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14. ABSTRACT
This report summarizes our three-year effort on advanced micro and nanostructures for fundamental studies of fluid manipulation and enhanced two-phase heat transfer. First, we studied the role of micro/nanostructures on pool boiling heat transfer. We fabricated well-defined microstructured surfaces in silicon and performed systematic pool boiling experiments in which we demonstrated that increasing surface roughness increased critical heat flux. We developed a force-balance based model, and elucidated the important role of the surface roughness in increasing the contact line length, which as a result augments the capillary force pinning the contact line of the bubble and so delaying vapor film formation. Next, we translated this understanding to investigate the effect of microstructures on two-phase heat transfer in microchannels. We fabricated and characterized microchannels with micropillars arrays on the heated channel wall. Small fluctuations in the measured heater surface temperature (± 3-8 °C) indicated increased flow stability, and the heat transfer coefficient for the structured surface microchannel was 37% higher compared to the flat surface microchannel. More importantly, the mechanism for the increased flow and thermal stability is that the structures, with an enhanced

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Advanced Nanostructures for Two-Phase Fluid and Thermal Transport

AFOSR Grant FA9550-11-1-0059 Final Report

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Abstract:

This report summarizes our three-year effort on advanced micro and nanostructures for fundamental studies of fluid manipulation and enhanced two-phase heat transfer. First, we studied the role of micro/nanostructures on pool boiling heat transfer. We fabricated well-defined microstructured surfaces in silicon and performed systematic pool boiling experiments in which we demonstrated that increasing surface roughness increased critical heat flux. We developed a force-balance based model, and elucidated the important role of the surface roughness in increasing the contact line length, which as a result augments the capillary force pinning the contact line of the bubble and so delaying vapor film formation. Next, we translated this understanding to investigate the effect of microstructures on two-phase heat transfer in microchannels. We fabricated and characterized microchannels with micropillars arrays on the heated channel wall. Small fluctuations in the measured heater surface temperature (± 3-8 °C) indicated increased flow stability, and the heat transfer coefficient for the structured surface microchannel was 37% higher compared to the flat surface microchannel. More importantly, the mechanism for the increased flow and thermal stability is that the structures, with an enhanced capillary wicking capability, help maintain a liquid film on the heated surface. Finally, we successfully developed a flexible uniform responsive microstructure (μFUR) array for dynamic manipulation capability that can be used to promote bubble departure real time in boiling systems. We demonstrated uniform, continuous, extreme tilt angles with precise control and an instantaneous response. Furthermore, we showed that μFUR is capable of real-time manipulation of fluid spreading directionality, fluid drag, and can tune optical transmittance over a large range simply by adjusting the applied magnetic field. The collective fundamental insights gained from our work promises the development of advanced thermal management approaches, among others, for various defense systems.

Motivation and Program Goals:

In this research program, we studied the role of advanced nanostructures to manipulate coupled fluidic and heat transport processes for high performance thermal management devices. Thermal management is a critical bottleneck for the advancement of a variety of important defense, space, and commercial applications. Pumped phase-change based microfluidic systems promise compact solutions with high heat removal capability. However, challenges in implementation lead to poor heat transfer performance. One of the primary limitations is the inability to remove bubbles during boiling, which results in large interfacial resistances, flow instabilities, and drastic decreases in cooling performance. We developed state-of-the-art micro and nanoengineered surfaces and investigated the role of these surfaces on enhancing boiling heat transfer. Furthermore, we demonstrated a platform that promises real time bubble removal for enhanced flow stability. Below is a summary of our achievements that elucidate the role of micro/nanostructures for boiling heat transfer and demonstrate real time manipulation with magnetically tunable structures.

1. Role of Micro/Nanostructures on Pool Boiling [1, 2]

We investigated the role of micro/nanostructures to enhance boiling for high heat flux dissipation. While fundamental boiling research has for decades focused on increasing the critical heat flux (CHF) to extend the heat transfer efficiency of phase-change systems, the role of surface roughness on CHF has not been well-understood. This is the first step towards implementing such surface structures for enhanced phase-change heat transfer. Previous studies have demonstrated that the use of nanostructures, such as silicon nanowires, can increase CHF to >200 W/cm^2, which has been attributed to the capillary pumping mechanism, *i.e.*, for smaller spacing between structures, higher capillary pressure is available to provide the liquid supply to delay CHF [3].

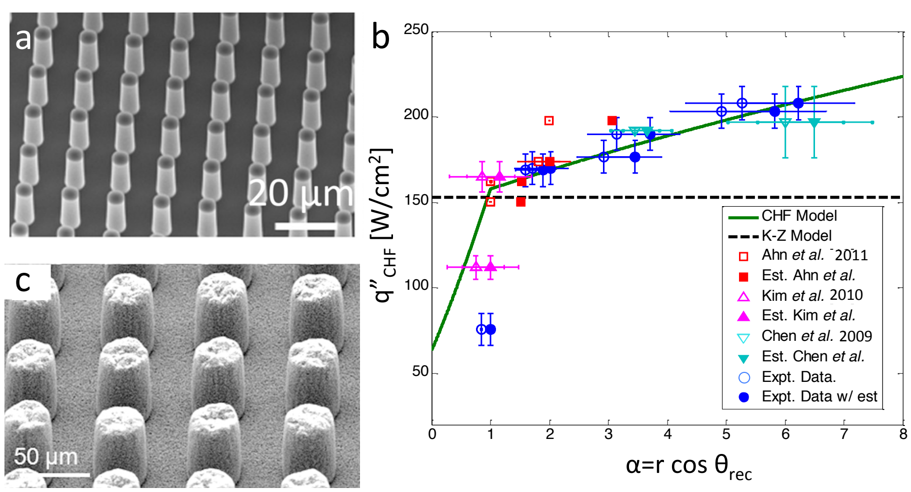

Figure 1 Enhanced pool boiling heat transfer. a) Microfabricated well-defined pillar arrays in silicon to investigate role of surface roughness on CHF [1]. b) CHF as a function of α, where *r* is the roughness and θ_{rec} is the receding contact angle. The symbols are from data in our work as well as reported in literature. The solid line is our developed model. The dotted line is the K-Z model based on hydrodynamic instability [1]. c) Image of fabricated hierarchical surfaces with copper oxide nanostructures and copper pillars [2].

We fabricated well-defined microstructured surfaces in silicon (Figure 1a) and performed systematic pool boiling experiments in which we demonstrated that increasing surface roughness, *r* (=total area/projected area), increased CHF. Furthermore, the results showed that microstructures could also dissipate heat fluxes comparable to those on nanostructures, which indicated that the capillary pumping mechanism did not well-explain the CHF mechanism in this case. Accordingly, we developed a force-balance based model, and elucidated the important role of the surface roughness in increasing the contact line length, which as a result augments the capillary force pinning the contact line of the bubble and so delaying vapor film formation [1]. Our model showed excellent agreement with our experiments as well as those reported in past work (Figure 1b). Note that the commonly used Kutateladze-Zuber (K-Z) model based on hydrodynamic instabilities does not capture the effects of surface roughness on CHF. In addition, these insights suggested a path to further enhance CHF by increasing surface roughness *via* hierarchical designs. We recently demonstrated CHF values of ≈250 W/cm^2 using copper oxide nanostructures on electroplated copper micropillars with a r=13.3 (Figure 1c), which showed excellent agreement with the developed model and further supports our explanation for CHF enhancement [2]. These studies show new insight of the role of structured surfaces in enhancing CHF and provide basic design guidelines as a first step for new surface technologies with high heat removal capability for advanced thermal management applications.

2. Enhanced Flow Boiling Heat Transfer in Microchannels with Structured Surfaces [4]

Building on the understanding gained from the research described in Section 1, we subsequently studied the fundamental effect of microscale surface structures on flow boiling, which is more practical for implementation. However, with the introduction of the flow, the role of the structures on phase change will be different than in the case of pool boiling. Therefore, we performed systematic parametric studies to investigate the details of the flow with the incorporation of surface structures. We fabricated and characterized 500 μm × 500 μm × 10 mm microchannels with micropillars arrays (heights of ~ 25 μm, diameters of 5–10 μm and pitches of 10–40 μm) on the bottom channel wall, where heat was applied (Figure 2). With a custom experimental setup, we investigated the effects of the geometry of the micropillar arrays on the heat transfer performance with degassed, de-ionized water as the working fluid. The flow patterns were simultaneously visualized, which indicated that nucleation occurred primarily on the side walls.

The experimental data showed a significant heat dissipation capability through the structured surface microchannel (q" = 1470 W/cm^2 and h = 2.7×105 W/m^2 K, with a mass flux of 1849 kg/m^2•s and a heater temperature rise of 45 °C). The small fluctuations in the measured heater surface temperature (±3-8 °C) indicated increased flow stability. When compared to the structured surfaces, higher fluctuations in both pressure and heater temperature were observed for a flat surface microchannel at lower heat fluxes. While the overall maximum heat flux values were comparable, the heat transfer coefficient for the structured surface microchannel was 37% higher. The enhanced performance and reduced temperature fluctuations support the idea of using structured surfaces to mitigate flow instability and increase heat transfer performance. We attribute the increased flow and thermal stability to the fact that the structures, with an enhanced capillary wicking capability, help maintain a liquid film on the heated surface.

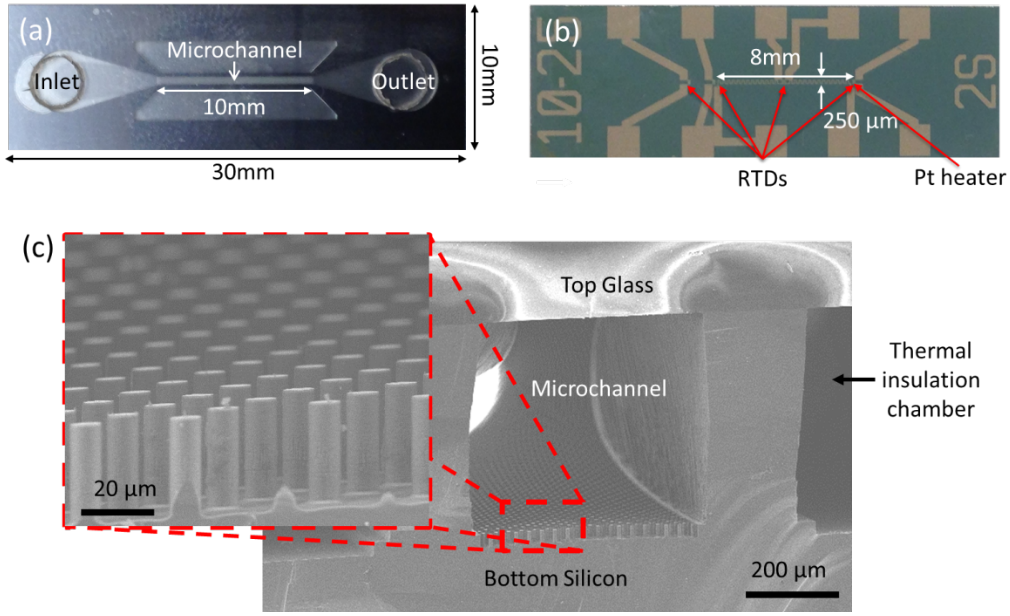

Figure 2 Images and SEM of fabricated microchannel. (a) Top and (b) bottom view image. (c) SEM of the cross section image of a representative, fabricated microchannel and magnified view of micropillars on the channel bottom surface (inset).

Our observations suggest that with these microchannel designs, two-phase heat transfer and fluid flow behavior can be decoupled. Bubbles are generated via the less hydrophilic sidewalls while the superhydrophilic microstructures at the bottom of the channel enhance the capillary wicking capability to prevent dry out. This approach can potentially increase the critical heat flux and is an important step towards understanding the role of microstructured surfaces in microchannels for high performance two-phase microchannel heat sinks.

3. Real-Time Manipulation with Magnetically Tunable Structures [5-7]

We successfully developed a flexible uniform responsive microstructure (µFUR) array for dynamic manipulation capability that can be used to promote bubble departure real time in boiling systems. Responsive actuating surfaces have attracted significant attention as promising materials for liquid transport in microfluidics, cell manipulation in biological systems, and light tuning in optical applications via their dynamic regulation capability. Significant efforts have focused on fabricating static micro and nanostructured surfaces, even with asymmetric features to realize passive functionalities such as directional wettability and adhesion. Only recent advances in utilizing materials that mechanically respond to thermal, chemical or magnetic stimuli have enabled dynamic regulation. However the challenges with these surface designs are associated with the tuning range, accuracy, response time and multi-functionality for advanced systems.

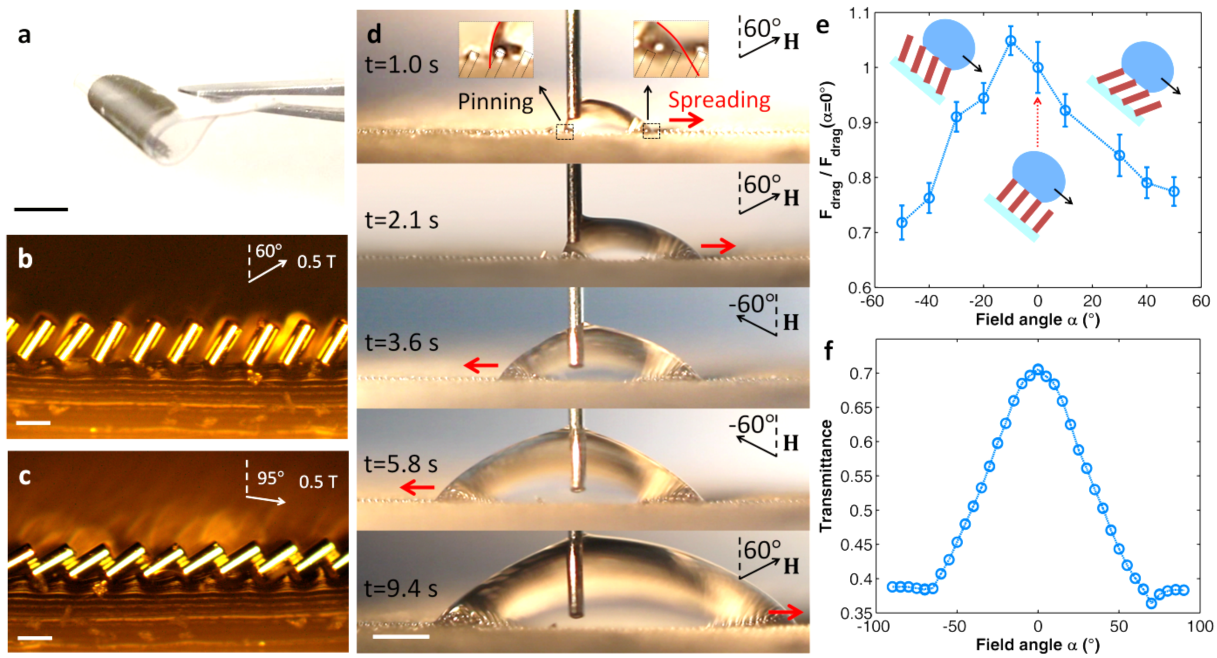

Figure 3 a) The fabricated flexible uniform responsive microstructures (μFUR). Scale bar is 5 mm. Side view images of the fabricated μFUR with an applied magnetic field strength of 0.5 T and field angle of b) α = 60° and c) α = 95° respectively. Scale bars are 50 μm. d) Fluid (30% IPA and 70% water) spreading direction is dynamically controlled while the fluid only propagates in the pillar tilt direction (red arrow) and is pinned in all other directions. Field strength is 0.5 T. Scale bar is 0.5 mm. e) Normalized drag force as a function of the field angle. Field strength is 0.35 T. The negative sign represents that the tilt direction is against the sliding direction. f) Transmittance of a 635 nm laser as a function of the magnetic field angle. Magnetic field strength is 0.35 T.

In this work, we demonstrated dynamically tunable micropillar arrays (Figure 3a) with uniform, reversible, continuous and extreme tilt angles (Figure 3b and 3c) with precise control for real-time fluid and optical manipulation. Inspired by hair and motile cilia on animal skin and plant leaves for locomotion, liquid transportation and thermal-optical regulation, our flexible uniform responsive microstructures (μFUR) consist of a passive elastic polymer skin and active ferromagnetic microhair whose orientation is controlled by a magnetic field. We experimentally showed uniform tilt angles ranging from 0° to 57°, and developed a model to accurately capture the tilting behavior.

The surfaces were created by fabricating ferromagnetic micropillars and then bonding to a soft PDMS substrate. A dense array of nickel pillars with diameters (d) of 26-30 μm, heights (h) of 70-75 μm, and spacings (l) of 60 μm was electroplated. The nickel posts were subsequently bonded to a PDMS surface through a silica adhesion layer. The fabrication of μFUR was demonstrated repeatedly over an area of 8 mm × 8 mm and can be easily scaled to larger arrays.

We showed that μFUR is capable of *real-time* manipulation of liquid spreading directionality, fluid drag, and optical transmittance. First, we achieved real-time liquid directional spreading by dynamically changing the pillar tilt orientation and angle (Figure 3d), where past studies have only shown uni-directional wetting in a fixed direction on static asymmetric structures. We also showed that μFUR can tune the drag force with high surface tension fluids, e.g., water, with a maximum reduction in drag of 28% (Figure 3e). Furthermore, we demonstrated that by utilizing the asymmetry of the microstructures, the surface can function similar to 'window blinds', where the transmittance can be tuned in a range of 0.38 to 0.71 (Figure 3f). The versatile surface developed in this work enables new opportunities for real-time fluid control, cell manipulation, drag reduction and optical tuning in a variety of important engineering systems, including applications that require manipulation of both fluid and optical functions. Furthermore, we anticipate such a surface can be incorporated into microchannels to increase flow stability during phase-change by promoting bubble departure real time.

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