

## Lasered Roughness to Increase Wicking Rates in Pin-Fin Microstructure

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### ABSTRACT

*In this study, we demonstrate an inexpensive and fast method of creating hybrid microstructures for enhancement of capillary wicking by using UV laser ablation. We have also experimentally observed that capillary wicking rates are greatly increased by laser-machining induced surface roughness in pin-fin microstructures, and in one case the amount of enhancement was as large as 116%. The capillary wicking enhancement is a strong function of the geometry of the largescale pin-fin microstructures as well as the surface roughness of the flat areas. This study will help lead to the better understanding of capillary wicking in hybrid structures that in turn can assist with more informed designing and optimization processes of evaporator wicks in vapor chambers.*

### INTRODUCTION

Capillary wicking has been a widely studied phenomenon which is important in a variety of applications like microfluidics [1], thermal management systems [2], electro-chromatography [3] and biomedical devices [4]. More importantly, capillary wicking rate is one of the major parameters that govern the performance of Silicon based vapor chambers for effectively spreading extreme levels of heat flux from localized hot-spots in power electronics cooling applications. Faster capillary wicking in the wick microstructure, which is associated with higher fluid replenishment rate in the wick leads to better thermal performance of these vapor chambers. Recently, it has also been observed that hybrid structures formed by the combination of nanoscale roughness elements overlaid on top of a much larger microstructure backbone leads to much faster wicking and thereby higher thermal performance. Zhang et al. created a 3D hierarchical hybrid structure growing nanowire like elements on the surface of pillar arrays. This required a combination of very

expensive processes such as mirror interference lithography, Atomic Layer Deposition (ALD), hydrothermal nanowire synthesis followed by pattern transfer and Reactive Ion Etching (RIE). [5] In this study, we first demonstrate the ability to create hybrid microstructure out of Silicon with ease using a commercial benchtop UV laser marking system – a method which is more than 20x cheaper and faster than the one employed by Zhang while fabricating hybrid structures [5]. Next, we aim to experimentally observe the effect of roughness on capillary wicking rates of different designs of microstructure. We have fabricated a set of micropillar arrays using deep reactive ion etching (DRIE) process and another using a Nd/YVO<sub>4</sub> UV laser system – the laser cut samples having much higher surface roughness than the DRIE etched ones. It has been shown experimentally that for most samples, the roughness induced by laser fabrication leads to increased wicking rate, by more than 100% in one case depending on the microstructure geometry.

### EXPERIMENTAL METHODS

#### *Sample Fabrication*

We have chosen a square array of circular pillars with diameter of 100  $\mu\text{m}$  as the choice of our microstructures because such pin-fin based microstructure is very commonly used in evaporator wicks of vapor chambers. Two sets of samples, one set smooth and the other, rough, have been fabricated –

#### 1. DRIE etched smooth samples –

Deep reactive ion etching has been a widely used technique by the semiconductor industry for achieving high aspect ratio anisotropic structures. First, we clean 4'' dia. Si wafers in piranha solution (10% H<sub>2</sub>O<sub>2</sub>, 90% H<sub>2</sub>SO<sub>4</sub>) at 120°C for 20 mins. Following HMDS (HexaMethylDiSilazane) priming for better adhesion of photoresist to the wafers, we coat it with a

uniform 4  $\mu\text{m}$  thick coating of SPR 220-3 by spinning the wafer at 2000 RPM. The wafers are exposed with our microstructure design in the Heidelberg Maskless Aligner (wavelength: 405nm, Energy dose: 240 mJ/cm<sup>2</sup> with the exposing beam defocused 2  $\mu\text{m}$  above the photoresist surface) and then developed by using MF26A developer via a two-step puddle dispensation for 90s. Subsequently, the wafers are baked at 110°C for 2 hours to harden the photoresist before the etching step. Then, the wafers are etched in the Plasma Therm Versaline deep Si etcher which uses a Fluorine/Chlorine based Bosch process to achieve the desired height of the microstructure. Finally, the wafer is cleaned again in hot piranha solution to remove the photoresist and diced in the DISCO WaferSaw to obtain individual chips for experiments. The chips were each of size 12 x 5.5 mm with pillar arrays dispersed uniformly. The RMS roughness of the pillar surfaces were found to be around 0.5  $\mu\text{m}$ .

## 2. Laser cut rough samples –

The DPSS Samurai UV laser marking system have been used to fabricate these set of samples. The drawing file for the

microstructure is first made in Solidworks and then exported to WinLase Professional, which is used to interface with the laser. Several parameters can be tuned in the laser that controls the etch depth and surface roughness. We have operated the laser at 100% power which is equivalent to a sustained average power of 1 kW, the lasing speed has been set at 100 mm/s. Fill spacing, which is the spacing between two consecutive and adjacent lasing paths, has been identified as an important parameter that governs the surface roughness obtained in the microstructure. In this study, we have kept the fill spacing constant at 10  $\mu\text{m}$  – this value produces samples with the best surface finish and smallest surface roughness. The number of laser passes can be changed to control the height of the microstructure. It has been observed previously that the intense laser ablation process creates nanoscopic roughness elements overlaid on top the larger pillar backbone creating a hybrid rough microstructure. [8] The RMS surface roughness in our samples was characterized to be around 2.5 to 3  $\mu\text{m}$ , which is only about 2  $\mu\text{m}$  greater than that of the smooth samples.

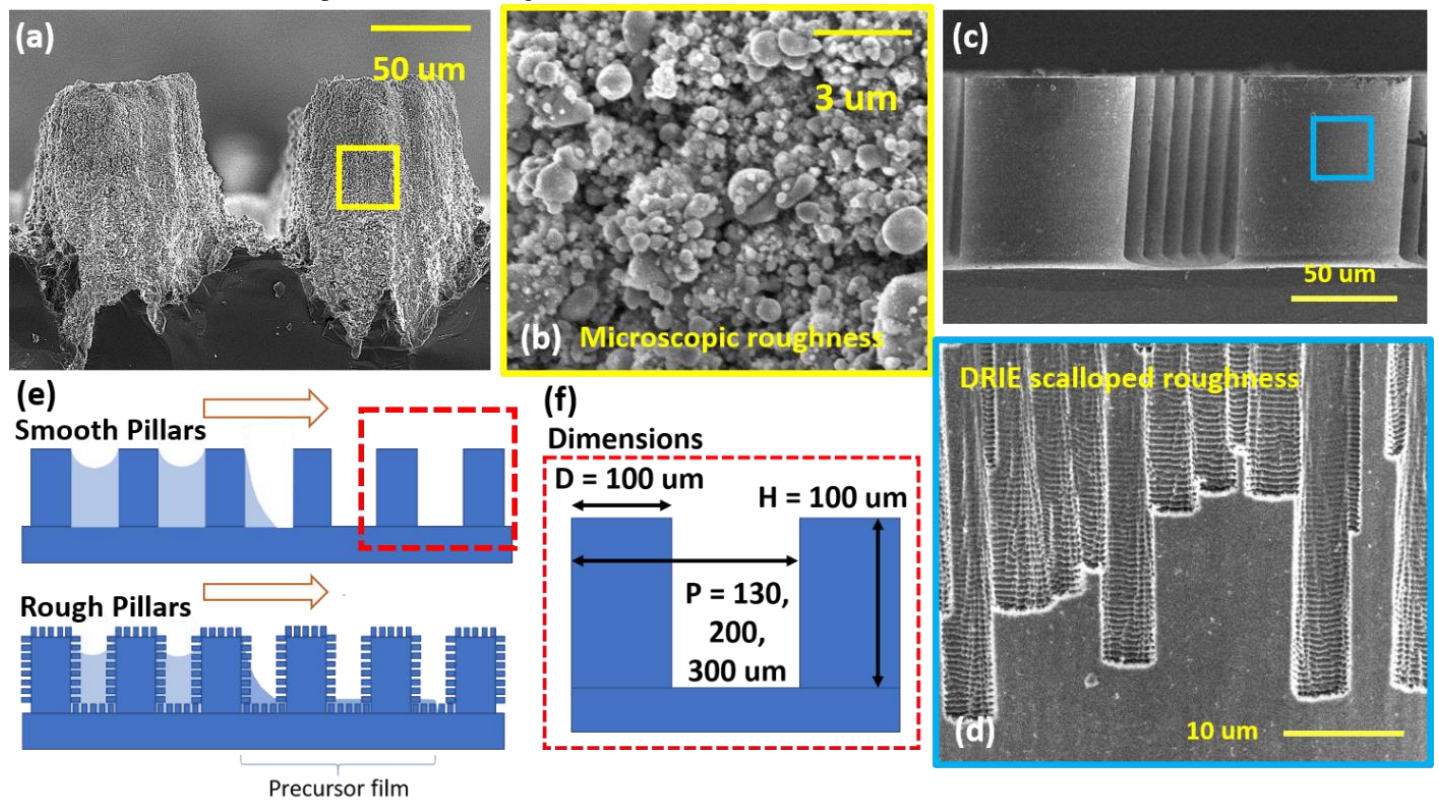


Fig. 1. a) SEM image of the laser ablated rough pillars; b) SEM image of polyp like roughness seen on the laser ablated pillar surface; c) SEM image of the smooth pillars fabricated through DRI Etching; d) Scalloped sidewall profile seen in these smooth pillars, roughness within these scallops were of the order ~500 nm; e) Shows topographical differences between smooth microfabricated samples with the rough laser ablated samples through a schematic. Also shows the differences in fluid wicking behavior in the smooth and rough samples. In the smooth sample, liquid zips from one pillar to the other while in the rough samples, the base roughness forms a thin liquid precursor film that drives the bulk fluid into the microstructure; f) Dimensions of the pillars that were fabricated and tested using DRIE and UV Laser ablation.

## Experiments

One dimensional vertical capillary rate of rise experiment is a very common technique to characterize the wicking performance of different structures. [7] The samples are first washed thoroughly in acetone and IPA, followed by 2 mins of oxygen plasma treatment to remove organic contaminants from the surface. The samples are then mounted vertically on a z-stage

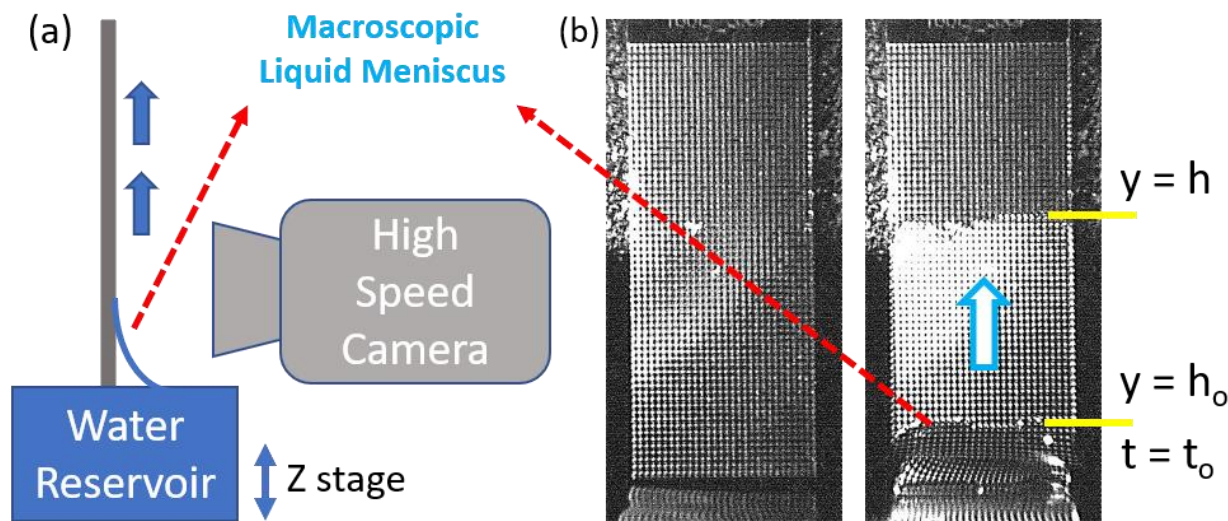


Fig. 2: a) Schematic showing the capillary rate of rise experimental setup, with the sample mounted vertically facing the high-speed camera. As it is dipped in the liquid reservoir, liquid rises in the microstructure because of its capillary pressure; b) Actual images of the capillary rise in our samples, the macroscopic liquid meniscus formed at the interface between water and sample is also shown

This one-dimensional capillary spreading behavior can be modeled by balancing the capillary force within the sample with the viscous resistance and gravitational effect as done by Washburn [6] –

$$\frac{\sigma}{R_{eff}} = \frac{\varepsilon\mu h}{K} \frac{dh}{dt} + \rho gh$$

In our cases relative importance of gravitational forces (quantified by Bond Number) and inertial forces (quantified by Weber Number) with surface tension forces were found to be in the order of  $10^{-3}$  and  $10^{-4}$  respectively, and thus were neglected. This enabled us to reduce the previous equation further to obtain the Washburn equation. [6]

$$h = \sqrt{\left(\frac{2\sigma}{\varepsilon\mu}\right)\left(\frac{K}{R_{eff}}\right)t} \text{ or } h = Gt^{1/2}$$

The exact values of permeability,  $K$  and effective pore radius,  $R_{eff}$  of a microstructure is very difficult to estimate independently. The parameter  $\left(\frac{K}{R_{eff}}\right)$  has thus been widely used as a metric that governs fluid wicking in any microstructure [7]. We further simplified it to include the fluid properties (since water was the only wicking fluid used) and microstructure

and slowly dipped into a liquid reservoir. The motion of the liquid meniscus from the reservoir into the microstructure is tracked by using a Hadland iX high speed camera. (fig. 2) The obtained videos are processed in MATLAB to obtain the capillary rise curves for each of our samples. Experiments were repeated multiple times for each sample to demonstrate repeatability and reliability of performed tests.

porosity in it to identify a parameter  $G$ , which we call the rise coefficient. A larger value of  $G$  indicates faster wicking in the microstructure.

## RESULTS AND DISCUSSIONS

After conducting capillary rate of rise experiments for our samples, we observed that roughness obtained in the laser fabricated samples showed faster capillary wicking. The reason for wicking enhancement in rough samples as compared to the smooth samples can be attributed to the difference in flow patterns in these two types of samples as schematically represented in fig. 1e. The liquid meniscus zips from one pillar to the other in the smooth samples. In the rough samples, the base roughness specifically induced by the intensive laser ablation acts to pull the liquid into the microstructure. This base roughness induced wicking action happens via a thin precursor film that precedes the bulk fluid film and aids the bulk film to flow within the microstructure with ease. The amount of increase in wicking rate by roughness have been seen to depend heavily on the geometry of the microstructure, with the highest enhancement (116%) being seen for the sample with the largest pitch of 300  $\mu\text{m}$ . (fig. 2) This further confirms that the base roughness, which wicks the thin precursor film, dominates the

wicking mechanism in rough pillar arrays. Fig. 2 shows a comparison of capillary rise plots for different microstructure

with smooth and rough walls – whose dimensions and rate of rise coefficient (G) are listed in Table 1.

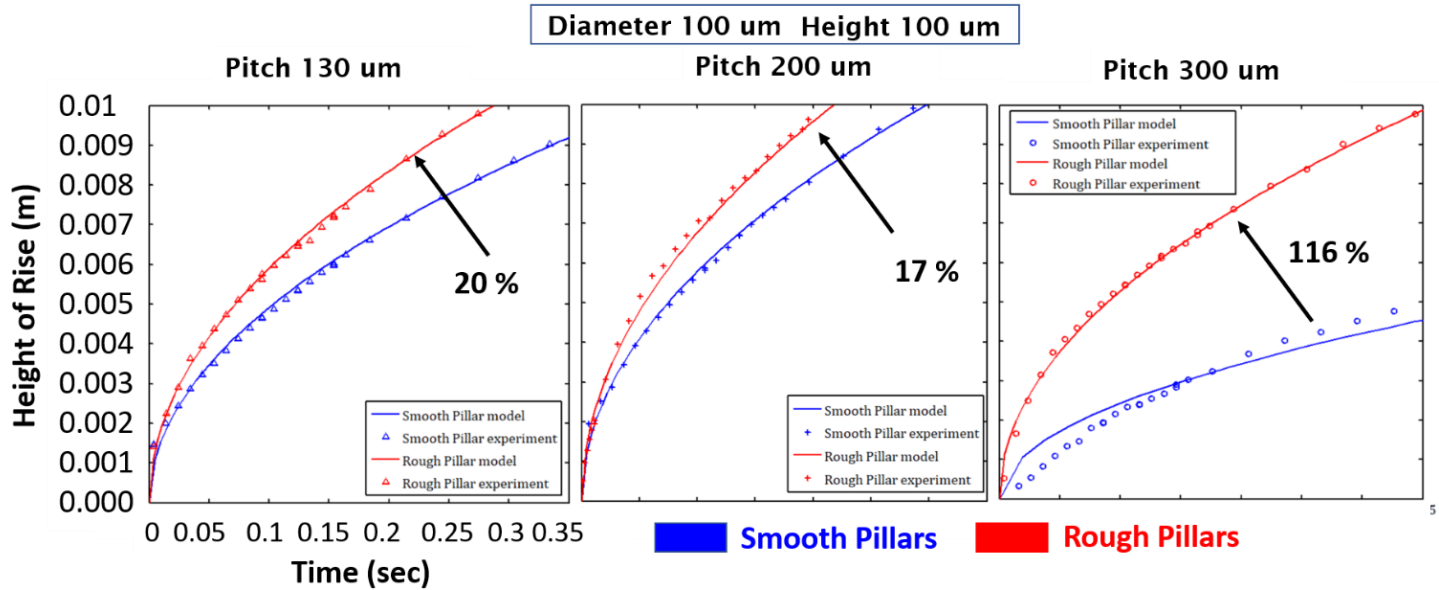


Fig 3. (Solid Lines) – Washburn fit to the experimental data (markers). Rougher samples (red) show faster wicking than the smooth samples (blue) in all of the cases, and the degree of enhancement is the highest for the geometry with pitch = 300 um – this indicates that the base roughness in between the pillar structures are responsible for faster wicking.

Dimensions			Experimentally fitted rate of rise		
$D$	$P$	$H$	$G$	$G$	$increase\ G$
[ $\mu\text{m}$ ]	[ $\mu\text{m}$ ]	[ $\mu\text{m}$ ]	[Smooth]	[Rough]	[%]
100	130	100	0.0155	0.0187	20.6451613
100	200	100	0.0183	0.0214	16.9398907
100	300	100	0.0077	0.0167	116.883117

Table 1. Dimensions of used microstructure along with their capillary wicking rates (G)

### FUTURE SCOPE

Precise characterization of this roughness is crucial to further modeling efforts to understand exactly how the enhancement of wicking rates occur. We aim to do this by using several profilometers, and both contact probe-based and optical methods will be used for characterization. AFM scans will also be used for validating these characterization methods. Further work will be performed on quantifying the effect of surface contamination on smooth and rough samples. Preliminary tests indicate that the smooth microstructures are very prone to fast surface degradation and leaving them exposed to air can cause them to lose their hydrophilicity completely. However, the same level of degradation is not observed in the laser ablated rough surface, which can only happen at a microscopic surface level. This observation prompts us to study only the roughness elements induced by DRIE etching and laser ablation in greater details.

This will be performed by performing static contact angle measurements on laser ablated and DRIE etched samples without any underlying microstructure. Experiments will also be conducted on a broader range of microstructure geometries with varying roughness. Eventually, the bulk of experimental data accumulated would be used to set up empirical and more ambitiously, fully analytical models to predict the role of geometry and surface roughness on capillary wicking rates of different types and topographies of hybrid microstructure.

### CONCLUSIONS

In this study, we have demonstrated an inexpensive, quick and easy way of creating hybrid microstructure using UV laser ablation which is very suitable for use as evaporator wick material in vapor chambers. We have identified the mechanism by which capillary wicking rate is increased by the roughness.

Moving forward, we have fabricated these structures with identical dimensions but varying surface roughness with the help of cleanroom processing as well as UV Laser marking. Then, we conducted vertical 1D capillary wicking experiments, to observe and report the capillary wicking enhancement effect caused by the surface roughness induced by laser ablation. This study will mark the beginning of wick optimization in vapor chambers and other applications relying on capillary wicking, by solely varying surface roughness. These findings also encourage the adoption of cheap, commercially available UV Laser systems for the fabrication of Cold Plate microstructure for use in heat exchangers and vapor chambers.

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