



Saturated pool boiling heat transfer from vertically oriented silicon surfaces modified with foam-like hexagonal boron nitride nanomaterials



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ABSTRACT

In this work, the ability of a foam-like hierarchical hexagonal boron nitride (h-BN) nanomaterial to act as a scalable surface modifier for improved pool boiling performance is investigated. The h-BN foam samples were grown using an atmospheric pressure chemical vapor deposition process onto the surfaces of open-cell nickel foam followed by selective etching. Saturated pool boiling experiments were conducted in degassed deionized water for unaltered silicon surfaces, silicon surfaces modified with planar or foam-like h-BN materials plus adhesion layer, and a silicon sample with only the adhesion layer present. Results from the unaltered silicon surface obtained in this study were found to be in excellent agreement with previous studies. For the planar h-BN control sample the observed critical heat flux (CHF) occurred at $24.2 \pm 2.4 \text{ W/cm}^2$ at wall superheat of $28.0 \pm 2.1 \text{ K}$, a factor of three lower CHF than for the unaltered Si surface. CHF for h-BN foam samples occurred at $69.1 \pm 6.9 \text{ W/cm}^2$ at wall superheat of $25.0 \pm 2.1 \text{ K}$ and $87.9 \pm 8.8 \text{ W/cm}^2$ at wall superheat of $24.9 \pm 2.1 \text{ K}$. These CHF results are comparable to the bare silicon values but significantly enhanced compared to the adhesion layer only and planar h-BN samples, thereby indicating foam-like h-BN nanomaterials have the potential to facilitate significant CHF enhancement but that means of integration is critical to determining overall performance. Comparison of boiling curves reveals the h-BN foam samples demonstrated higher heat transfer coefficient at moderate and high heat flux relative to bare silicon, with CHF being reached at $\sim 30\%$ lower wall superheat.

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1. Introduction

Phase change thermal transport processes play a critical role in the successful operation of power plants, refrigeration systems, manufacturing processes, food production, and many other vital human endeavors throughout the world. Beyond these established application areas, the exceptionally high heat transfer rates associated with phase change processes have motivated scientists and engineers to explore new ways of leveraging them to address emerging challenges such as the efficient thermal management of 3D chipstacks [1] and large scale data centers [2,3]. Due to the already pervasive nature of phase change processes in modern technology, performance gains in pool boiling heat transfer could have widespread global impact including but not limited to smaller

and more reliable heat exchangers, lower emission power plants, and ultra-high efficiency data centers. Early research in surface modifications to achieve enhanced pool boiling performance included the use of dendritic formations [4], drilled artificial cavities [5–7], sanding and vapor blasting [7,8], and inclined micro-grooves [6]. More recently, several experimental studies have found significantly improved pool boiling heat transfer performance from surfaces with micro/nanoscale features such as micro-pin fins, nanowire arrays, and graphene-based coatings [9–15]. Inspired by these studies, we report here on our experimental work regarding saturated pool boiling performance enhancement from vertically-oriented silicon (Si) substrates in degassed deionized (DI) water using foam-like hexagonal boron nitride (h-BN) nanomaterials as a surface modifier. Bulk h-BN is a lightweight ceramic material known for its low chemical reactivity and high thermal stability (up to $\sim 800\text{--}1000 \text{ }^\circ\text{C}$ in air [16–18] and $2700\text{--}3000 \text{ }^\circ\text{C}$ in inert atmospheres [19,20]). At the atomic level, h-BN possesses a similar layered arrangement to graphite with strong hexagonally

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arranged covalent B–N bonds within each plane and weak van der Waals interactions in the crossplane direction. Also similar to graphite, h-BN has an exceptionally high in-plane thermal conductivity near 350 W/mK at 300 K [21]. However, unlike graphite h-BN possesses a wide bandgap (4–6 eV) [22,23] which essentially classifies it as an electrical insulator. Hence, for pool boiling applications there is no danger of accidental shorting out electrical components as there might be with metallic or graphitic surface enhancers (foams, porous coatings, nanowire arrays, etc.). These collective attributes – namely high thermal conductivity, chemical inertness, and electrically insulating nature – coupled with the large surface areas possible in an open-cell foam arrangement would seem to give foam-like h-BN nanomaterials a high degree of potential to act as an effective surface modifier for achieving enhanced phase change heat transfer. However, to our knowledge this has never before been ascertained experimentally.

2. Materials and methods

Images of the foam-like h-BN nanomaterials under study are shown in Fig. 1. Complete details of the synthesis process and in-depth material characterization efforts can be found in our previously published work [24]. Briefly, a section of open-cell nickel foam (MTI Corp.) was inserted into the center of a 25.4 mm outer-diameter quartz tube furnace (Lindberg/Blue M Mini-Mite) to act as a template for the surface deposition of h-BN atomic layers. Directly upstream of the entrance to the furnace's heating zone, 500 mg of borane–ammonia complex – also known as borazane – powder (Sigma Aldrich) was loaded in a quartz boat to serve as the precursor material. Before beginning h-BN growth, the nickel foam was annealed under hydrogen gas at 160 sccm flow rate for 2 h. During both the annealing and h-BN deposition, the process pressure and temperature were maintained at ~ 7 kPa gauge pressure (108 kPa absolute pressure) and 1000 °C, respectively, making this an atmospheric pressure CVD (APCVD) process. For the h-BN growth period, the hydrogen flow rate was increased to 360 sccm and the borazane powder was sublimated to vapor by heating to 120 °C via a pair of external band heaters. After 1 h

under these conditions, the band heaters and furnace were turned off and the sample allowed to cool under continuous hydrogen flow [24]. This same APCVD h-BN growth process was also performed on stock 0.03 mm thick Ni foil (MTI Corp.) to create planar h-BN as a control surface by which the effects of the foam-like architecture on boiling performance could be ascertained.

Following the h-BN growth, the nickel foam template was selectively wet etched away to yield freestanding h-BN foam. To do this, the sample was first dipped in a 4.5 wt.% PMMA/chlorobenzene solution and then cured at 100 °C on a hot plate for 45 min to serve as structural protection during wet etching. The sample then underwent a 6 M HCl etch on a hot plate at 100 °C for approximately 2 h until nickel removal was complete. Samples were gently rinsed in a bath of DI water and allowed to dry before being placed in an open-ended quartz tube furnace at 450 °C to burn the PMMA off in air for 90 min. Raman spectroscopy, X-ray diffraction, electron dispersive spectroscopy, and other characterization details about the resulting freestanding h-BN foam can be found in Ref. [24]. For these growth conditions, strut wall thicknesses were observed to be 311 ± 82 nm, with the struts themselves being hollow due to the selective etching of the parent Ni foam (Fig. 1 (d)). From field emission scanning electron microscopy (FE-SEM), the total surface area per unit volume is estimated to be 1.8×10^4 mm²/mm³ if only the exteriors of the strut walls are considered. If the hollow strut interior surfaces are also considered, this nearly doubles to 3.5×10^4 mm²/mm³ due to the thin nature of the h-BN walls.

To create samples suitable for pool boiling experiments, a 1.0 cm \times 1.0 cm \times 0.5 mm Si chip was first mounted to a 1 cm \times 1 cm \times 10 mm mesa machined into the end of a 25.4 mm \times 25.4 mm square copper bar using lead solder. Prior to soldering, a 10 nm adhesion layer of chrome followed by 50 nm of gold was sputtered onto the backside of the Si chip to promote solder wetting. A Si chip was chosen as the surface upon which to mount the sample for several reasons: (1) it provides a relatively featureless surface for easy mounting, (2) pool boiling studies from unmodified Si surfaces can be used as a validation benchmark of the experimental setup used in this work through comparison against literature data [7,9,11,12,25,26], and (3) it makes the

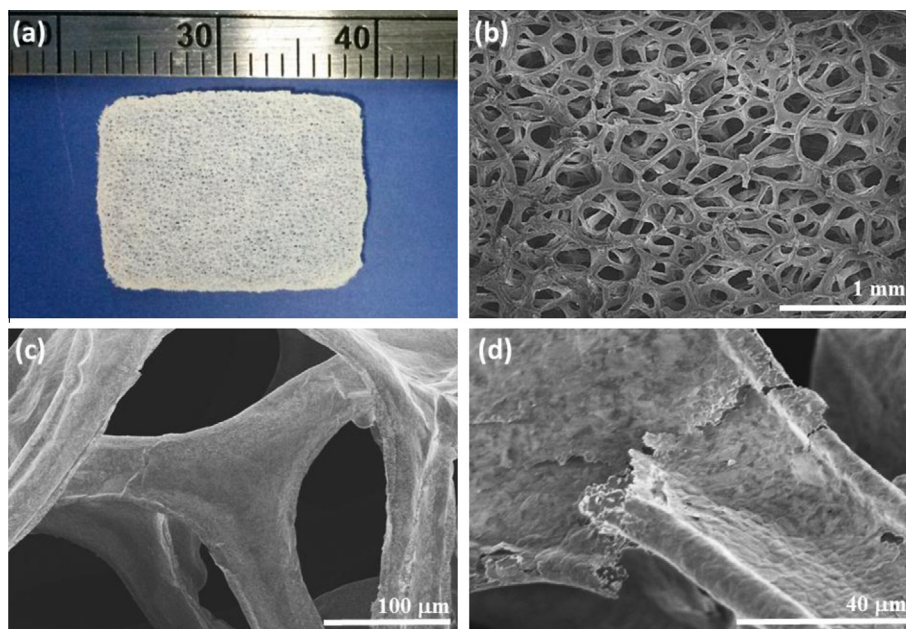


Fig. 1. Images of foam-like h-BN nanomaterials: (a) freestanding foam with millimeter scale shown for reference, (b) FE-SEM large area view, (c) a single branched node, and (d) a fractured strut showing the hollow nature of the interior after selective etching of the parent nickel foam.

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