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Short communication

# Dual-scale micro/nanostructures for high-efficiency water collection

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ABSTRACT

We describe a simple method of synthesizing dual-scale dome-like micro/nanostructures on copper using temperature controlled surface oxidation. The produced surfaces show two conflicting attributes, large contact angles and large droplet departure radii. Together, these two attributes promote water collection from air. A range of 80%-100% collection rate enhancements was observed for copper surfaces with a number of different wettability characteristics. Theoretical results showed that large departure droplets introduce strong disturbances in the diffusion boundary layer, which may be responsible for decreasing the vapor mass transfer resistance and enhancing the rate of water collection through moisture condensation.

## 1. Introduction

The issue of water shortage has become one of the major global concerns [1–3]. Approximately one billion people live without clean water sources in rural areas of African, Asian, and Latin American countries. However, the earth atmosphere is a large water reservoir which has a total water amount of approximately $1.4 \times 10^7$ tons [4,5]. Even in the desert, the moisture content per unit volume in atmosphere is larger than $10\,g/m^3$. Water collection through moisture condensation appears to be an extremely promising water harvesting system for drinking water, crop irrigation, livestock beverage and forest restoration in dry land mountains and deserts [6]. Such system also has critical benefits in many industrial applications including the passive cooling in nuclear power plant, condenser systems in sea water desalination and energy recovery systems [7–9].

Dew condensation phenomenon of animals and plants provide important inspirations for water collection systems [10]. The most typical ones are Stenocara beetle surface [11], spider net[12] and cactus [13], of which the special micro- and nano-structures facilitate moisture in atmosphere condense and collection [14,15]. These findings stimulate the development of artificial water collectors mimicking the moisture condensation of natural livings [16–19]. Many studies show that surface characteristics, such as surface free energy, roughness and surface topography [20–23], have significant effects on the performance of water collection because these physical chemistry properties can directly influence the configurations and motions of condensate droplets, including droplet growth, coalescence and sweeping [24–28]. It should be noted another essential parameter, vapor diffusion resistance, also great influences the collection efficiency. In many cases, the residue of non-condensable gases near the condensing surface severely prevents water vapor diffusing onto the collecting surface [29–31]. A comprehensive study of the effects of surface characteristic and vapor diffusion on the efficiency of water collection is thus important.

In this study, we report a simple method of making a type of multi-scale dome-like micro/nanostructures on copper. Experimental results showed that the water collection efficiency of the produced surface can be 0.8-1 times larger than several other types of surfaces (e.g., hydrophilic, hydrophobic and super-hydrophobic). Process image analyses and droplet dynamic simulations were used to interpret the mechanisms. We found that the increased vapor pressures caused by strong disturbances during droplet departure can be the cause for the enhancements. The special micro/nanostructures produced on the copper surface facilitate larger droplet formation, coalescence and departure and can generate stronger turbulence in the steam-air diffusion layer.

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## 2. Experimental procedure

A controlled-oxidation method was used to fabricate the dome-like micro/nanostructures on copper surfaces, similar to the process used for the synthesis of wettability gradients on copper [20]. Fig. 1(a) illustrates the fabrication process. A copper substrate was first polished and cleaned in an acetone solution using an ultrasonic cleaning instrument. After air drying, the copper substrate was heated for 2 min in air by using a combustor with a flame temperature of approximately 1500 K. A thin oxidation layer formed after heating was subsequently washed off from the surface by water jets. The copper substrate was then immediately chilled using a Peltier cooling device to a temperature 10 °C below the dew point of the environment (20 °C with an accuracy of 0.2 °C and 100% relative humidity with an accuracy of 2%, controlled by an environmental chamber) to allow the nucleation of water. The chilling and water nucleation processes were repeated three times and lasted approximately 3–5 h each time. Three other types of copper surfaces were also prepared for comparison purposes (Table 1): a hydrophobic, waxed copper surface (surface B), a super-hydrophobic surface fabricated on copper using a one-step solution-immersion process proposed by Jiang et al. (surface C) [32], and a hydrophilic, freshly polished copper surface (surface D).

**Table 1**
List of condensing surfaces in the experiments.

| | Sample surface | Fabrication method |
|---|---|---|
| A | Oxidation copper surface | Controlled oxidation |
| B | Hydrophobic surface | Wax vapor deposition |
| C | Super-hydrophobic surface | One-step solution-immersion |
| D | Polished copper surface | Finely polished |

## 3. Results and discussion

The surface morphology is shown in Fig. 1(b). Dome-like micro- and nanostructures densely grew on the produced copper surface over the entire area. Similar to many biological surfaces, such as the lotus leaf and rose petal, the produced surface consisted of two scale roughness factors (Fig. 1(c)): one at approximately 1 μm (i.e., a microscale rough structure) and the other at approximately 100 nm (i.e., a nanoscale fine structure,). The nano-domes were located on top of the micro-domes. The contact angle of a 0.5 μL drop of water on the oxidation copper surface was 119° (Fig. 2(b)), which was larger than that on a polished copper surface (Fig. 2(a)). The advancing and receding contact angles were 120° and 90°, indicating a large contact angle hysteresis (CAH). The wetting mode is similar with the so-called Cassie-impregnating state where a droplet with a high contact angle on a surface also displays very high adhesion [33,34]. The Cassie-impregnating state may arise on surfaces with hierarchical surfaces where droplets are pinned on the microscale asperities while the air remains entrapped in nanoscale asperities, as shown in Fig. 2(c). In the case, the contact angle, $\theta$, can be theoretically predicted by the Cassie-Baxter equation

$$\cos\theta = \gamma F \cos\theta^{*} + \Phi - 1, \tag{1}$$

where $\gamma$ is the roughness factor, which is defined as the ratio of the true area of the solid surface with roughness to the apparent area if the surface were perfectly smooth, $\Phi$ is the ratio of the area that is wetted by liquid which equals to the microscale roughness, $\theta^{*}$ is the intrinsic contact angle of the smooth copper surface. Using the parameters given in Fig. 1(c), the theoretical contact angle is calculated as 117°, which is in agreement with the experimental result.

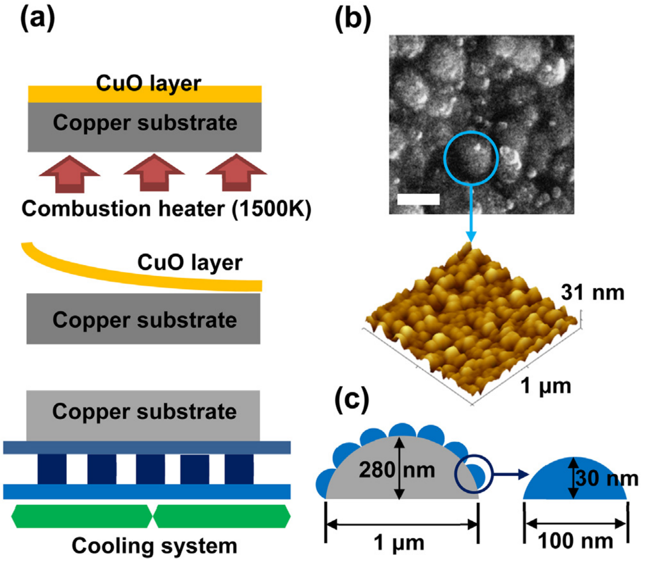

**Fig. 1.** Surface fabrication and characterization. (a) Schematic illustration of the fabrication process. (b) Scanning electronic microscope (SEM) and atomic force microscope (AFM) images of the oxidation copper substrate. The white scale bar is 1000 nm. (c) 2-D models of the micro- and nano-structures.

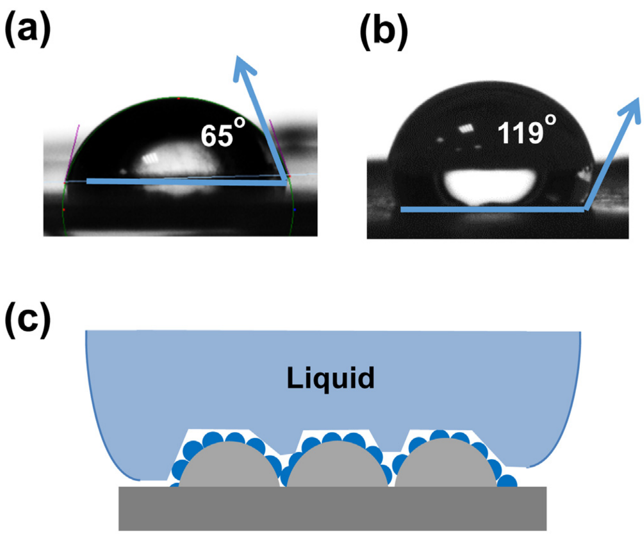

**Fig. 2.** Wettability analysis. (a) Contact angle of the fine polished copper surface. (b) Contact angle of the oxidation copper surface with micro- and nanostructures. (c) Wetting state on the oxidation copper surface.

In addition to above discussed wettability characteristics, the condensate droplet departure radius is another important factor affecting the efficiency of water collection. When a droplet departs from the tilted surface, the balance between the retention force $F$ and the in-plane component of the gravity force $G$ is barely broken. Assuming the droplet is hemispherical, the force balance can be expressed by

$$\rho V_d\, g \sin\alpha = F = \gamma r k(\cos\theta_R - \cos\theta_A) \tag{2}$$

where $\rho$ is the density of the liquid, $V_d$ is the volume of the departing condensate droplet, $\alpha$ is the tilt angle of the surface, $g$ is the gravitational acceleration constant, $\gamma$ is the liquid-vapor surface tension coefficient, $r$ is the radius of the departure droplet,