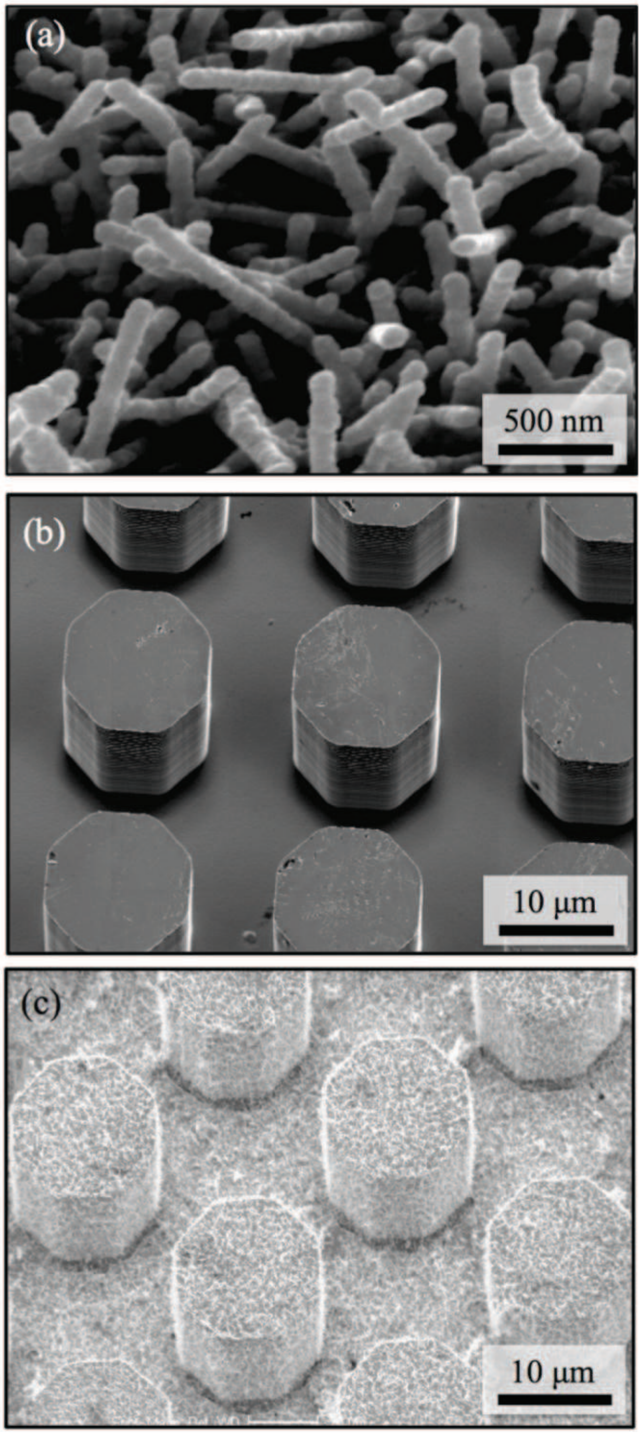

Fig. 2: SEM images of (a) TMV nanostructured surface, (b) microstructured surface, and (c) hierarchical surfaces with micropost array coated with TMV-templated nickel nanostructures

For TMV nanostructured surfaces, as shown in Fig. 2(a), 10 mm × 10 mm diced silicon chips were coated with a thin layer of gold (~40 nm) using thermal evaporation. Then the chips were overnight incubated in TMV1cys solution. After activating the self-assembled viruses with palladium catalyst solution, they were metallized with a thin layer of nickel (~ 40-50 nm) through electroless nickel plating.

For micro and hierarchical surfaces, silicon wafer was patterned through photolithography and deep reactive ion etching (DRIE). The 15 µm diameter and 21 µm center-to-center spacing and 20 µm height micropost arrays were used for the current pool boiling analysis are presented in Fig. 2(b) microstructured surface and in Fig. 2(c) micro/nano hierarchical surface.

EXPERIMENTATION

The pool boiling experimental setup used for the current study is shown in Fig. 3. The setup consists of a copper block with PTFE and mineral wool insulation module as the heating equipment. Two cartridge heaters with total 600 W heating powers controlled with variable autotransformer were embedded into the copper block.

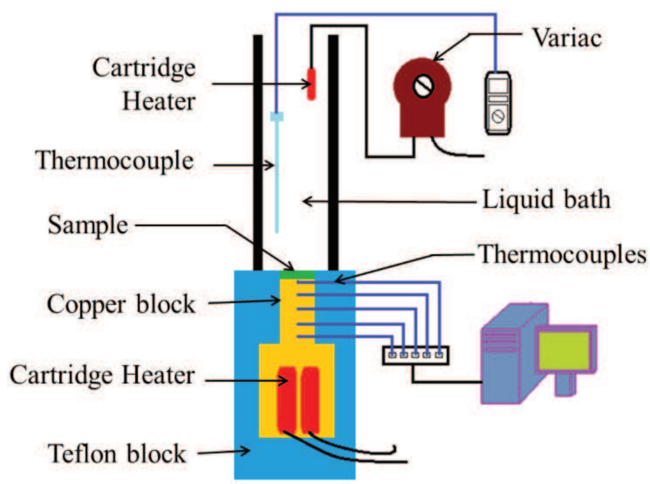

Fig. 3: Schematic of the pool boiling set-up

Five T-type thermocouples, 1 cm equally spaced, were inserted into the copper block to conduct the one dimensional heat flux measurements across the block and to the test surfaces. The silicon samples with 1 µm thermally evaporated copper at the back were soldered to the copper block to provide better thermal contact. The temperature and heat flux measurements were recorded using NI DAQ system.

Degassed, deionized water heated with a cartridge heater to maintain the bath temperature at 100 °C is inserted in a polycarbonate chamber couples with the heater block and test surface. The critical heat flux point is postulated to be the heat flux corresponding to the last observed stable wall superheat beyond which significant increase in surface temperature is observed.

POOL BOILING RESULTS

Figure 4 shows the pool boiling curves for fabricated surfaces comparing the heat dissipation performance of TMV coated nanostructured, microstructured and hierarchical surfaces with flat silicon surface. The CHF value of ~60 W/cm^2 for a flat silicon surface closely matches with the value reported in the literature [11]. TMV Nanostructured surfaces with low contact angle (~9^o) exhibits higher CHF of about 88 W/cm^2. This CHF value closely matches with the CHF value for copper nanowire surfaces with 2 µm nanowire height (85 W/cm^2) reported by Yao et al. [11]. The microstructured nickel surface shows significant heat flux enhancement (~150 W/cm^2) compared to flat silicon and nanostructured surfaces.

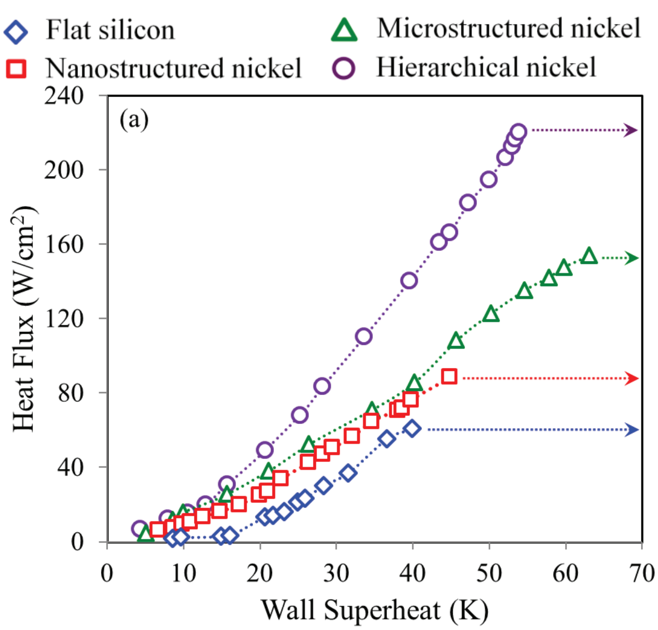

Fig. 4: Pool boiling curves for fabricated surfaces

The maximum critical heat flux value was achieved for hierarchical surface about 220 W/cm^2, more than 250 % higher than Flat Si CHF value. From the heat transfer coefficient curve (Fig. 5) it is evident that heat transfer coefficient for hierarchical surface is significantly enhanced compared to flat Si surface, especially in the high heat flux regions suggesting that micropost arrays are providing sufficient liquid inflow at high heat fluxes along with huge capillary effect by nanostructures [1].

CHF dependence on surface wettability requires an optimized surface morphology which makes a balance between the surface rewetting capability and bubble dynamics based on bubble size [4]. With increasing the surface wettability, surface capillary force increases while bubble diameter and active nucleation site density decreases. The bubble nucleation site density (N_a) can be estimated from Eqn. (1) based on static contact angle (θ) and active cavity mouth radius (D_c) for surfaces [12]. It is evident from Eqn. (1) that with decreasing contact angle the number of active nucleation site density decreases which indicates reduced bubble formation, growth and departure and finally low CHF value.

$$N_a = 5.0 \times 10^5 (1 - \cos\theta) . \frac{1}{D_c^6} \text{sites/cm}^2 \quad (1)$$

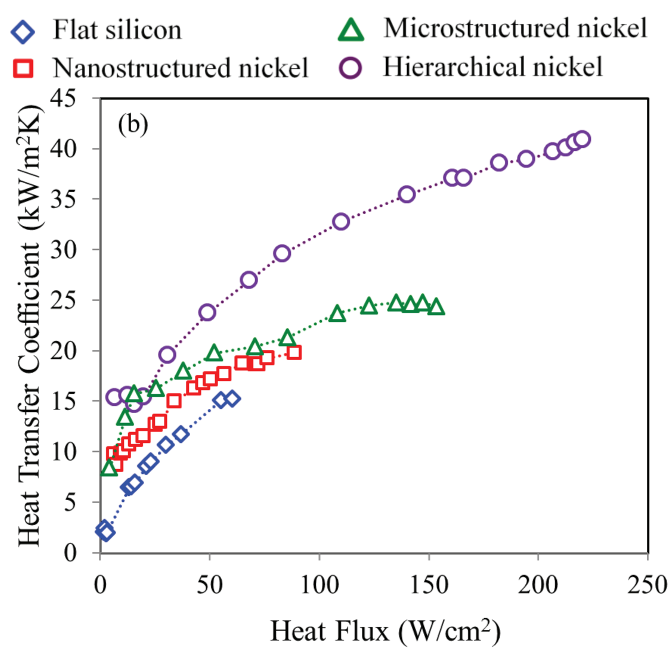

Fig. 5: Heat transfer coefficient curves for surfaces

On contrary, Liaw and Dhir [13] demonstrated that CHF can be increased by decreasing the static surface contact angle based on bubble dynamics analysis. Also, they validated their idea of CHF enhancement with reduced contact angle for a contact angle range of 27^o to 107^o. Hence, CHF augmentation for modified surfaces with static contact angle less than 27^o is not explainable by bubble dynamics only [3]. Pool boiling heat transfer analysis performed by Chen et al. [3] also justifies the concept that CHF enhancement depends on surface morphology providing optimized capillary effect and bubble dynamics. Subsequently, Yao et al. [11] demonstrated that with increasing the nanowire height, the naturally formed microcavity density also increases which in turn enhances CHF significantly. Also, Hendricks et al. [4] showed that CHF increases with decreasing static contact angle up to a value below which based on surface morphology CHF might again decrease with decreasing CA. Hence, these analyses justifies the low CHF enhancement for our nanostructured surface suggesting that a balance between the surface capillary action and bubble dynamics is required to enhance the surface maximum heat flux [4].

From nucleate boiling results, the microstructured surface is showing better heat flux compared to both flat and nanostructured surfaces. During pool boiling, not only surface wettability but also lateral liquid spreading to rewet the dry zones after bubble departure plays an important role in CHF enhancement [14]. Though nanostructured surfaces provide huge capillary force, the significant CHF enhancement for microstructured surface can also be explained by difference in liquid spreadability for both surfaces.

The huge capillary action provided by nanostructures combined with excellent liquid spreadability by micropost arrays could be one reason for significant CHF enhancement for the hierarchical surface [1]. Another reason for CHF enhancement of hierarchical surface could be multiple scale roughness-augmented wettability. Chu et al. [15] demonstrated that with increasing the surface roughness, significant heat transfer can be achieved from a surface. Hence, by adding TMV nanostructures on micropost based rough surface, the surface roughness factor also increases which in turn enhances the maximum heat flux value.

CONCLUSION

This work demonstrates the feasibility of using the *Tobacco mosaic virus* as a nanotemplating material for phase-change heat transfer enhancement. Surface-assembled metal-coated TMV have been used to fabricate superhydrophilic surfaces, which have been characterized during pool boiling. Superhydrophilic nanostructured, microstructured and dual-scale hierarchical surfaces have been characterized. Significant CHF enhancement, of more than 250% for hierarchical surfaces (220 W/cm^2) compared to a flat silicon surface (60 W/cm^2), has been achieved. In addition, the hierarchical surfaces also demonstrated HTC enhancement for all heat flux values.

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