JUMPING-DROPLET ENERGY HARVESTING WITH NANOENGINEERED SURFACES

*N. Miljkovic, D.J. Preston, E.N. Wang**
Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

ABSTRACT

We experimentally demonstrate jumping-droplet-based energy harvesting with nanoengineered surface designs. With recent advancements in micro/nanofabrication techniques, non-wetting engineered surfaces have enabled condensing coalesced droplets to spontaneously jump and simultaneously obtain electrostatic charge. In this work, we take advantage of these droplet characteristics to demonstrate energy harvesting for the first time. The charged droplets jump between superhydrophobic copper oxide (CuO) and hydrophilic copper (Cu) surfaces to create an electrical potential and generate electrical power during formation of atmospheric dew. We demonstrated power densities of ~0.06 nW/cm^2, which can be improved near term to ~100 μW/cm^2.

INTRODUCTION

Controlling micro/nano-scale wetting phenomena has been an active research area for over two decades, promising improvements in power generation, thermal management, and desalination [1]. With the significant advancements in micro/nanofabrication techniques, engineered surfaces have enabled improved non-wetting characteristics, and in certain cases, allow condensing coalesced droplets to spontaneously jump *via* the conversion of surface energy into kinetic energy [2]. Furthermore, we recently discovered that these jumping droplets are electrostatically charged and can be manipulated with electric fields [3, 4]. In this work, we take advantage of these unique droplet characteristics with nanoengineered surface designs to demonstrate energy harvesting for the first time.

EXPERIMENTAL APPROACH

To create these nanoengineered surfaces (Fig. 1) for energy harvesting, commercially purchased Cu was chemically oxidized to form CuO nanostructures [3]. These structures were then coated with a ≈30 nm conformal fluoropolymer coating (Fig. 1b) [3].

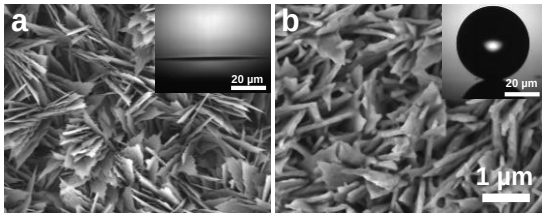

Figure 1: Field emission scanning electron micrographs (FESEM) of (a) a 10 min oxidized CuO surface (Inset: water droplet contact angle on the clean nanostructured CuO surface, $\theta_a \approx 0°$) and (b) a CuO surface coated with a ≈30 nm thick layer of P2i fluoropolymer (Inset: Water droplet advancing contact angle on the superhydrophobic nanostructured surface, $\theta_a = 171°\pm3°$). The sharp, knife-like CuO structures have characteristic heights $h \approx 1$ μm, a solid fraction $\varphi \approx 0.023$, and a roughness factor $r \approx 10$.

To first demonstrate jumping-droplet charging and field control, we used an external electrode biased to manipulate the positively charged droplets. Figures 2a and b show the concept, where a copper electrode placed beneath the tube was voltage biased with -300 and +300 V, respectively, to form an electric field. Due to electric-double-layer charge separation at the liquid-hydrophobic coating interface, the jumping droplets depart the surface with a droplet radius dependent electrostatic charge (≈10-100 fC) [3] and are easily manipulated by the external electric field.

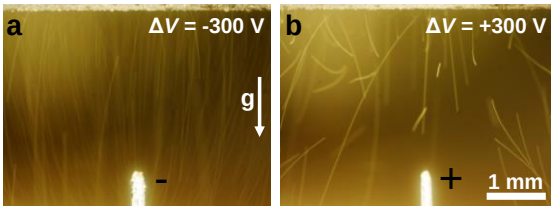

Figure 2: Droplet interactions with an electric field. A copper wire electrode was placed ≈5 mm beneath the superhydrophobic nanostructured surface and voltage biased relative to the sample (ΔV). The voltage potential difference created an electrostatic field allowing for charged droplet interactions with the field. The results indicate that the droplets are positively charged (chamber water vapor pressure P_v = 2,700±68 Pa, and supersaturation $S = P_v/P_{sat}(T_c) = 1.04$).

Analogous to the electric field control of droplet motion, jumping-droplet energy harvesting was achieved where charged droplets jump between a superhydrophobic and hydrophilic surface to create an electrical potential and generate electrical power. To investigate the jumping-droplet energy harvesting mechanism, we interdigitated nanostructured superhydrophobic CuO and hydrophilic Cu combs (Fig. 3a).

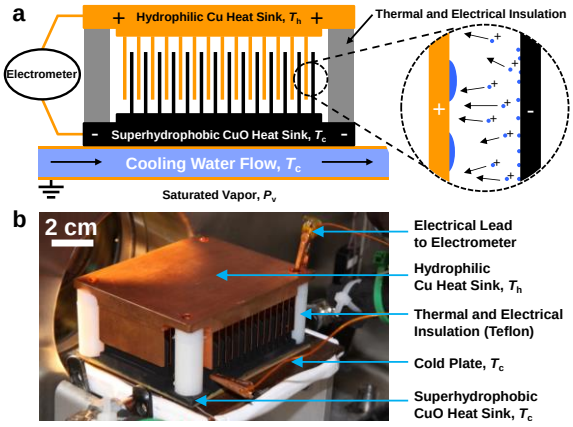

Figure 3: (a) Schematic of the jumping-droplet power generator showing the two combs in an interdigitated arrangement. The combs were electrically and thermally isolated from each other. Images of the jumping-droplet power generator showing (b) an isometric view of the two combs integrated in the test chamber for experimentation. Commercially purchased Cu combs were used (478 copper) with dimensions 26 x 89 x 75 mm (height x width x depth) (E1U-NPFSS-30, Cooler Master). To observe droplet jumping, the interdigitated device was tested in a controlled condensation chamber.

The temperature of the CuO comb (T_c) was reduced *via* a cooling water flow until jumping-droplet-condensation commenced. The jumping-droplets travelled from the CuO comb fins to the conducting Cu hydrophilic fins (Figure 3a inset), resulting in an electrical potential buildup, which was measured using an electrometer (6517B Electrometer, Keithley).

EXPERIMENTAL RESULTS AND DISCUSSION

To replicate atmospheric dew conditions, the energy harvesting potential was studied at $T_c \approx 8°C$ and $P_v \approx 1800$ Pa. Figures 4a and b show the experimentally measured open circuit voltage (V_{OC}) and short circuit current (I_{SC}) of the device, respectively. Prior to condensation, V_{OC} and I_{SC} were ≈0 (Fig 4, no condensation region). After condensation began, charge separation resulted in the buildup of positive charge on the hydrophilic comb and V_{OC} and I_{SC} reached +15 V and +1.15 nA, respectively. The maximum energy harvesting rate in these experiments was ≈0.06 nW/cm^2. The relatively low energy density of our device was mainly due to: i) the low cooling rates (<0.01 W/cm^2), and ii) the non-optimum fin arrangement, resulting in the coldest temperature being at the base of the superhydrophobic fins and the inability to maximize the use of the whole comb area for droplet jumping.

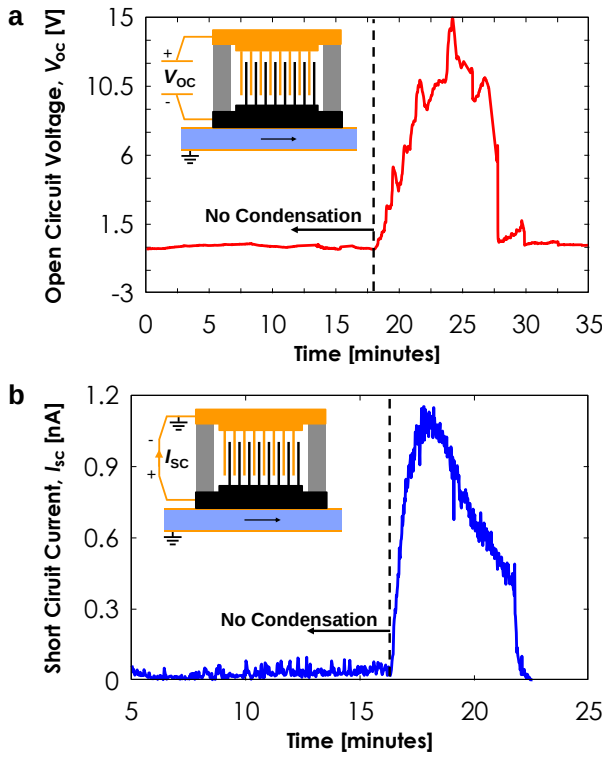

Figure 4: Experimentally measured (a) open circuit voltage (V_{OC}) and (b) short circuit current (I_{SC}) of the interdigitated device. The maximum energy harvesting rate in these experiments ($P = V_{OC}I_{SC}$) was ≈17.3 nW or ≈0.06 nW/cm^2 (based on the prototype active jumping area of 278 cm^2). The experiments were conducted by filling the controlled chamber with saturated water vapor and closing off the vapor inlet valve. Once pressure and temperature equilibrium was reached, the cooling water temperature (T_c) was gradually decreased and the water vapor began to condense. Due to the finite volume of water vapor in the chamber, the saturation pressure decreased as well, resulting in a corresponding decrease in droplet-jumping frequency, V_{OC}, and I_{SC}.

Future devices with higher condensation rates (>0.1 W/cm^2) and high-surface-area designs have the potential to achieve energy harvesting rates in the 10-100 μW/cm^2 range (Fig. 5), making them more attractive to power small electronic devices (>1 μW, *i.e.*, chemical batteries, thermoelectrics, and piezoelectrics).

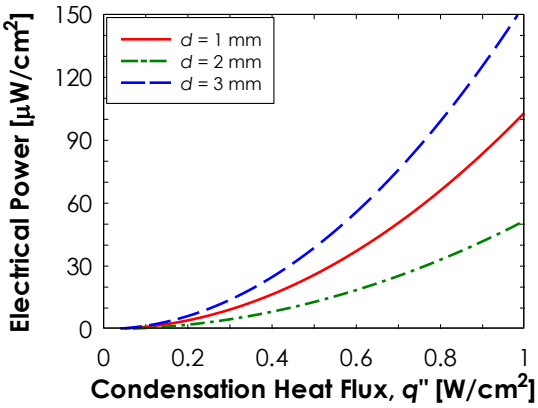

Figure 5: Theoretically calculated electrical energy harvesting rate from jumping-droplet condensation. By dividing the heat flux (q") with the latent heat of phase change (mh_{fg}) per droplet, a jumping-droplet frequency per unit area (f) was determined. Assuming departing droplets with radii ≈5 μm [1], individual droplet charge ≈8 fC [3], and an active area ≈1 cm^2, I_{SC} and V_{OC} were calculated and multiplied to obtain the harvesting power.

This work demonstrates a novel surface engineered platform for atmospheric energy harvesting and electric power generation.

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CONTACT

*E.N. Wang, tel: +1-617-324-3311; enwang@mit.edu