Capillarity-Based Reversible Super-Adhesion

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Abstract:

This project draws inspiration from the palm beetle's defense mechanism by creating an adhesion pad in which a large array of water droplets is controlled by an electro-osmotic pump to achieve reversible super-adhesion. In order to enhance the adhesion performance, three modifications were made to a previous design. First, the droplet diameters were reduced from the previously fabricated 150-500 μm hole devices to 50-100 μm, which allows more liquid bridges per unit area and thereby increases the adhesion force. Second, a raised frame around the array was fabricated to allow easy detachment and is a first step in optimizing the liquid bridge length during attachment. Third, the depth of the water reservoir was varied. The functionality of these devices was tested.

Introduction / Background:

The palm beetle defends itself from predators by using small droplets of oil that it manipulates using the bristles of its tarsi. These droplets form liquid bridges with a substrate leaf, allowing the beetle to stick with a force equivalent to approximately 60-100 times its body weight. When the danger has passed, the beetle can then break these liquid bridges and continue on its way, leaving behind small amounts of oil residue.

This strategy is ideal for creating reversible adhesion, which has been accomplished by creating adhesion pads that use large arrays of droplets of water in place of the palm beetle's oil. Such devices are predicted to increase in the adhesive force per unit area they can exert as the droplet size is decreased. However, scaling features down in size is a significant fabrication challenge.

Objectives:

The goal of this project was to create a new generation of adhesion pads that would reduce the droplet diameter from 100 μm to 50 and 75 μm. Two variations on the basic design of the adhesion pad were also fabricated: first, a raised lip or frame around the array of holes was created on half the plates created, and second, the depth of the water reservoir was varied.

Device Design and Operation:

The adhesion pad consists of a sandwich of silicon plates with an array of holes fabricated in them using a reactive ion etcher (Labels 1 and 5 in Figure 1). These plates are coated on their inside-facing sides with a thin gold electrode (Labels 2 and 4). A porous polymeric layer—in the case of the devices fabricated, made of polyethersulfone, or PES—is placed between the plates (3), and a small reservoir of water (6) is attached to the bottom.

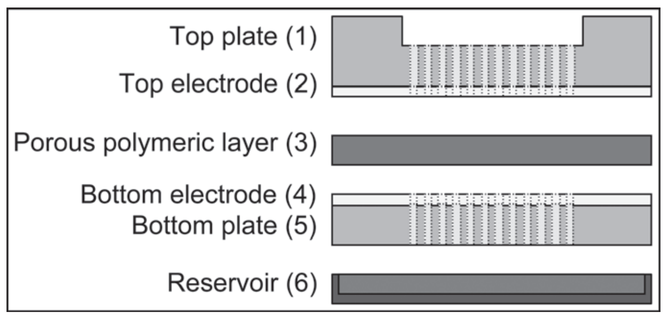


Figure 1: Adhesion pad design.

When a voltage is applied across the electrodes, electro-osmosis, enhanced by the small pores of the PES layer, pulls water up from the reservoir and forces it out of the holes in the top plate. This creates an ordered array of droplets, which may then contact a substrate and form liquid bridges.

Fabrication and Testing:

Three adhesion devices were assembled: (1) a 75 μm unframed device with a 6 mm deep reservoir, (2) a 50 μm framed device, and (3) a 75 μm unframed device with a 2 mm deep reservoir.

Two types of tests were performed on the devices: syringe-pumped tests and electro-osmosis-pumped tests. In the first case, water was forced into the device's reservoir using a syringe and tube arrangement. In the second case, voltage was applied across the PES layer so that electro-osmosis could be used to move the water.

Results:

Syringe-Pumped Testing. Difficulties in assembly and testing made overall array uniformity difficult to achieve with syringe testing. Pump condition and position proved especially important to overall performance, as porous layer misalignment resulted in the formation of abnormally large droplets.

In comparing their performance during syringe pumping, the shallow (2 mm) and deep (6 mm) reservoir devices were shown to have roughly comparable droplet distributions after variations in assembly are discounted, as can be seen in Figures 2 and 3. This performance is surprising because the reservoir depth at which significant variation in droplet height from the edge to the center of the array was predicted to be around 2 mm.

Electro-Osmosis-Pumped Testing. Of the three devices tested, two of the electro-osmotic (EO) pumps were functional. In the case of the 50 μm framed device, EO pumping resulted in significantly better performance than syringe pumping, as holes or folds in the PES layer did not result in large droplets, as can be seen in Figure 4. EO pumping the 75 μm shallow reservoir device did not provide as much of an improvement in performance, and in fact seemed to increase the incidence of large droplet formation.

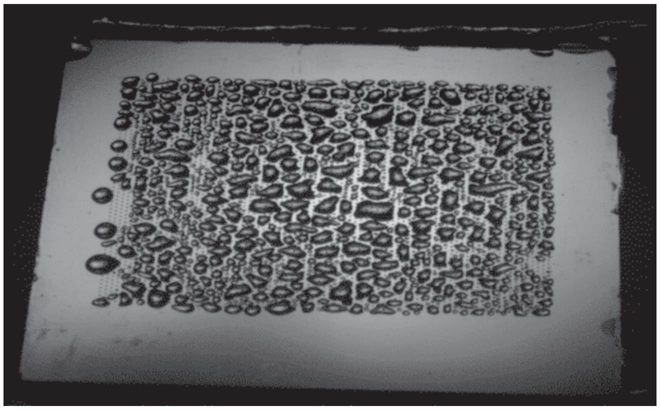
Conclusions and Future Work:

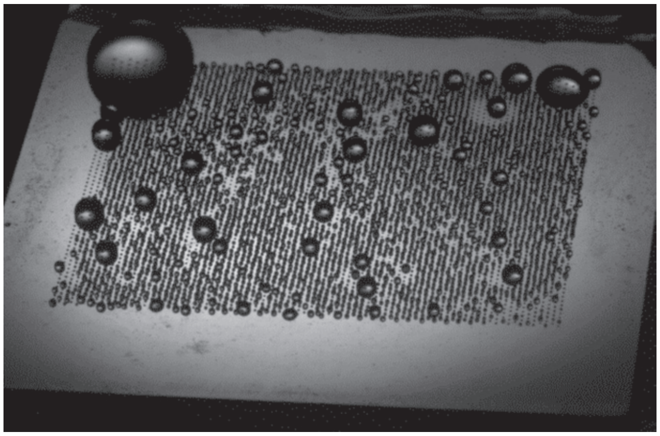
50 μm and 75 μm droplet diameter adhesion pads were fabricated, and initial tests of their functionality were carried out. These devices were found to have the best performance characteristics when operated using their integrated EO pump at relatively low voltages. The performance of shallow and deep reservoir devices during syringe pumping was found to be comparable after accounting for variations in assembly such as frit misalignment.

In the future, adhesion measurements of the assembled devices will be performed, determining how much adhesion force per unit area was gained relative to the reduction in droplet size.

Acknowledgements:

I would like to thank my wonderful PI, Prof. Paul Steen, and awesome mentors, David Anderson and Xiumei Xu, for all their support and encouragement during my time at Cornell. I would also like to acknowledge the National Nanotechnology Infrastructure Network Research Experience for Undergraduates Program and the National Science Foundation for helping to make this experience possible for me.





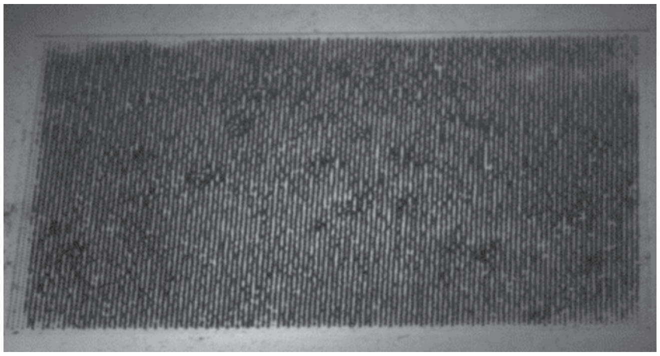


Figure 2, top: 75 µm shallow reservoir device, syringe pumped (photographed using a macro lens).

Figure 3, middle: 75 µm deep reservoir device, syringe pumped (photographed using a macro lens).

Figure 4, bottom: 50 µm deep reservoir device, EO pumped (photographed using a macro lens).

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