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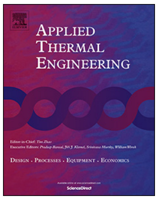

Research Paper

# Wettability and boiling heat transfer study of black silicon surface produced using the plasma immersion ion implantation method

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## HIGHLIGHTS

- A new plasma immersion ion implantation method was used to produce black silicon.
- The contact angle of the BSi surfaces becomes larger than that of silicon.
- BSi surfaces enhance the HTC at low heat flux by increasing nucleation sites.
- BSi surfaces depress the HTC at high heat flux due to the decline of wettability.
- PIII is a promising fabrication method for its large-scale treatment ability.

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## ABSTRACT

Black silicon (BSi) has gained attention among renewable energy materials for its nanoscale surface structures. Here we present a new plasma immersion ion implantation (PIII) method to produce BSi, as fabricating nanoscale surface structure has drawn recent attention for improving phase change heat transfer. The wettability and boiling heat transfer performance of the BSi surface were measured and compared with the untreated silicon surface. The roughness and contact angle of the BSi surface become larger than that of silicon, which create more nucleation sites. However, the declined wettability leads to a greater possibility of bubble coalescence. This phenomenon increases the departure diameter and decreases the departure frequency, which worsens the boiling heat transfer. The PIII method is a promising treatment to produce nanostructures on silicon for its large-scale production ability. In further studies, different fabrication parameters would be used to change the surface characteristics using the PIII method to enhance the boiling heat transfer and the CHF of the BSi surface.

## 1. Introduction

With the tremendous growth of computers and electronic instruments, the need for high heat flux cooling is increasing at a rapid speed [1]. The greater computational ability generates more heat and the smaller chip sizes further increase the heat flux. Heat flux dissipation rates have increased from approximately 30 W/cm$^2$ a few years ago to 100 W/cm$^2$ nowadays, and the challenge now is to reach 300 W/cm$^2$ and higher. Therefore, a more effective cooling approach is needed, and two-phase flow boiling in micro-channels is expected to be one of the solutions, but it meets some challenges such as its reliability and high heat transfer performance [2]. Regarding boiling heat transfer, HTC (heat transfer coefficient) and CHF (critical heat flux) are two main parameters for estimating the cooling surface heat transfer performance. During a typical boiling curve, after the critical point from nucleate boiling to film boiling, the heat flux drops dramatically, which results in an increase in the wall temperature. The upper limit of the nucleate boiling regime is defined as CHF, which should be avoided and taken into consideration regarding engineering issues [3]. Therefore, the HTC needs to be improved while avoiding the CHF to design a boiling heat transfer system.

Nucleate boiling heat transfer is preferred in cooling issues, and it is affected by parameters including heat flux, saturation pressure, and the material properties. The phase change heat transfer is impacted by the texture and surface energy; therefore, many researchers have tried to change the material surface to increase its heat transfer ability. Increasing roughness, coating with micro- and nano-structures, or using nanofluid are the main methods. Kurihara and Myers [4] started to research the influence of HTC by surface roughness. They found that increasing roughness might increase active nucleation sites, which leads to a higher HTC. However, simply roughening the surface is not suitable for industrial application for the fast aging of the surfaces [5,6]. Nano-structures, such as carbon

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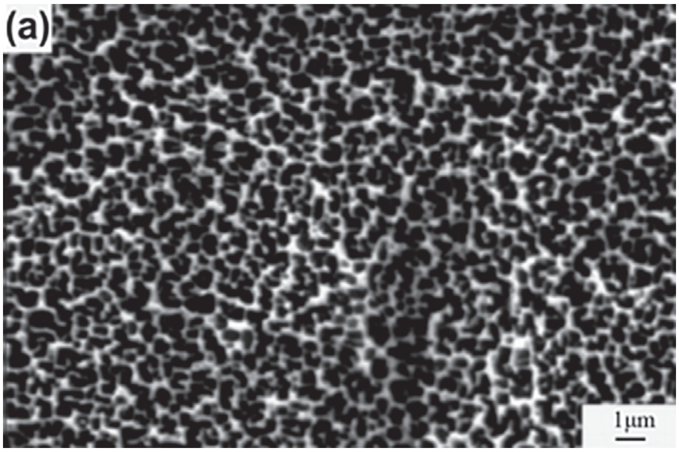
nanotubes [7,8], nanostructured surfaces on metals [9,10] and nanowires [3,11,12], enhanced the HTC in boiling heat transfer. Nanofluid has been used as a boiling coolant because the nano-particles gather on the surface to increase roughness and nucleation sites and even change its hydrophilicity [13,14]. Wettability is also important for boiling heat transfer. Hydrophobicity promotes nucleation and HTC at low heat flux, while hydrophilicity maintains liquid transport to hot surfaces to prevent CHF [15]. The combination of hydrophilicity and hydrophobicity has been found to increase both HTC and CHF [16–19].

Due to the development in micro- and nano-manufacture approaches, heat exchange surfaces can be fabricated using roughening, coating, and lithographic fabrication methods, and so on [20]. Photolithography is mostly used to produce certain surface structures on silicon. For example, Chu et al. used photolithography produced nano-size silicon pillars on silicon surfaces [21]. Choi and Kim also created Si pillars on larger scales using interference lithography [22]. Another fabrication method to produce nanoscale patterns on silicon surfaces is etching, which has been an active research area in renewable energy materials, especially in black silicon (BSi) solar energy applications [23]. The influence of the BSi surface on phase change heat transfer has not been studied before.

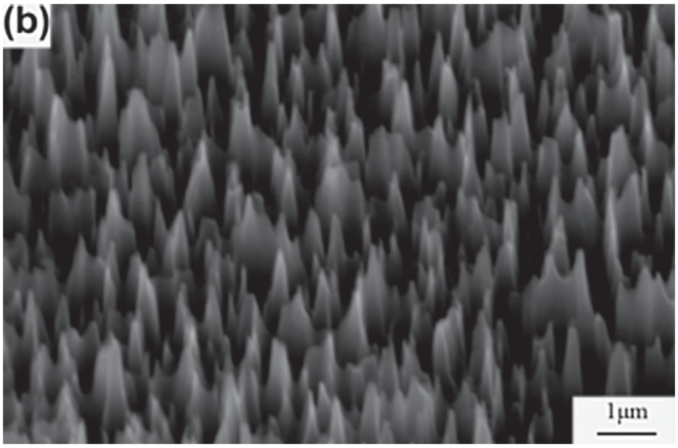
In this paper, a new plasma immersion ion implantation method was used to produce BSi surfaces. The wettability and boiling heat transfer performance of BSi surfaces were measured and compared with the untreated silicon surface.

## 2. Surface fabrication and wettability

In 1998, the BSi was first developed by Mazur et al. [24]. They created arrays of sharp conical spikes by repeatedly irradiating silicon surfaces with femtosecond laser pulses in $SF_6$ or $Cl_2$. The nanoscale structures decrease the silicon reflectivity to less than 1% and the silicon surfaces turn to black. Fig. 1 shows the BSi SEM images with its nanoscale needle-like surface structure.

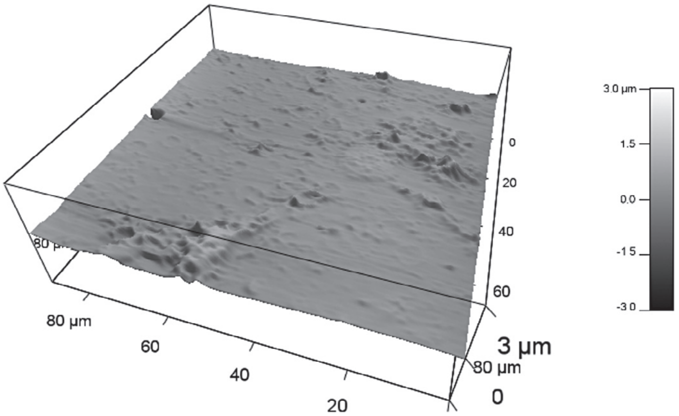


a) Top view

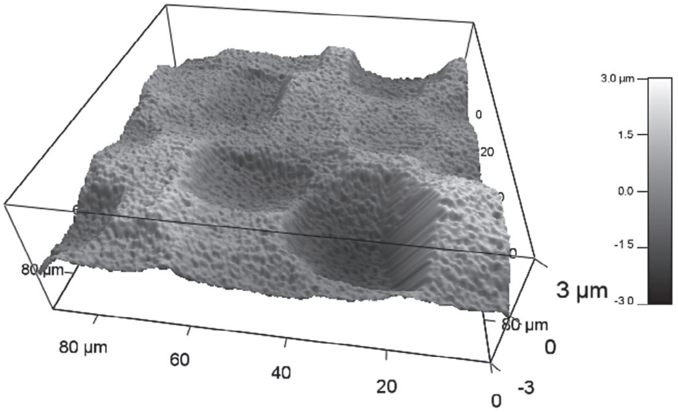


b) Side view (30º to the normal)

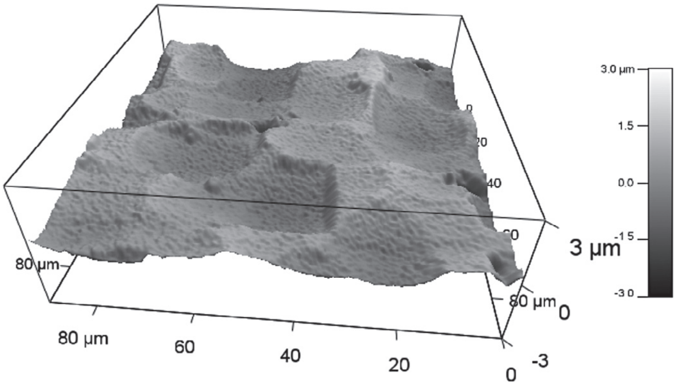
**Fig. 1.** SEM images of black silicon.



a) Silicon Surface



b) BSi-1 surface



c) BSi-2 surface

**Fig. 2.** AFM images of samples.