Supplementary information for:

Open-channel, Water-in-oil Emulsification in Paper-Based Microfluidic Devices

*Chao Li, Mathew Boban, and Anish Tuteja**

Experimental Details

Preparation of Superomniphobic Fluoro-paper Substrates: Cellulose filter papers (Whatman Grade 3, pore size 6 μm, thickness 390 μm) were purchased from GE Life Sciences. The fluorosilane (heptadecafluoro-1,1,2,2-tetrahydrodecyl trichlorosilane) was purchased from Gelest. All of the materials and reagents were used as received. The filter papers were first pre-treated by O_2 plasma etching with a Plasmatherm 790 (chamber vacuum 20 mTorr, O_2 flow rate 20 sccm, bias RF source power 200 W, etching time 10 min) to produce nanoscale fibrillar texture. Then each batch of the cellulose filter papers was treated with fluorosilane (400 μL per 400 cm^2, an excess quantity) by vapor phase deposition in a vacuum oven (Fisher Scientific, 60 °C, < 5 mmHg) for 24 h. Contact angles on the fluoro-paper are reported in Table S1. Movie S1 shows a hexadecane droplet bouncing on the fluoro-paper.

Preparation of Open-channel Flow-focusing Devices: A schematic of the entire fabrication process is presented in Figure S1. The superomniphobic fluoro-paper was attached to solvent-resistant double-sided tape (3M 444) on the back side, and laser cut with the desired dimensions (Full Spectrum Laser H-Series) using patterns designed in Inkscape, an open-source vector design software. To make the channel walls hydrophobic and oleophilic to ensure sufficient flux of the carrier fluid, they were selectively exposed to O_2 plasma between a glass slide and a laser-cut PMMA mask to protect the top surface (Harrick Plasma PDC-001, 30W, 250 mTorr, 0.4 sccm O_2, 5 min).

The channel substrate was either a glass slide or silicon wafer, cleaned with glassware detergent and deionized water, air-dried, and then exposed to a vapor of 1,3-dichlorotetramethyldisiloxane (Gelest SID3372.0) for 10 min at room temperature, then thoroughly rinsed with toluene. This process yielded a robust hydrophobic/oleophilic PDMS-

grafted monolayer[1] that enhanced the flux of oil in the channel, and allowed submerged aqueous droplets to slide (Table S1). The laser-cut, adhesive-tape-backed fluoro-paper channel was then adhered to the substrate, and assembled with laser-cut PMMA components as shown in Figure 1a,b.

Materials: Deionized water was generated with a Pall Corporation Cascada RO-water purification system. n-Hexadecane was purchased from Fisher Scientific. FD&C Red 40 food coloring (McCormick) was used to dye water for visibility. Oil Blue N (Alfa Aesar) was used to dye hexadecane. Ethylene glycol (Acros Organics) and poly(vinyl alcohol) (98% hydrolyzed, 88 kDa, Acros Organics) were used to tune the surface tension, density, and viscosity of the aqueous dispersed phase according to the literature.[2] The outer fluid was hexadecane with 10 wt.% Span 80 nonionic surfactant (TCI Chemicals) to enhance emulsification.

Model drug delivery hydrogel particles were fabricated from cross-linked polyethylene glycol diacrylate (PEGDA, Mn = 700, Sigma-Aldrich), photo-initiated with 1 wt.% 2-Hydroxy-2-methyl-1-phenyl-propan-1-one (Ciba Darocur 1173), and loaded with 25 wt.% of an 800 μg/mL doxorubicin aqueous solution (drug purchased from Adooq Bioscience).

Open-channel Emulsification and Particle Generation:

The organic continuous phase and aqueous dispersed phase flow rates were independently controlled with syringe pumps (KD Scientific KDS-230). Flow through the flow focusing geometry of the channel forced the formation of monodisperse droplets of aqueous solutions (Figure 2, Movie S2) or hydrophilic polymer precursors (Figure 3, Movie S3). The polymer precursor droplets were flowed past a 365 nm UV LED spot source (Henkel EQ CL10, 3% intensity, 6 mm spot diameter, placed 5 mm above the channel) to initiate the photocuring reaction. A silicon wafer was substituted for the glass slide for the particle generation experiments as it was necessary to localize the transmission of UV light to the flow-focusing region. Stable operation was observed for over an hour with this configuration. The droplets

or particles were collected from the channel by applying vacuum into a jar serving as a reservoir. Particles were rinsed with hexane and water to remove surfactant and unreacted monomer, then filtered, collected, and stored in hexane until imaging or drug delivery studies.

Drug Release:

Drug release measurement was performed by placing 350 mg of dry particles into a vial with 2 mL deionized water. Visible absorbance spectra were periodically collected for 1 mL of the supernatant transferred to a cuvette, then returned to the vial. The absorbance at 499 nm was compared to a reference curve generated by measuring aqueous doxorubicin solutions of known concentration to determine the concentration of doxorubicin released from the particles, and therefore the percentage released compared to the total drug content.

Characterization Methods: Photographs and videos were recorded with a digital camera (Nikon D3200). Image analysis for particle sizing was performed with ImageJ. Fluorescent images were obtained with a Nikon Eclipse 80i. SEM images were acquired with a Hitachi SU8000 ultra-high resolution SEM with an accelerating voltage of 10 kV. UV-visible spectra were collected with an Agilent/Varian Cary 50. High speed video was captured with a Fastec Imaging HiSpec 1 at 500 fps for water and hexadecane droplets released from a microsyringe at 10 cm and 1 cm above the fluoro-paper substrate, respectively. All contact angle measurements were obtained using a Ramé-Hart 200-F1 goniometer. The advancing and receding contact angles measurements were performed starting with a 3 μL droplet on the surface and then growing and shrinking it by adding and removing a small volume (≈ 2 μL) using a 2 mL micrometer syringe (Gilmont) while continually measuring contact angles. Contact angle hysteresis was calculated as the difference between advancing and receding contact angles. At least three measurements were performed on each sample surface. Typical error in measurements was ± 2^{o}.

References

1. K. Golovin, S. P. Kobaku, D. H. Lee, E. T. DiLoreto, J. M. Mabry and A. Tuteja, *Sci. Adv.*, 2016, **2**, e1501496.
2. R. K. Shah, H. C. Shum, A. C. Rowat, D. Lee, J. J. Agresti, A. S. Utada, L.-Y. Chu, J.-W. Kim, A. Fernandez-Nieves, C. J. Martinez and D. A. Weitz, *Mater. Today*, 2008, **11**, 18-27.

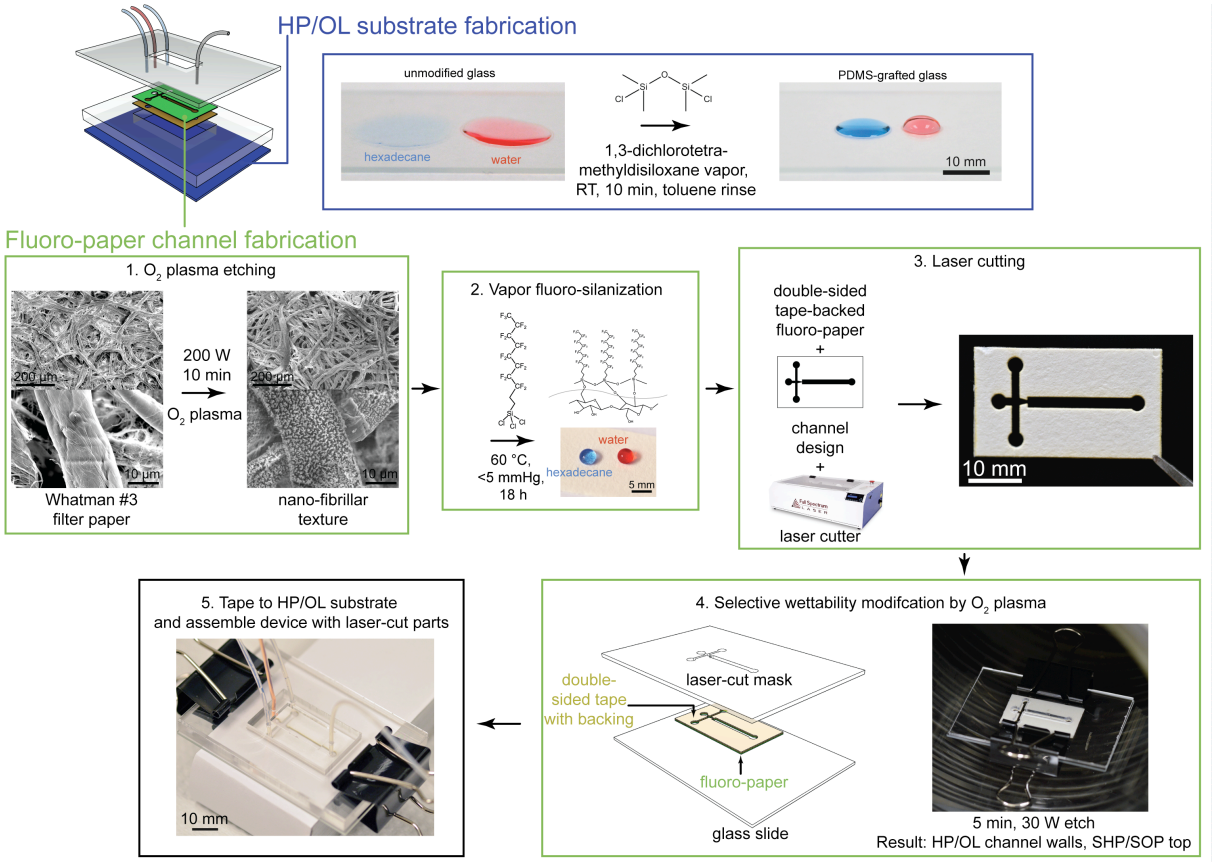

Figure S1. Overview of the fabrication process for the major components of the open-channel flow-focusing emulsification device – namely, the hydrophobic/oleophilic substrate, the laser-cut fluoro-paper channel with superomniphobic top surface, and the hydrophobic/oleophilic walls.

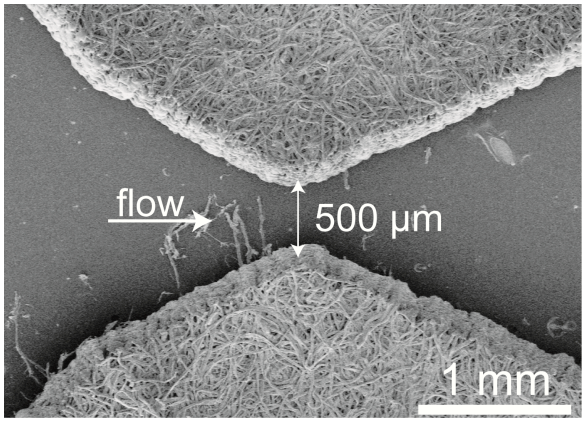

Figure S2. An SEM micrograph for the flow-focusing region on the device used for drug delivery particle fabrication (nozzle width 500 µm). This modification was made to reduce the particle size and improve the emulsification stability with the more viscous polymer precursor solution.

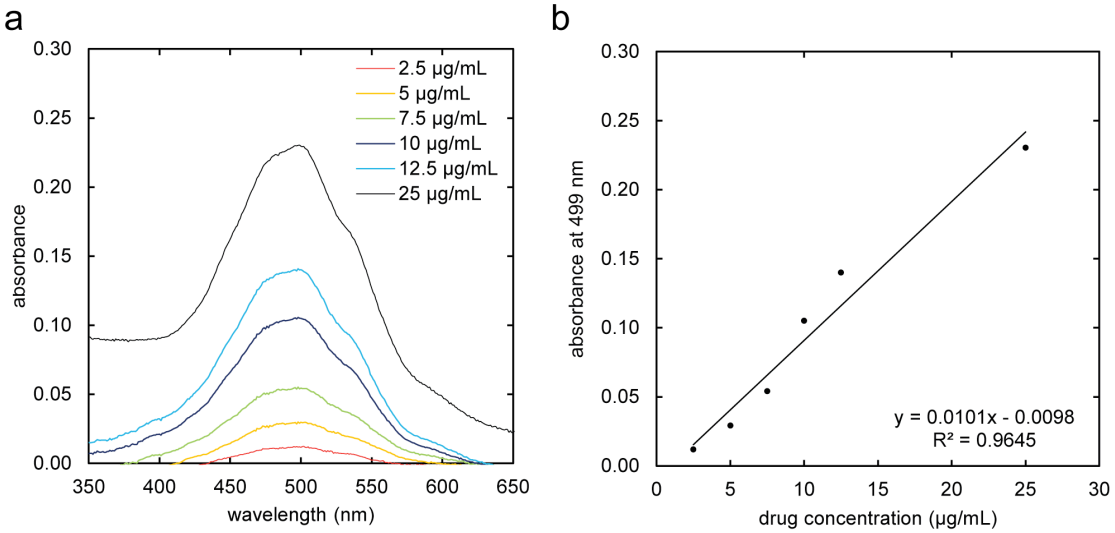

Figure S3. (a) Absorbance spectra for varying concentrations of aqueous doxorubicin solutions and (b) the calibration curve generated from these absorbance spectra for determining doxorubicin concentration released from the particles.

Table S1. Contact angles and hysteresis for water and hexadecane on superomniphobic fluoro-paper, unmodified glass, and PDMS-grafted glass.

		θ^*_{adv} (°)	θ^*_{rec} (°)	$\Delta\theta$
Fluoro-paper	Water	167	157	10
	Hexadecane	162	151	11
Unmodified glass	Water	12	0	12
	Hexadecane	31	0	31
PDMS-grafted glass	Water	115	96	19
	Hexadecane	39	32	7
PDMS-grafted silicon wafer	Water	105	100	5
	Hexadecane	36	34	2

Movie S1. Water and hexadecane droplets bouncing on fluoro-paper when dropped from heights of 10 cm and 1 cm, respectively.

Movie S2. Water-in-hexadecane emulsification with flow conditions shown in Figure 2.

Movie S3. PEGDA-in-hexadecane particle generation, as shown in Figure 3a.