

## Beetle Inspired Electro Spray Vapor Chamber

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### Abstract

We present the proof-of-concept for a biomimetic electro spray vapor chamber (BEVAC) which can potentially eliminate the wick structures and thermal interface materials used in conventional vapor chambers, and enable direct cooling of the backside of a microprocessor. This vapor chamber has a beetle-inspired superhydrophobic condenser with hydrophilic bumps on which condensate of the working fluid accumulates. The condensate is returned to the evaporator by electrostatic forces (electrospray atomization). We have demonstrated this novel liquid return mechanism with an open-system BEVAC prototype in which an external voltage is applied between a wickless evaporator and a microfabricated condenser with hybrid wettability.

**Keywords:** vapor chamber, wickless, biomimetic, hybrid wettability, electro spray, microfabrication

### 1. Introduction

Vapor chamber is a planar version of the heat pipe, a device of very high thermal conductance which is widely used in military, industrial and commercial applications [1]. In the heat pipe, heat is carried away from the evaporator by vaporization of the working fluid and rejected at the condenser, while the working fluid is returned to the evaporator by capillary forces exerted by the porous wick structures. The wick is of utmost importance to the proper functioning of heat pipes and vapor chambers, and is responsible for the capillary limit typically determining the maximum heat-carrying capacity of moderate temperature heat pipes [1]. The low-thermal-conductivity wick is also responsible for the majority of the thermal resistance in a heat pipe [2].

In an effort to eliminate the wick structures, we are developing a new type of vapor chamber consisting of a beetle-inspired condenser and a wickless evaporator, in which the liquid return is enabled by electro spraying from the condenser to the evaporator (Fig. 1). The working fluid vaporizes from the evaporator and condenses on the hydrophilic bumps of the beetle-inspired condenser. The condensed working fluid is returned to the evaporator by electro spray atomization. The proposed electro spray vapor chamber has the additional benefit of enabling direct cooling

of the backside of a microprocessor chip, and thereby eliminating the thermal interface materials conventionally used between the evaporator and the chip.

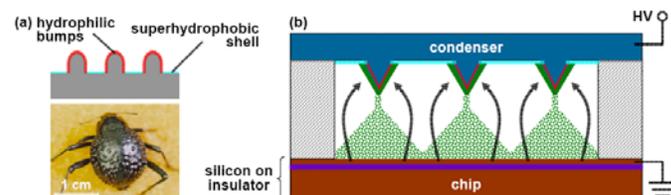


Figure 1. (a) Desert beetle shell with alternating wettability for water harvesting [3]. (b) Electro spray vapor chamber using electrostatic atomization to return working fluid from the beetle-mimicking condenser to the wickless evaporator.

For use in the proposed electro spray vapor chamber (Fig. 1), the biomimetic condenser must be fabricated using electrically conducting material. Further, the hybrid structure should consist of sharp hydrophilic tips (which is also long enough to focus the electric field) on a hydrophobic base (ideally superhydrophobic, so that the condensate only accumulates on the hydrophilic tips). Patterned surfaces with hybrid wettability have been fabricated by microcontact printing [4-6], photolithography [7] and mask coating [8-9]. However, these approaches can only generate hybrid structures within an essentially flat surface, and have so far only been applied to non-conductive materials.

In this paper, we developed a lithographic method to microfabricate a pseudo-3D hybrid structure on a silicon condenser. Using a prototypical BEVAC system consisting of such a condenser and a wickless evaporator, we demonstrated the proof-of-concept for the novel liquid return mechanism.

### 2. Microfabrication of Beetle-Mimicking Condenser

We fabricated the hybrid surface with hydrophilic-superhydrophobic wettability using standard cleanroom process (Fig. 2a-f). The substrate was 400  $\mu\text{m}$ -thick, P-type,  $\langle 100 \rangle$  silicon wafer coated with 1  $\mu\text{m}$  thermal oxide (Fig. 2a). The thermal oxide was patterned by photolithography and etched with reactive ion etching (RIE) to create the etching window (Fig. 2b). Silicon pillars were subsequently generated by KOH etching (Fig. 2c). By controlling the etch time, the

thermal oxide caps were retained on top of the silicon pillars. Next, a thin layer (~ 5 nm) of gold particles was sputter-coated on the chip (Fig. 2d). The silicon substrate with Au coating was etched by a HF/H<sub>2</sub>O<sub>2</sub> solution (49% HF, 30% H<sub>2</sub>O<sub>2</sub>, and H<sub>2</sub>O with a volume ratio of 1:5:10) to generate nanoscale roughness (Fig. 2e) [10]. The gold coating and thermal oxide layer were then removed by wet chemical etching (Fig. 2f).

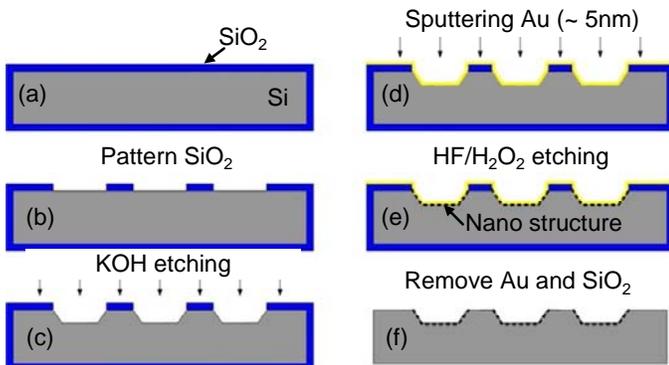


Figure 2. Fabrication process for a hybrid surface with alternating hydrophilic-superhydrophobic wettability.

Finally, the chip was coated with a Cr(~10 nm)/ Au(~20 nm) layer and immersed in 1 mM hexadecanethiol (in ethanol), making the nanostructured surface superhydrophobic. The resulting structure is hydrophilic on top of the pillars and superhydrophobic everywhere else (including the sidewalls of the pillars). The scanning electron microscope (SEM) pictures of the hybrid surface are shown in Fig. 3. Note that because of the pinholes on top of the pillars, the contact angle is somewhat ambiguous even after the treatment with the hydrophobic thiol reagent. However, it was clear that the apparent contact angle on top of the pillars (~90°) was much smaller than that on the rest of the surface with nanostructured pillars (>170°), and the chip was indeed hybrid with alternating wettability (see results below).

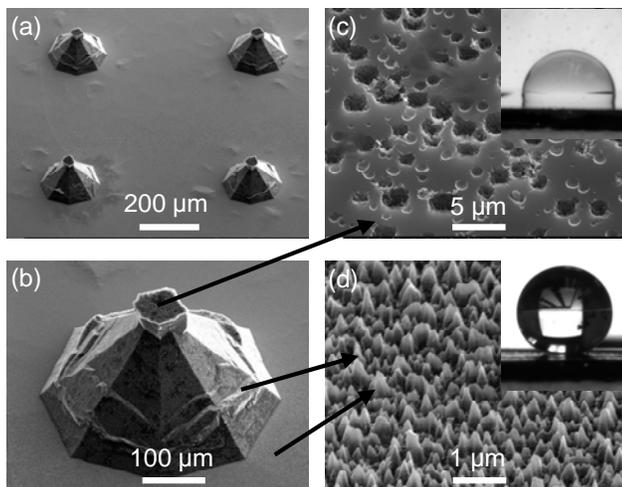


Figure 3. The hybrid surface with (a-b) Microscale pillars 185 μm in height; (c) "Flat" surface on top of the micropillars (the pinholes are artifacts of wet etching). The apparent contact angle on this "flat" surface is ~90°; (d) Nanoscale pillars on the side walls of the micropillars and the rest of the substrate. The apparent contact angle on this nanostructured surface is >170°. The hybrid structure is superhydrophobic everywhere except the top area of the micropillars.

### 3. Proof-of-Concept Electro spray Vapor Chamber

Using the microfabricated hybrid chip as the condenser, we demonstrated the proposed liquid return mechanism with an open-system prototype shown in Fig 4. A flat aluminum plate with attached heater was used as the wickless evaporator. The hybrid chip was held parallel to the aluminum plate with a 2.5 mm spacing. Deionized water was placed on the aluminum plate as the working fluid, which vaporized on the aluminum plate heated at 60 °C. The water vapor condensed on the hybrid surface held approximately at the room temperature of 23 °C. When needed, a high voltage was applied between the hybrid chip and the aluminum plate to create an external electric field. The circulation of the working fluid was monitored by a Phantom 7.1 camera through an Infinity K2 lens.

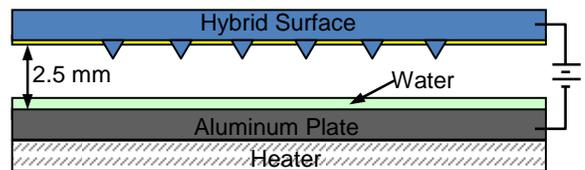


Figure 4. Experimental setup showing the open-system proof-of-concept for an electro spray vapor chamber.

The preferential condensation on a surface with alternating wettability is shown in Fig. 5. A water droplet was placed on the evaporator as shown in Fig. 5a and the surface temperature was heated to 60 °C. The water condensate accumulated preferentially on the hydrophilic bumps compared to the rest of surface which was superhydrophobic (Fig. 5b). Note that because the prototype is an open system, most of the water evaporated to the surrounding.

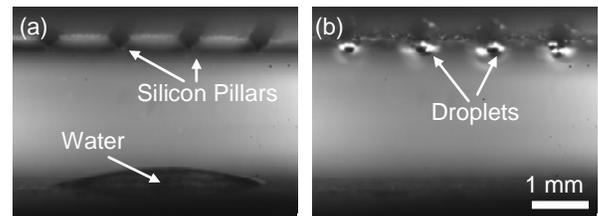


Figure 5. Preferential condensation on the hydrophilic bumps instead of the superhydrophobic portions of the hybrid surface.

The liquid return mechanism driven by electrostatic forces is shown in Figure 6. The experimental conditions were identical to Figure 5 except that a voltage of 4.7 kV was applied in Figure 6 (with a nominal electric field of  $1.9 \times 10^6$  V/m). Again, water vaporized from the evaporator and condensed on the hydrophilic silicon bumps as shown in Fig. 6b (similar to Fig. 5b). When the water droplets accumulated to a critical size (~300 μm in diameter for the case shown here), they were detached from the condenser by electrostatic forces and returned to the evaporator as shown in Fig 6c-d. As long as the drop diameter crossed the threshold value, the electrostatically driven drop return was accomplished nearly instantaneously, which is evident from Fig 5b-d captured 10 ms apart.

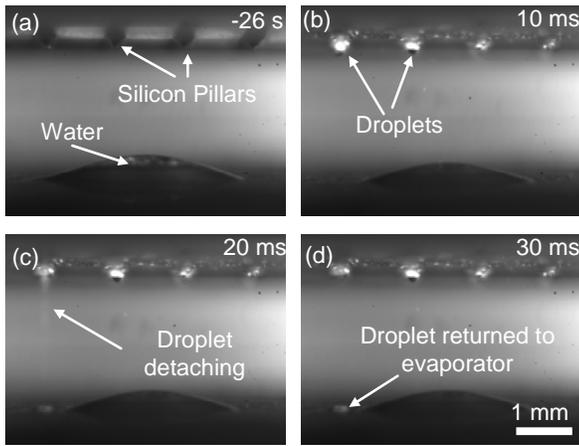


Figure 6. BEVAC proof-of-concept using the hybrid condenser and electrostatically driven liquid return. The experimental conditions are identical to Figure 5 except that a voltage of 4.7 kV was applied.

#### 4. Summary and Future Work

We have demonstrated the proof-of-concept for a novel beetle-inspired electrospray vapor chamber. The preferential condensation on beetle-mimicking surface was shown on microfabricated structures with hybrid wettability, and the electrostatically driven liquid return was shown in an open-system prototype.

By eliminating the wick structures and thermal interface materials used in conventional vapor chambers, improved heat transfer performance is envisioned for BEVAC systems. However, rigorous thermal characterization of a closed-system BEVAC vapor chamber is still needed to establish this novel system as a viable heat spreader. It is also highly desirable to reduce the voltage required for liquid return while achieving genuine electrospray atomization.

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