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Regular Article

Porous micropillar structures for retaining low surface tension liquids

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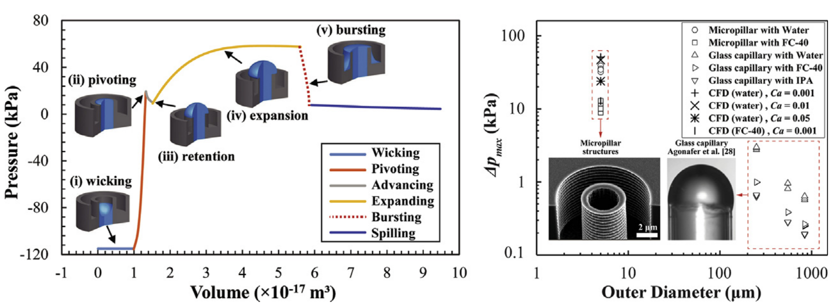
GRAPHICAL ABSTRACT



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ABSTRACT

The ability to manipulate fluid interfaces, e.g., to retain liquid behind or within porous structures, can be beneficial in multiple applications, including microfluidics, biochemical analysis, and the thermal management of electronic systems. While there are a variety of strategies for controlling the disposition of liquid water via capillarity, such as the use of chemically modified porous adhesive structures and capillary stop valves or surface geometric features, methods that work well for low surface tension liquids are far more difficult to implement. This study demonstrates the microfabrication of a silicon membrane that can retain exceptionally low surface tension fluorinated liquids against a significant pressure difference across the membrane via an array of porous micropillar structures. The membrane uses capillary forces along the triple phase contact line to maintain stable liquid menisci that yield positive working Laplace pressures. The micropillars have inner diameters and thicknesses of 1.5–3 μm and ~1 μm, respectively, sustaining Laplace pressures up to 39 kPa for water and 9 kPa for Fluorinert™ (FC-40). A theoretical model for predicting the change in pressure as the liquid advances along the porous micropillar structure is derived based on a free energy analysis of the liquid meniscus with capped spherical geometry. The theoretical prediction was found to overestimate the burst pressure compared with the experimental measurements. To elucidate this deviation, transient numerical simulations based on the Volume of Fluid (VOF) were performed to explore the liquid pressure and evolution of meniscus shape under different flow rates (i.e., Capillary numbers). The results from VOF simulations reveal strong dynamic effects where the anisotropic expansion of liquid along the outer micropillar edge leads to an irregular meniscus shape before the liquid spills along the micropillar edge. These findings suggest that the analytical

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Nomenclature

Bo	bond number ($\rho g L^2/\gamma$)
CAH	contact angle hysteresis
Ca	capillary number ($\mu V/\gamma$)
D	micropillar outer diameter (m)
D_t	trench diameter (m)
d	micropillar inner diameter (m)
E	free energy (J)
F	force (N)
g	gravitational acceleration (m/s^2)
h	height of porous micropillar used in VOF simulation (m)
L	characteristic length
n	mode of characteristic length
P	micropillar pitch (m)
p	pressure (Pa)
$\Delta p_{La,max}$	maximum Laplace pressure
$\Delta p_{La,tot}$	total burst pressure
Q	volumetric flow rate (m^3/s)
R	radius of curvature of meniscus (m)
r	radius of curvature of pore edge (m)
$r_{droplet}$	radius of liquid droplets (m)
SE	Surface Evolver
TPL	triple phase contact line
t	time (s)
t_f	bursting time (s)
t_1	trench depth (m)
t_2	membrane thickness (m)
V	volume (m^3)
$\vec{V}$	velocity (m/s)
We	Weber number ($2\rho VL/\gamma$)

Greek symbols

α	volume fraction
β	meniscus center-point angle (°)
γ	surface tension (N/m)
θ_a	apparent contact angle (°)
θ_y	intrinsic contact angle (°)
θ^*	critical contact angle (°)
κ	surface curvature (m^{-1})
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
τ	time constant for the oscillation of liquid droplet
φ	angular location of triple line (°)
ω	angle between the top surface and outer micropillar edge

Subscripts

f	fluid
g	vapor
La	laplace
l	liquid
la	liquid-air interface
NW	non-wetting
sl	solid-liquid interface
sa	solid-air interface
tot	total
W	wetting

prediction of burst Laplace pressure obtained under quasi-static condition (i.e., equilibrium thermodynamic analysis under low capillary number) is not applicable to highly dynamic flow conditions, where the liquid meniscus shape deformation by flow perturbation cannot be restored by surface tension force instantaneously. Therefore, the critical burst pressure is dependent on the liquid velocity and viscosity under dynamic flow conditions. A numerical simulation using Surface Evolver also predicts that surface defects along the outer micropillar edge can yield up to 50% lower Laplace pressures than those predicted with ideal feature geometries. The liquid retention strategy developed here can facilitate the routing and phase management of dielectric working fluids for application in heat exchangers. Further improvements in the retention performance can be realized by optimizing the fabrication process to reduce surface defects.

1. Introduction

Porous structures with the capacity to retain low surface tension liquids (e.g. dielectric refrigerants, oils) against an imposed pressure difference are increasingly needed in many applications, including oil transportation [1], water/oil separation [2,3], microfluidics [4], and thermal management of micro/power electronic systems [5]. In the microelectronics industry, increasing performance demands necessitate both more memory and more central and graphics processing unit (CPU and GPU) cores, resulting in increased device density and consequent thermal management challenges. Likewise, for power electronic systems, gallium nitride (GaN) high-electron-mobility transistors (HEMT) can improve the performance of radar amplifiers, hybrid/electric vehicles, and LED arrays; however, thermal limitations prevent full exploitation of this technology, where transistor-level power densities can exceed 10 kW cm^{-2} [6]. For these applications, thin-film evaporative cooling in porous media (<40 μm) with a small pore size (<5 μm) can enable high heat transfer coefficients, exceeding 10^6 W m^{-2} K^{-1} at operating temperatures <100 °C [7–9]. However, this performance requires stable liquid-vapor interfaces in porous structures. A stable liquid-vapor interface can greatly benefit from low surface tension liquid retention in these structures under pressure, which is currently a challenge.

This problem is especially important for data centers, which represent about 2% of U.S. electricity consumption and are responsible for 2% of global CO_2 emissions (similar to the aviation carbon footprint), [10,11]. In particular, the miniaturization of computing systems and electronic circuits has culminated in three-dimensional (3D) stacked chips for high-end servers. Though offering dramatic manufacturing and electrical design advantages, this approach poses significant thermal problems in the implementation of high-performance 3D integrated circuits (3D ICs) with power densities that will soon exceed 5 kW cm^{-2} [12]. As a potential solution, interlayer two-phase evaporative cooling is considered a promising approach for heat removal, but it requires dielectric working fluids to avoid the difficulties associated with water in direct contact with microelectronic devices [13].