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Effects of black silicon surface structures on wetting behaviors, single water droplet icing and frosting under natural convection conditions

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ABSTRACT

In this research, the effects of black silicon and two-stage black silicon surface structures on the characteristics of wetting, icing process of a single water droplet, and frost accumulation under natural convection conditions were investigated. Black silicon and two-stage black silicon surfaces were first designed and fabricated, and then examined by means of scanning electron microscopy (SEM). Wetting behavior was measured by contact angle measurement system. The icing and frosting processes were acquired through high-speed photography. The test surfaces were cooled down from room temperature to well below 0 °C by circulating ethyl alcohol via a constant temperature system. The results show that compared with uncoated silicon, black silicon and two-stage black silicon surfaces can largely increase the surface hydrophobicity, reduce the freezing thickness deformation and show anti-frosting performance. This study provides a new type of hydrophobic surface structure and plays an important role in designing anti-icing/anti-frosting surfaces for practical applications.

1. Introduction

Surface icing/frosting is a complicated process of heat and mass transfer that can cause various problems in aircrafts, wind turbines, power lines, ships and telecommunication systems. These problems could result in severe accidents and large economic losses [1,2]. Therefore, the issues of removing ice from surfaces have attracted wide attention recently. The techniques of removing ice from surfaces can be divided into two categories: active and passive. The active method including mechanical scraping, thermal agents and using de-icing chemical agents is employed after the ice formation, and has the disadvantages of high cost, heavy load, huge energy consumption and detrimental environmental consequences [3–8]. The passive method can prevent the ice formation or ice adhering to surfaces even though the icing occurs. It has the advantage of less energy consumption owing to the lower ice adhesion strength [9]. In recent decades, a new passive anti-icing technique has aroused attention, namely fabricating super-hydrophobic surfaces.

Super-hydrophobic surfaces are potentially “anti-icing/anti-frosting” because of their extraordinary water-repellency [10]. Many researches and experiments that are related to the anti-icing or anti-frosting characteristics of super-hydrophobic surfaces have been carefully studied [11–24]. Super-hydrophobic surfaces may delay freezing time, prevent ice accumulation and reduce ice adhesion strength [9]. However, the relationship between surface wettability and their anti-icing/anti-frosting properties is still controversial. V.F. Petrenko [3] and A. Dotan [15] found that ice adhesion decreases with water contact angle (CA) increases, while S.A. Kulinich [16] reported that solid surfaces with high CA may not behave the better performance of anti-icing/anti-frosting. A.J. Meuler [21] suggested that ice adhesion can be reduced with receding CA or CA hysteresis (CAH) decreases. M. Zou [23] held that ice adhesion strength correlates with CA on condition that the surfaces have similar roughness. Besides, Yang he [25] investigated the effect of microstructure geometry on ice adhesion and concluded that the micro-nano-pillar surface had the least ice adhesion which was far less than that of micro-surface despite the geometry changes. Obviously, the fundamental understanding of relationship between wetting behaviors and icing/frosting property is not yet clear and needs to be further studied. However, it is more important to design optimal “ice/frost-repellency” surfaces not “water-repellency” surfaces when considering ice-phobic applications.

Black silicon is a special type of byproducts when etching silicon in the ion reaction [26]. It has properties of sequential microstructure, low reflectivity and broad spectrum absorption [27]. It applies abroad in the fields of photoelectric detector, efficient solar cells and luminescent devices. However, the water-repellency and anti-icing/anti-frosting characteristics of black silicon have not yet been experimentally studied. Considering black silicon's microstructure and hydrophobic property which was found in the surface cleaning, its wetting behavior and anti-icing/anti-frosting property need to be studied. In the present study, black silicon and two-stage black silicon designed based on black silicon and micro-pillar silicon were firstly fabricated. Then surface wettability, freezing of a single water droplet and frosting process

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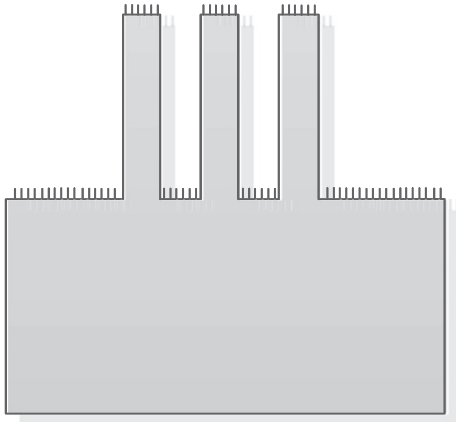

Fig. 1. Schematic diagram of two-stage black silicon.

on these samples were measured. The visualization results of water freezing processes under different surface temperatures were compared, and the droplet deformation characteristic was quantitatively analyzed. Moreover, the frost layer thickness and structure were studied. The present study is aimed to provide a new type of surface structure and examine its wetting behavior as well as anti-icing/anti-frosting property, which reflect its underlying value in the "water-repellency" and "ice-repellency" research fields.

2. Experiments

2.1. Fabrication of black silicon and two-stage black silicon

Black silicon was fabricated by means of plasma etching. The major procedures contained: (1) incise the smooth silicon using scribing machine; (2) clean the silicon; (3) place the samples in the inductively coupled plasma etching (ICP) and adjust the etching and passivation circle time to control the density/characteristics of scale of samples. Finally, two 15 mm × 15 mm × 15 mm aperiodic black silicon samples of different scales were acquired.

Table 1
Parameter of the first-stage periodic structure in two-stage black silicon.

Sample number	Arrangement mode	Periodic structure	a/μm	b/μm	h/μm
1	Square	Cube	12	30	50
2	Square	Cylinder	12	30	50
3	Triangle	Cylinder	12	30	50
4	Triangle	Cylinder	12	48	50

Two-stage black silicon is a new type of surface structure designed by combining periodical micro-pillars and aperiodic black silicon. Periodical micro-scale geometry on silicon surface can be fabricated via the deep reactive etching method. Fabricating a micro-pillar silicon surface with certain parameters, the width and space could be controlled by photolithography mask design, and the height could be controlled through adjusting etching/passivation circle time. However, the fabrication difficulty and cost would be highly increased with the width decreases to less than 10 μm and the height increases to larger than 80 μm, which would limit the surface hydrophobicity. Besides, in the previous introduction, it has been mentioned that micro-nano-pillar surface had the least ice adhesion that was far less than that of micro-surface despite the geometry changes [25]. Hence, hierarchical structured surfaces may behave better performance in anti-icing or anti-frosting applications. However, the fabrication of micro-nano-pillars is much more difficult than that of micro/nano pillars and it always could not satisfy specific scale requirements. Inspired by the natural super-hydrophobic surface of the lotus leaf and black silicon's properties, a new type of similar micro-nano-structures combining micro-structure and small-scale black silicon is designed and named "Two-stage black silicon". The fabrication of two-stage black silicon mainly

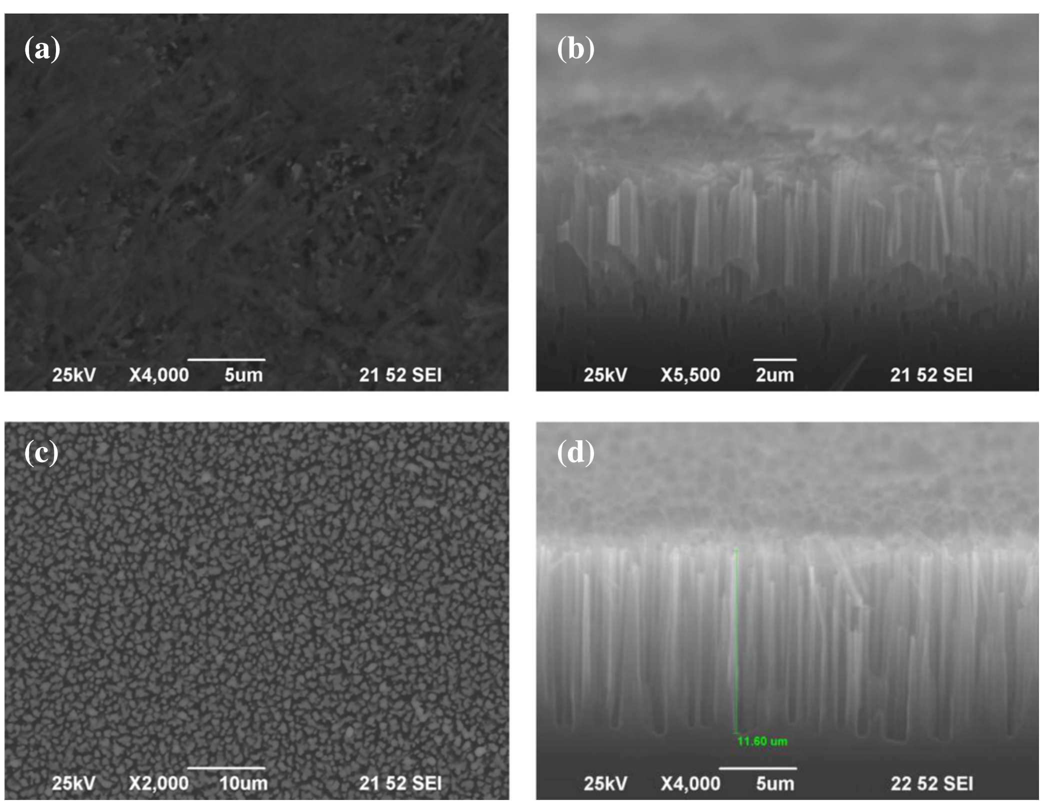

Fig. 2. SEM images of two black silicons with differernt magnification from top and side view directions: (a, b) top and side view of black silicon 1, (c, d) top and side view of black silicon 2 (left: top view and right: side view).