



Cite this: DOI: 10.1039/c8nr06217j

Root-growth of boron nitride nanotubes: experiments and *ab initio* simulations†

Biswajit Santra,^a Hsin-Yu Ko,^a Yao-Wen Yeh,^b Fausto Martelli,^a Igor Kaganovich,^b Yevgeny Raitses^b and Roberto Car^{*a}

We have synthesized boron nitride nanotubes (BNNTs) in an arc in the presence of boron and nitrogen species. We find that BNNTs are often attached to large nanoparticles, suggesting that root-growth is a likely mechanism for their formation. Moreover, the tube-end nanoparticles are composed of boron, without transition metals, indicating that transition metals are not necessary for the arc synthesis of BNNTs. To gain further insight into this process we have studied key mechanisms for root growth of BNNTs on the surface of a liquid boron droplet by *ab initio* molecular dynamics simulations. We find that nitrogen atoms reside predominantly on the droplet surface where they organize to form boron nitride islands below 2400 K. To minimize contact with the liquid particle underneath, the islands assume non-planar configurations that are likely precursors for the thermal nucleation of cap structures. Once formed, the caps are stable and can easily incorporate nitrogen and boron atoms at their base, resulting in further growth. Our simulations support the root-growth mechanism of BNNTs and provide comprehensive evidence of the active role played by liquid boron.

Received 2nd August 2018,
Accepted 24th August 2018

DOI: 10.1039/c8nr06217j

rsc.li/nanoscale

1. Introduction

Boron nitride nanotubes (BNNTs) have attracted great attention because of their extraordinary thermal, mechanical, electronic, and optical properties.¹ However, the applications of BNNTs have been hampered by the limited yield of the synthesized materials. Among many synthesis routes, the nitridation of boron or various boron precursors (*e.g.*, boron oxides) is one of the most popular approaches to grow BNNTs due to its potential for scalability.² The nitridation methods employed to date can be broadly classified into two categories depending on the operating temperature of the synthesis. The class of low-temperature methods includes chemical vapor deposition (CVD) and ball-milling, typically occurring between 700 K and 2000 K, *i.e.*, below the melting temperature of bulk boron (~2350 K at 1 bar). In ball-milling, precursor powders of boron and metal catalysts are annealed under an N₂ or ammonia gas atmosphere,^{3–5} whereas in CVD, a boron-containing vapor (for example B₂O₃) reacts with a nitrogen-containing gas.^{6,7} These techniques typically produce large diameter (20–100 nm) BNNTs, and the tubes are frequently found with defects.^{4,6} In the class of high-temperature methods

boron or boron nitride (BN) powder is vaporized, and the vapor reacts with nitrogen to form BN nanostructures. The required temperature can be provided by laser irradiation^{8–10} or arc discharge^{11–16} or can be generated in plasma reactors.^{17–19} The tubes produced by the high-temperature method are highly crystalline with few walls (1–5) and small diameters (2–6 nm). Early laser irradiation and arc discharge techniques have produced only small quantities (milligrams) of BN nanomaterials due to the difficulty of controlling the nitridation reaction.^{8,11,12} In recent years, it was found that radiofrequency plasma torches allow for better control of thermal and chemical conditions to achieve large-scale production of BNNTs, *i.e.*, several grams per hour.^{17–19} However, in spite of the significant progress in the yield, the growth mechanisms are still poorly understood.

BNNTs are structurally similar to carbon nanotubes (CNTs), suggesting important similarities in the respective growth mechanisms. The growth of the CNTs has been studied extensively with the aim of controlling their chirality, which is a key feature of electronics applications. Compelling evidence for the root growth of CNTs came from *in situ* measurements using environmental transmission electron microscopy (TEM) in nickel-catalyzed²⁰ and iron-catalyzed²¹ CVD synthesis. In the iron-catalyzed synthesis at 600 °C, time-resolved images showed the nucleation of a cap on the surface of iron-carbide nanoparticles and subsequent growth of CNTs *via* root-feeding from the nanoparticle underneath.²¹ Moreover, further support for the root-growth mechanism was provided by ato-

^aDepartment of Chemistry, Princeton University, Princeton, NJ 08544, USA.

E-mail: bsantra@princeton.edu, rcar@princeton.edu

^bPrinceton Plasma Physics Laboratory, Princeton, NJ 08543, USA

†Electronic supplementary information (ESI) available. See DOI: 10.1039/C8NR06217J

mistic simulations, which suggested that the growth process of CNTs on metal nanoparticles can be decomposed into the following key steps: (i) incorporation of carbon species into the metal clusters, (ii) precipitation of carbon atoms on the surface of the clusters, (iii) cap nucleation, and (iv) growth *via* root-feeding.^{22–28}

In contrast to CNTs, much less is known about the growth mechanism of BNNTs. A comprehensive effort to understand the growth was provided by Arenal *et al.*⁹ In their study, hexagonal-BN (*h*-BN) powder was vaporized by heating with a laser under an N₂ environment. 80% of the BNNTs produced in this way were found to be single-walled, either isolated or in small bundles.⁹ Therein, post-synthesis high-resolution TEM images showed that boron particles were attached at the end of the BNNTs, analogous to the images of CNTs attached to metallic nanoparticles.^{20,21} Arenal *et al.*⁹ suggested that the growth involves the following steps: (1) vaporization of boron-containing precursors, *e.g.*, boron or *h*-BN powder; (2) condensation of vapor into liquid boron droplets upon cooling; (3) interaction of the droplets with nitrogen-containing species leading to the formation of BN caps on the surface of the droplets; (4) nanotube growth *via* progressive incorporation of nitrogen and boron at the interface between the cap and the liquid droplet. The root-growth mechanism was also supposed to be effective in other high-temperature BNNT syntheses. For example, Smith *et al.*¹⁰ were able to increase the BNNT yield by cooling the boron vapor rapidly and flowing N₂ gas at high pressure (2–20 times atm. pressure), which allowed the reaction rate between the boron droplets and N₂ molecules to be increased. In another study, Zettl and co-workers also used high-pressure (up to 10 atm.) N₂ gas interacting with condensed boron to produce high-quality BNNTs at an unprecedented rate of 35 grams per hour.¹⁷ Essentially, these experiments suggest that boron may play a catalytic role and the interaction of nitrogen-containing species with the boron droplets is a critical step in controlling the yield of BNNTs. However, so far, no compelling evidence for the root-growth mechanism of BNNTs has been obtained from *in situ* measurements or atomistic simulations as in the case of CNTs.

The extreme conditions for high-temperature BNNT synthesis are challenging for direct *in situ* imaging. Indeed, the *in situ* TEM imaging of CNT growth was performed at temperatures below 900 K,^{20,21} which are much lower than the temperatures required for BNNT synthesis. Laser-based *in situ* diagnostics under high-temperature conditions have just started to emerge,^{29–32} but they are yet to be applied to BNNT synthesis. A few *in situ* images captured using high-speed cameras provide a qualitative confirmation of the evaporation and condensation process of boron during BNNT synthesis.³³ However, there is a lack of knowledge of the conditions required for the organization of BN structures on the boron surface and for the subsequent growth of BNNTs. The atomistic details for the root-growth mechanism, *i.e.*, assembly, cap formation, and growth *via* root feeding on the liquid boron surface, are unclear. The thermodynamics and kinetics of nitrogen on the surface of boron are fundamental to under-

stand the early stage of BNNT growth. To our knowledge, no atomistic simulations of these non-equilibrium processes have been reported in the literature.

In this work, experiment and theoretical modeling were combined to study the BNNT growth. BNNTs were synthesized by a dc arc discharge in the N₂ gas environment at near-atmospheric pressure. From post-synthesis high-resolution TEM images, we found that BNNTs were often attached to nanoparticles which are much larger than the diameters of the attached BNNTs. Chemical analysis using energy dispersive X-ray spectroscopy (EDS) shows that the tube-end nanoparticles are composed of boron and do not contain tungsten or any other transition metals, indicating that transition metals are not necessary for the arc synthesis of BNNTs. The TEM images suggest that the boron particles played an important role in the nucleation and growth of BNNTs. To gain a microscopic understanding of the early stage of nucleation and growth of BNNTs on the liquid boron surface, we have performed density-functional theory (DFT)-based *ab initio* molecular dynamics (MD) simulations. We used periodic slab models to mimic the near-surface region of a large boron particle. We studied the interaction of the slabs with atomic nitrogen, BN, and N₂ molecules in the temperature range 1600–4000 K. We found that nitrogen atoms reside predominantly on the surface of liquid boron and diffuse fast. With increasing nitrogen coverage on the surface, at temperatures in the range 2000–2400 K the nitrogen atoms organize with boron and form BN islands consisting of hexagonal building blocks. The BN islands are not flat but assume curved forms that minimize the contact with the liquid surface underneath. Larger curvatures would further reduce the contact region and could drive the nucleation of nanotube caps. This process would involve coordinated switches of several BN bonds and did not occur spontaneously on the timescale of our simulations. However, once formed, a cap is stable on the timescale of the simulations and can easily incorporate additional boron and nitrogen atoms at its interface with the liquid boron particle. These results underlie the catalytic role played by the liquid boron particles, strongly supporting a root-growth mechanism.

2. Results and discussion

2.1. Experimental evidence that BNNTs form on boron droplets in arc

In our arc discharge synthesis, a pure boron target was immersed in the arc plasma maintained between two tungsten electrodes at near-atmospheric pressure of the N₂ gas (Fig. S1†). At the arc temperature, boron vaporizes and then condenses into droplets in the region outside the arc where nanotube synthesis is supposed to occur. The droplets are in liquid form. The post-arc produced BN-containing materials were analyzed using high-resolution TEM. Single and double walled tubes were predominant among all the observed BNNTs. Moreover, the tubes were often attached to nano-

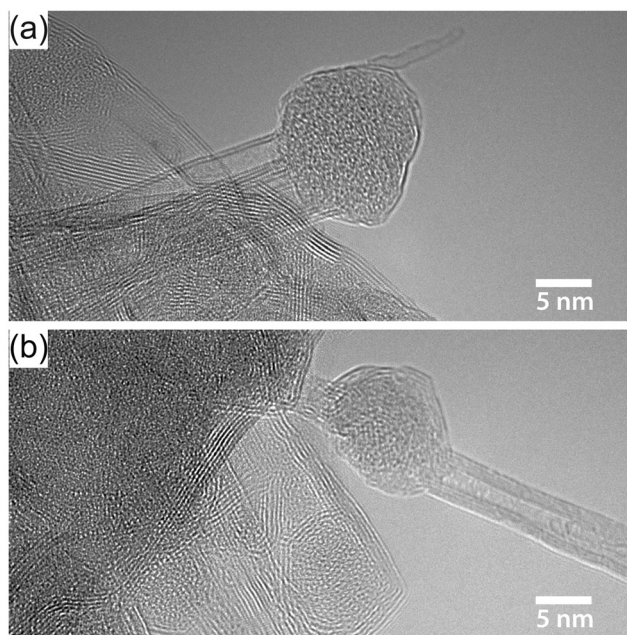


Fig. 1 Post-synthesis high-resolution TEM images showing BNNTs attached to a boron nanoparticle. The BN material is obtained from an arc discharge synthesis.

particles. Fig. 1 shows two TEM images in which BNNTs are attached at one end to nanoparticles much larger than the radius of the nanotubes. Also, it can be seen from the TEM images that both the nanotubes and the nanoparticles attached at the tube-end have similar brightness. The contrasts in Fig. 1 differ from the TEM images reported in earlier arc syntheses of BNNTs.^{11,12,14} In the previous arc studies, the nanoparticles attached at the tube-end had much darker contrast compared to the nanotubes. It was presumed that the darker region of the nanoparticles contained transition metals¹¹ or metal-boride nanocrystals.¹² Recently, a chemical analysis using energy dispersive X-ray spectroscopy (EDS) confirmed that the dark contrasts in arc-synthesized nanoparticles appeared due to the presence of transition metals, *e.g.*, nickel and cobalt,¹⁴ indicating that transition metals may have played some role in the BNNT synthesis using arcs. However, there is no discernible contrast between the TEM images of the BNNTs and the tube-end nanoparticles as produced in this experiment (Fig. 1), suggesting that both are composed of similar elements. In order to characterize the chemical contents of the nanoparticles, we have performed EDS on multiple samples extracted from our experiment. A typical EDS spectrum is shown in Fig. S2 of the ESI.† The EDS spectrum shows that the nanoparticles are composed of boron and do not contain tungsten or any other transition metals. Our observation indicates that transition metals are not necessary for arc synthesis of BNNTs.

We emphasize that the metal-free growth of BNNTs as observed here is due to the novel arc method employed in our experiment. Previously, the electrodes used for arcing con-

tained *h*-BN or metal-doped boron, and to circumvent the insulating nature of BN, transition metal particles were fused into those electrodes in various ways. For example, Chopra *et al.*¹¹ used anodes made of a BN rod inserted into a hollow tungsten electrode, whereas, Loiseau *et al.* used electrodes made from hot pressed HfB_2 .¹² A few other studies were also conducted using electrodes that were made from boron ingots containing $\sim 4\%$ of transition metal impurities, typically nickel and cobalt.^{13,14} During arc synthesis, the electrodes were consumed to a large extent and metal particles were typically found in different parts of the synthesized materials. In particular, clusters of transition metal particles were found within tube-end nanoparticles, and because of this, the role of metals in the arc synthesis of BNNTs was not clear.^{11–14} In contrast, the present work used pure tungsten electrodes and a separate boron source. Due to the higher melting temperature of tungsten the electrodes are consumed much less during our synthesis compared to previous arc studies.^{11–14} The combination of pure tungsten electrodes and a feedstock boron-rod containing less than 0.1% metal impurities is a key factor for the metal-free growth of BNNTs in our arc experiment.

As such, BNNTs with radii significantly smaller than the dimension of the nanoparticle to which they are attached constitute a typical outcome of our experiment. These findings suggest that BNNTs form *via* root-based growth on metal-free boron particles. Although BNNTs grown on metal-free boron particles were not observed in earlier arc produced materials, they were observed in laser vaporization^{8–10} and radiofrequency plasma torch^{18,19} experiments where BNNT synthesis was supposed to be controlled by the root-growth mechanism.

2.2. Nitrogen in liquid boron

To complement the experimental observations and to gain atomistic details of the BNNT growth mechanisms we have performed *ab initio* simulations. Since experiments show that typical boron nanoparticles have dimensions much larger than the diameter of the BNNTs we have modeled a boron nanoparticle with a thin periodic slab and focused our attention on the processes occurring near its surface. To connect with the high temperatures of arc discharge synthesis, we consider a temperature range of 1600 K to 4000 K. The boron slab exhibits good liquid-like diffusivity for temperatures above 1800 K as illustrated in Fig. S3.† Upon lowering the temperature below 1800 K we observe a sudden drop in the diffusivity indicating the onset of glassy behavior.

We studied the evolution of nitrogen atoms in the liquid boron slab as a function of nitrogen coverage and temperature. We randomly distributed nitrogen atoms on the surface of the boron slab and computed the probability density of finding the nitrogen atoms at different depths within the slab. We started with a low nitrogen coverage (*i.e.*, one nitrogen atom per $9.1 \times 9.1 \text{ \AA}^2$, which is the surface cell of our periodic slab) and accumulated statistics from MD simulations lasting ~ 250 picoseconds at each temperature. Fig. 2a shows that at low coverage a nitrogen atom predominantly resides on top of the

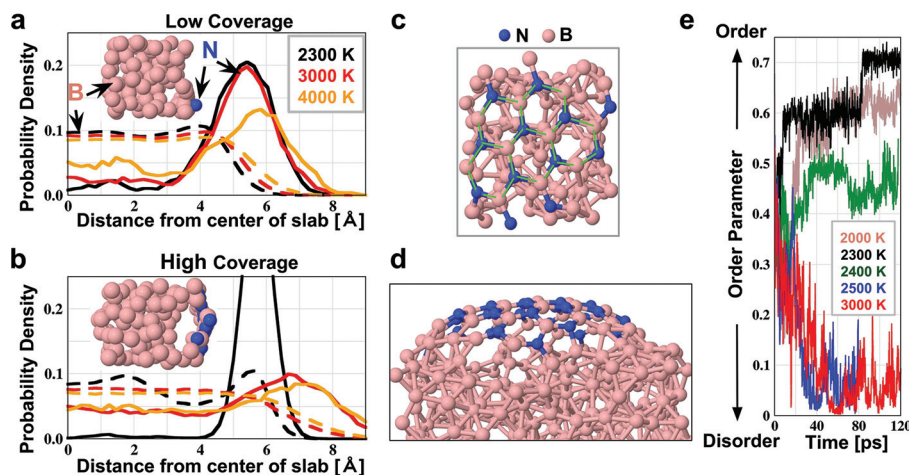


Fig. 2 The probability density of the population of boron (dashed lines) and nitrogen atoms (solid lines) as a function of the distance from the center of the liquid slab in the case of (a) the low nitrogen coverage (see text) and (b) the high nitrogen coverage (see text) on the surface of liquid boron. In (b) the inset shows the side view of a representative structure found at 2300 K. (c) The top view of a representative structure found at 2300 K. The BN island consists of several connected hexagonal rings as highlighted in green. (d) The side view of a representative cap-like structure obtained with a larger BN island at 2300 K (see text). (e) The time evolution of the order parameter (see text) in the boron nitride structures at different temperatures.

boron surface, *i.e.*, near the tail of the boron density profile, independently of the temperature. The nitrogen atoms only transiently move to the subsurface layers at 2300–3000 K. At 4000 K, the nitrogen population of the subsurface region increases but only slightly. We observe that a nitrogen atom coordinates with 2–3 boron atoms on the surface and with more than three atoms in the inner layers. These findings indicate that the higher coordination geometry in the subsurface region is less favorable for the nitrogen atom. To further support this observation, we performed a few simulations in which a nitrogen atom is initially placed near the center of the slab. In all these simulations the nitrogen atom diffuses from the center towards the surface rather quickly. Also, we find that the nitrogen atoms on the surface diffuse rapidly by switching B–N bonds. The surface diffusivity of the nitrogen atoms ranges from 1.3 to 4.8 Å² ps^{−1} at 2000–4000 K, and follows closely the surface diffusivity of the boron atoms in the same regime (Fig. S3†). Below 1800 K, the diffusivity of nitrogen atoms drops by more than one order of magnitude, indicating that the rates of the processes depending on the mobility of nitrogen atoms, such as BN organization and growth, should be severely hampered below 1800 K.

2.3. Formation of BN islands and cap-like structures

With high nitrogen coverage (*i.e.*, twelve nitrogen atoms per 9.1 × 9.1 Å²) a more significant fraction of nitrogen atoms populate the inner subsurface layers at 3000–4000 K as shown in Fig. 2b. However, at 2300 K, the nitrogen population is maximal about ~5.5 Å away from the center of the slab, and is negligible in the sub-surface layers, indicating that all nitrogen atoms reside on top of the surface. On the surface, fast diffusion makes possible frequent interactions among the nitrogen atoms, leading to the formation of small BN chains.

Further interactions among these chains stabilize hexagonal BN rings, which are the basic building blocks of BN nanomaterials. In our simulations, it took a few tens of picoseconds to form stable BN islands. Fig. 2c shows a snapshot of a BN island formed at 2300 K.

We also observe that a formed BN island tends to minimize the contact with the boron surface. The density profile of boron at 2300 K (Fig. 2b) shows that the population of boron increases near the location of the nitrogen density maximum and decreases in the region immediately underneath, indicating a separation of the BN island from the surface. Indeed, the center of the BN island moves away from the surface as shown in the inset of Fig. 2b. The central part of the BN island binds weakly with the boron slab because the nitrogen and boron atoms at the center of the island have nearly saturated B–N chemical bonds with 3-fold coordination in the plane of the island, similar to the atoms in an sp² hybridized *h*-BN sheet. The BN island remains attached to the surface only through the atoms at its periphery. The detachment of the center of the island from the surface creates a curved shape, which could be a precursor for the formation of a BN cap.

To further investigate whether a cap-like protrusion could form spontaneously in our simulation, we consider a larger (18 × 18 Å²) surface cell and implant a flat BN island (containing 25 nitrogen atoms) on the surface of the liquid boron slab. Here we observe that the implanted flat island acquires a curvature on a timescale of a few picoseconds at 2000–2300 K. The curved island is bound to the surface of the slab only at its periphery. Fig. 2d shows the curved structure in which the central atoms are ~3 Å away from the boron slab, and the peripheral atoms are bound to the slab. The separation of the central atoms of the island from the slab did not increase further in a simulation lasting a few tens of picoseconds. A

larger separation would require the formation of a BN nanotube cap, which has a higher curvature than a BN island. Caps are not made only of 6-membered rings of BN bonds like those present in a spontaneously formed island. For example, the armchair-type BN cap that will be considered later in the paper includes 4-, 6-, and 10-membered rings. Only even membered rings occur to avoid N–N or B–B bonds. The transformation of 6-membered rings into 4- and 10-membered rings involves concerted bond switches and is a rare event on the timescale of our simulation. For example, estimates from tight-binding and force-field based simulations of CNT growth on transition metal clusters suggest that timescales of at least 0.4–1.0 nanosecond are necessary for cap nucleation.^{25,26} Even longer times might be needed in the BN case because of the constraint on the even parity of the rings.

2.4. Temperature dependence of BN organization

The organization of BN structures on the liquid boron surface strongly depends on temperature. Above 2400 K, no ordered BN islands form on the surface. Instead, we observe the formation of disordered BN mixtures that included atoms in the subsurface layers. A snapshot of a structure obtained at 3000 K is shown in Fig. S4.† To quantify the time evolution of the structural organization of the nitrogen atoms, we have utilized a local geometry-matching order parameter, S , which measures the overlap between the hexagon formed by the six nitrogen atoms neighboring a nitrogen site and the hexagon formed by the six nitrogen neighbors of a nitrogen site in an ideal planar h -BN sheet (section A5†). The order parameter tends to 1 for perfect matching and tends to zero with increasing disorder. Using this order parameter, we monitor how the system evolves at four different temperatures starting from a configuration in which the nitrogen atoms are randomly distributed on the surface of the boron slab. The evolution of the order parameter is shown in Fig. 2e. The initial value of S is close to ~ 0.4 , reflecting the initial random distribution. At or below 2400 K, the atoms near the top layer become more ordered as the simulation progresses. We observe the formation of hexagonal BN rings that eventually coalesce into a BN island. As a result, the value of the order parameter increases with time. At 2300 K, maximum order ($S \sim 0.7$) is achieved after ~ 85 picoseconds. At this temperature all the nitrogen atoms belong to the coalesced hexagonal rings as shown in Fig. 2c. When the temperature is elevated to 2400 K, not all nitrogen atoms belong to hexagonal rings within 120 picoseconds. On further increasing the temperature to 2500–3000 K, the value of the order parameter decreases from its initial value of ~ 0.4 to values of ~ 0.1 or less, indicating increasing disorder with several nitrogen atoms in the subsurface layers. On the other hand, by lowering the temperature to 2000 K, the BN organization becomes relatively sluggish, and not all nitrogen atoms belong to hexagonal rings within 120 picoseconds. A further reduction in the rate of BN organization is expected to occur at lower temperatures since the surface diffusivity of both nitrogen and boron atoms drops by orders of magnitude for temperatures below 1800 K (Fig. S3†). These findings suggest that

the rate of BN organization should be optimal for temperatures in the range of 2000–2300 K.

To further investigate the temperature dependent organization of nitrogen atoms solvated in a boron slab, we anneal the system from 3000 K to below 2500 K, starting from an equilibrium structure at 3000 K. Upon cooling to 2000–2300 K, all the solvated nitrogens precipitate from the subsurface layers onto the surface region where they form a well defined island made of BN hexagons only. The solvation and precipitation processes of nitrogen in liquid boron are similar to the more widely studied carbon precipitation in metal nanodroplets in the context of CNT growth.^{23–28} Our findings provide comprehensive evidence that nitrogen atoms segregate from liquid boron and organize into BN islands on the surface when the temperature is below 2400 K.

2.5. Cap stability and growth *via* root feeding

Caps are precursors of nanotube formation. The stability of BN caps on the liquid boron surface is thus critical for the growth of BNNTs. Since we can not observe the spontaneous formation of a BN cap in the accessible timescale of our simulation, we construct a cap by thermalizing at 2000 K a cylindrical (5,5) armchair BNNT with an open edge. We observe rapid reconstruction of the open edge into an approximately hemispherical cap to eliminate the dangling bonds present at the open edge. This process leads to the formation of 4- and 10-membered rings. We then cut the cap from the BNNT and plant it on top of the liquid boron surface to explore its stability with MD simulations. To perform reasonably long MD simulations, we choose a simulation cell with a sufficiently large surface area ($12 \times 12 \text{ \AA}^2$), which contains the cap and includes a minimal number of atoms (150) in the overall system (slab + cap). The simulation was run for at least 200 picoseconds at 2000 K. The slab behaves like a good liquid during this entire simulation while the cap diffuses on the surface by switching bonds at the interface between the cap and the liquid surface. More importantly, the floating cap remains upright on the surface and shows no sign of collapsing onto the surface (section A6†). Our findings suggest that small BN caps are stable on liquid boron surfaces.

According to the root-growth model, a stable cap will further grow upon incorporating boron and nitrogen atoms at its base. Since nitrogen atoms favor to stay on the surface and diffuse on a fast timescale, they are likely to get incorporated at the base of the cap. We performed a few simulations in which nitrogen atoms are fed to the slab surface near a (5,5) BN cap as shown in Fig. 3a. In this case, we chose a simulation cell with a larger surface area ($18 \times 18 \text{ \AA}^2$) in order to incorporate additional atoms on the surface. To begin with, we randomly place five nitrogen atoms on the surface of liquid boron as shown in Fig. 3a. These atoms are placed at least 2.2 \AA away from the base of the cap so that they need to diffuse more than one B–B bond length ($\sim 1.7 \text{ \AA}$) to reach the cap. We find that four out of five nitrogen atoms are incorporated at the base of the cap within 5 picoseconds as shown in Fig. 3b. At this stage, five more nitrogen atoms are randomly placed on

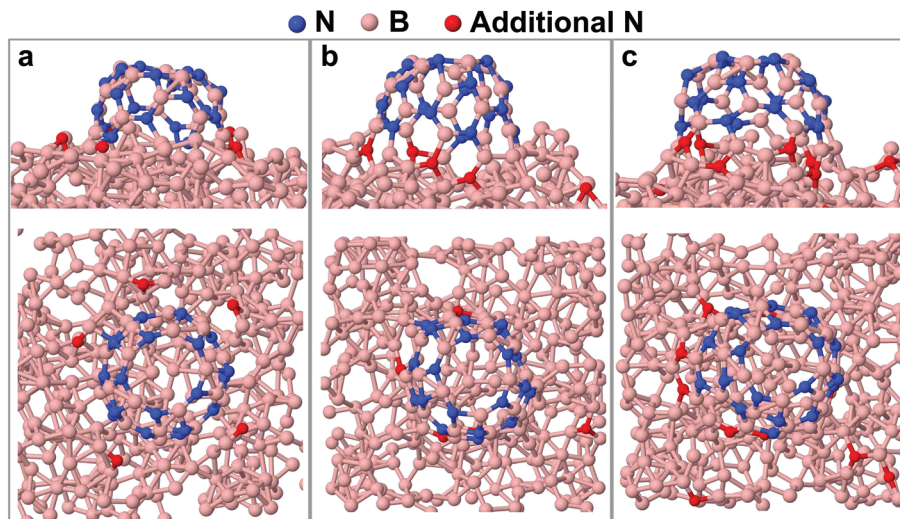


Fig. 3 (a) The side and the top views of the initial structure of the BN cap floating on the liquid boron surface with additional nitrogen atoms. (b) The structure after 5 picoseconds, showing that four out of five nitrogen atoms are incorporated at the base of the cap. At this stage, five additional nitrogen atoms are planted on the surface (not shown). (c) The structure after 12 picoseconds, showing that six out of ten nitrogen atoms are incorporated at the base of the cap.

the surface at least ~ 2.2 Å away from the cap. Within 7 picoseconds, two of them are incorporated at the base of the cap as shown in Fig. 3c. Overall, six out of ten nitrogen atoms are integrated within 12 picoseconds at the base of the BN cap, allowing the cap to grow. We also notice that with higher concentrations of nitrogen on the surface, short BN chains formed. The chains diffuse more slowly than isolated atoms and affect the rate of nitrogen incorporation into the cap. This indicates that for sustained growth of the tube, the feeding rate of nitrogen atoms is crucial. We considered a few possible sources for the nitrogen feedstock in high-temperature synthesis. We found that BN, $(\text{BN})_2$, and $(\text{BN})_3$ molecules are easily adsorbed on the liquid boron surface where they dissociate and release atomic nitrogen. On the other hand, N_2 molecules interact weakly with the boron slab and do not dissociate if deposited on the liquid boron surface. They do dissociate, however, if they penetrate in the subsurface region (section A7†).

3. Conclusions

In summary, BNNTs were synthesized by a dc arc discharge between two refractory tungsten electrodes with a boron target immersed in the nitrogen arc plasma at near-atmospheric pressure. From post-synthesis high-resolution TEM images, we found that BNNTs were often attached to boron nanoparticles. The EDS analysis confirms that the tube-end nanoparticles do not contain tungsten or any other transition metals, indicating that transition metals are not necessary for the arc synthesis of BNNTs. The TEM images indicate that the root-growth is a likely mechanism for BNNT formation. To understand better this mechanism, we have performed DFT-based *ab initio* simu-

lations focusing on the early stages of the BNNT growth. In particular, we studied two key issues in the growth process: (i) the dynamics of the dissolved nitrogen atoms and their organization into BN islands on a molten boron surface and (ii) the stability and growth of a nanotube cap *via* root feeding. We found that atomic nitrogen resides primarily on the surface of a liquid boron droplet if the temperature is not too high. In our simulations, the formation of ordered BN islands made of BN hexagons only occurs below approximately 2400 K. Lower temperatures favor the formation of ordered structures, but for temperatures below 2000 K the rate of island formation slows down and we expect that the entire process should be rapidly quenched as sluggish diffusion sets in below 1800 K. While the precise definition of the optimal temperature regime for growth may depend on the details of the model, such as the adopted DFT approximation, and may be affected by the size and timescale accessible in the simulations, we expect that the general trends observed in our study should be robust. The islands assume curved shapes to minimize contact with the underlying liquid boron surface and could act as precursors for the nucleation of BN caps having higher curvature. Cap nucleation does not occur on the short timescale of our simulations due to the activation free energy necessary for concerted bond switching. However, once formed, BN caps are stable and float on the liquid boron surface over the entire time span of simulations lasting more than 200 picoseconds at 2000 K. At this temperature nitrogen atoms diffuse rapidly on the liquid boron surface, allowing the cap to grow. We recall that the melting temperature of bulk boron is 2350 K but that of small droplets is expected to be considerably lower. Indeed, the thin slab used in our simulation is still a good liquid at 2000 K. Our simulations support a root-growth mechanism for BNNTs on liquid droplets made of pure boron, consistent with

our experimental findings. According to our simulations, the processes leading to cap nucleation and nanotube growth can only occur in the region of the arc chamber where the temperature is about 2400 K or lower. The temperature regime in which BN islands organize on a molten boron surface should also be relevant for other high-temperature synthesis methods, such as induction thermal plasma^{17–19} and laser irradiation^{8–10} techniques. The basic root growth mechanisms that we found, such as surface precipitation, island formation, cap nucleation and growth, are broadly relevant to nanotube growth beyond BNNT synthesis and have many common aspects with the mechanisms for carbon nanotube growth on the surface of transition metal particles.^{22–28}

4. Methods

4.1. Arc synthesis and electron microscopy

BNNTs were synthesized by a dc arc discharge under a pure nitrogen environment at 400 Torr. The cathode and the anode of the arcs were made from lanthanated tungsten rods of 3.125 mm diameter and 6.35 mm diameter, respectively (Fig. S1†). The arc was generated by briefly bringing the cathode and the anode into contact, after which the current was maintained at 40 A. An external control system increased the electrode gap until the specified discharge voltage (35–40 V) was reached. This voltage includes the voltage drop across the arc and along the electrodes. The gap between the electrodes did not exceed 1 cm width. A 99.9% boron target with 0.1% of metal impurities was immersed in the hot plasma region of the arc discharge. The target evaporated, providing boron feedstock for the synthesis of BN nanoparticles, including BNNTs. Transmission electron microscopy (TEM) samples were prepared by sonicating the acetone solution containing the white synthesized product for 2 minutes. The morphology of the synthesized products was studied using an FEI Talos scanning transmission electron microscope operated at 200 kV. A chemical analysis of the synthesized materials was performed using energy dispersive X-ray spectroscopy (EDS).

4.2. *Ab initio* simulations

All DFT-based molecular dynamics simulations were performed using the Quantum ESPRESSO software package.³⁴ We adopted the semi-local approximation of Perdew–Burke–Ernzerhof (PBE³⁵) for exchange and correlation in all calculations. Only the valence electrons were treated explicitly, and the interaction of the valence electrons with the nuclei and the frozen core electrons was modeled by norm-conserving pseudopotentials³⁶ taken from the Qbox public library (<http://fpmd.ucdavis.edu/potentials/>). A plane-wave kinetic energy cutoff of 40 Ry for the wavefunctions was employed. We performed Born–Oppenheimer molecular dynamics. The electronic wavefunction was minimized at each nuclear step using second order damped dynamics with a total energy convergence threshold of 10^{-5} Hartree. Nuclear dynamics was integrated with the Verlet algorithm and a timestep of 2 fs. The ionic

temperature was controlled using Nosé–Hoover chain thermostats. Using these settings the structure of liquid boron is in good agreement with experiment at 2600 K (section A8†). The surface of the liquid boron was modeled with a 2D periodic slab. The lattice parameters of the simulation cell were set to reproduce the experimental bulk density (2.3 g cm^{-3})³⁷ of liquid boron at the melting temperature (2350 K) and 1 bar. The smaller supercell used for the 2D slab has a surface area of $9.1 \times 9.1 \text{ Å}^2$ with 100 boron atoms in the cell. With this setting the slab includes approximately 6 layers of boron atoms. The lattice parameter along the surface normal was chosen to be 30 Å so that the periodic images are separated by at least 15 Å of vacuum. The larger supercell used in the simulations has a surface area of $18 \times 18 \text{ Å}^2$ with a reduced width in the normal direction (3/4th of the width of the smaller unit cell) consisting of 300 boron atoms. The order parameter is defined following the prescription of ref. 38. See section A5 in the ESI† for more details.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work was supported by the U.S. Department of Energy, Office of Science, Basic Energy Sciences, Materials Sciences and Engineering Division, *via* a grant through DOE Contract No. DE-AC0209CH11466. This research used resources of the National Energy Research Scientific Computing Center (NERSC), which is supported by the Office of Science of the U.S. Department of Energy. Additional computational resources were provided by the Terascale Infrastructure for Groundbreaking Research in Science and Engineering (TIGRESS) High Performance Computing Center and Visualization Laboratory at Princeton University. The authors acknowledge Predrag Krstic, Longtao Han, Shurik Yatom, Vlad Vekselman, Alexander Khrabryi, Mikhail Shneider, Bruce Koel, and Rachel Selinsky for fruitful discussions.

References

- 1 D. Golberg, Y. Bando, Y. Huang, T. Terao, M. Mitome, C. Tang and C. Zhi, *ACS Nano*, 2010, **4**, 2979–2993.
- 2 K. S. Kim, M. J. Kim, C. Park, C. C. Fay, S.-H. Chu, C. T. Kingston and B. Simard, *Semicond. Sci. Technol.*, 2017, **32**, 013003.
- 3 Y. Chen, J. Fitz Gerald, J. S. Williams and S. Bulcock, *Chem. Phys. Lett.*, 1999, **299**, 260–264.
- 4 J. Yu, B. C. P. Li, J. Zou and Y. Chen, *J. Mater. Sci.*, 2007, **42**, 4025–4030.
- 5 J. D. Fitz Gerald, Y. Chen and M. J. Conway, *Appl. Phys. A*, 2003, **76**, 107–110.

- 6 A. Pakdel, C. Zhi, Y. Bando, T. Nakayama and D. Golberg, *Nanotechnology*, 2012, **23**, 215601.
- 7 P. Ahmad, M. U. Khandaker, Z. R. Khan and Y. M. Amin, *RSC Adv.*, 2015, **5**, 35116–35137.
- 8 R. S. Lee, J. Gavillet, M. L. de la Chapelle, A. Loiseau, J.-L. Cochon, D. Pigache, J. Thibault and F. Willaime, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 2001, **64**, 121405.
- 9 R. Arenal, O. Stephan, J.-L. Cochon and A. Loiseau, *J. Am. Chem. Soc.*, 2007, **129**, 16183–16189.
- 10 M. W. Smith, K. C. Jordan, C. Park, J.-W. Kim, P. T. Lillehei, R. Crooks and J. S. Harrison, *Nanotechnology*, 2009, **20**, 505604.
- 11 N. G. Chopra, R. J. Luyken, K. Cherrey, V. H. Crespi, M. L. Cohen, S. G. Louie and A. Zettl, *Science*, 1995, **269**, 966–967.
- 12 A. Loiseau, F. Willaime, N. Demoncey, G. Hug and H. Pascard, *Phys. Rev. Lett.*, 1996, **76**, 4737–4740.
- 13 J. Cumings and A. Zettl, *Chem. Phys. Lett.*, 2000, **316**, 211–216.
- 14 Y.-W. Yeh, Y. Raites, B. E. Koel and N. Yao, *Sci. Rep.*, 2017, **7**, 3075.
- 15 M. Kuno, T. Oku and K. Suganuma, *Diamond Relat. Mater.*, 2001, **10**, 1231–1234.
- 16 M. V. P. Altoe, J. P. Sprunck, J.-C. P. Gabriel and K. Bradley, *J. Mater. Sci.*, 2003, **38**, 4805–4810.
- 17 A. Fathalizadeh, T. Pham, W. Mickelson and A. Zettl, *Nano Lett.*, 2014, **14**, 4881–4886.
- 18 K. S. Kim, C. T. Kingston, A. Hrdina, M. B. Jakubinek, J. Guan, M. Plunkett and B. Simard, *ACS Nano*, 2014, **8**, 6211–6220.
- 19 K. S. Kim, M. Couillard, H. Shin, M. Plunkett, D. Ruth, C. T. Kingston and B. Simard, *ACS Nano*, 2018, **12**, 884–893.
- 20 S. Hofmann, R. Sharma, C. Ducati, G. Du, C. Mattevi, C. Cepek, M. Cantoro, S. Pisana, A. Parvez, F. Cervantes-Sodi, A. C. Ferrari, R. Dunin-Borkowski, S. Lizzit, L. Petaccia, A. Goldoni and J. Robertson, *Nano Lett.*, 2007, **7**, 602–608.
- 21 H. Yoshida, S. Takeda, T. Uchiyama, H. Kohno and Y. Homma, *Nano Lett.*, 2008, **8**, 2082–2086.
- 22 A. J. Page, F. Ding, S. Irle and K. Morokuma, *Rep. Prog. Phys.*, 2015, **78**, 036501.
- 23 J. Gavillet, A. Loiseau, C. Journet, F. Willaime, F. Ducastelle and J.-C. Charlier, *Phys. Rev. Lett.*, 2001, **87**, 275504.
- 24 J.-Y. Raty, F. Gygi and G. Galli, *Phys. Rev. Lett.*, 2005, **95**, 096103.
- 25 Y. Ohta, Y. Okamoto, A. J. Page, S. Irle and K. Morokuma, *ACS Nano*, 2009, **3**, 3413–3420.
- 26 Z. Xu, T. Yan and F. Ding, *Chem. Sci.*, 2015, **6**, 4704–4711.
- 27 U. Khalilov, A. Bogaerts and E. C. Neyts, *Nat. Commun.*, 2015, **6**, 10306.
- 28 E. C. Neyts, A. C. T. van Duin and A. Bogaerts, *J. Am. Chem. Soc.*, 2011, **133**, 17225–17231.
- 29 S. Yatom, J. Bak, A. Khrabryi and Y. Raites, *Carbon*, 2017, **117**, 154–162.
- 30 A. Gerakis, M. N. Shneider, B. C. Stratton and Y. Raites, *Proc. SPIE*, 2017, **10093**, 100930O.
- 31 V. Vekselman, A. Khrabryi, I. Kaganovich, B. Stratton, R. S. Selinsky and Y. Raites, *Plasma Sources Sci. Technol.*, 2018, **27**, 025008.
- 32 S. Yatom, A. Khrabryi, J. Mittrani, A. Khodak, I. Kaganovich, V. Vekselman, B. Stratton and Y. Raites, *MRS Commun.*, 2018, 1–8.
- 33 A. L. Tiano, C. Park, J. W. Lee, H. H. Luong, L. J. Gibbons, S.-H. Chu, S. Applin, P. Gnoffo, S. Lowther, H. J. Kim, P. M. Danehy, J. A. Inman, S. B. Jones, J. H. Kang, G. Sauti, S. A. Thibeault, V. Yamakov, K. E. Wise, J. Su and C. C. Fay, *Proc. SPIE*, 2014, **9060**, 9060006.
- 34 P. Giannozzi, O. Andreussi, T. Brumme, O. Bunau, M. Buongiorno Nardelli, M. Calandra, R. Car, C. Cavazzoni, D. Ceresoli, M. Cococcioni, N. Colonna, I. Carnimeo, A. Dal Corso, S. de Gironcoli, P. Delugas, R. A. DiStasio, A. Ferretti, A. Floris, G. Fratesi, G. Fugallo, R. Gebauer, U. Gerstmann, F. Giustino, T. Gorni, J. Jia, M. Kawamura, H.-Y. Ko, A. Kokalj, E. Küçükbenli, M. Lazzeri, M. Marsili, N. Marzari, F. Mauri, N. L. Nguyen, H.-V. Nguyen, A. Otero-de-la Roza, L. Paulatto, S. Poncé, D. Rocca, R. Sabatini, B. Santra, M. Schlipf, A. P. Seitsonen, A. Smogunov, I. Timrov, T. Thonhauser, P. Umari, N. Vast, X. Wu and S. Baroni, *J. Phys.: Condens. Matter*, 2017, **29**, 465901.
- 35 J. P. Perdew, K. Burke and M. Ernzerhof, *Phys. Rev. Lett.*, 1996, **77**, 3865.
- 36 D. Hamann, M. Schlüter and C. Chiang, *Phys. Rev. Lett.*, 1979, **43**, 1494–1497.
- 37 F. Millot, J. C. Rifflet, V. Sarou-Kanian and G. Wille, *Int. J. Thermophys.*, 2002, **23**, 1185–1195.
- 38 F. Martelli, H.-Y. Ko, E. C. Oğuz and R. Car, *Phys. Rev. B*, 2018, **97**, 064105.

Supporting Information of Root-Growth of Boron Nitride Nanotubes: Experiments and *Ab Initio* Simulations

Biswajit Santra^{1,*}, Hsin-Yu Ko¹, Yao-Wen Yeh², Fausto Martelli¹, Igor Kaganovich², Yevgeny Raitses², and Roberto Car^{1†}
¹*Department of Chemistry, Princeton University,
Princeton, NJ 08544, USA*
²*Princeton Plasma Physics Laboratory,
Princeton, NJ 08543, USA*

A1. EXPERIMENTAL SET-UP FOR ARC

Fig. S1 shows the current experimental set up in which the arc runs between two conductive electrodes made from tungsten. A separate boron target is immersed in the arc plasma, which serves as the boron feedstock for synthesis of boron nitride nanotubes (BNNTs). The boron target contains less than 0.1% impurities including metals. In previous studies,^{1,2} electrodes were made with boron which simultaneously served as the boron feedstock. Since pure boron is a poor electrical conductor, in these prior experiments 2–4% metal impurities were added to the boron electrodes to make them electrically conductive, as needed for running the arc. The boron electrodes containing metallic impurities also served as the feedstock of boron for the synthesis of BNNTs.

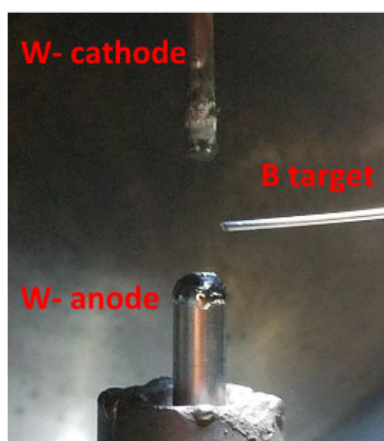


FIG. S1. A DC arc setup with two tungsten electrodes (cathode is top, anode is bottom) and the boron target for immersion to a nitrogen plasma produced by the arc. The target evaporated providing boron feedstock for synthesis of BN nanoparticles, including BNNTs.

A2. EDS ANALYSIS

We have performed energy dispersive X-ray spectroscopy (EDS) on multiple tube-end nanoparticles to characterize their chemical contents. A typical EDS spec-

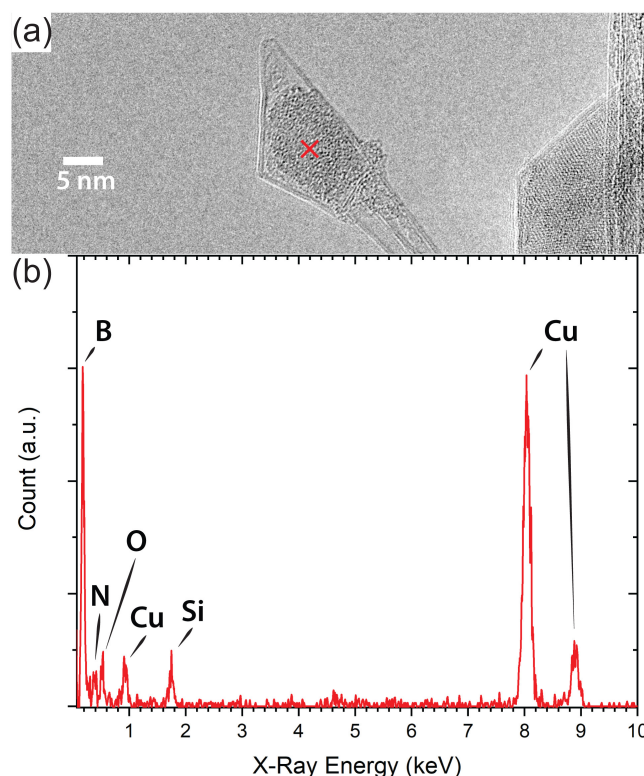


FIG. S2. (a) A TEM image of the BNNTs attached to a nanoparticle. The red cross indicates the position where EDS spectra were measured. (b) The EDS spectra of the nanoparticle.

trum of the particles is shown in Fig. S2(b). The corresponding TEM image of the sample is also shown in Fig. S2(a). The EDS spectrum confirms that the tube-end nanoparticles are composed of boron, without transition metals. Also, as shown in Fig. S2(a), the boron nanoparticle is wrapped by two layers of boron nitride shell, which is the source of the nitrogen signal in the EDS spectrum. The additional features of silicon and copper appear from the background support material and are not attributed to the examined sample. Moreover, we find presence of oxygen which is thought to appear due to partial oxidations after the synthesis. The EDS spectrum clearly shows that tungsten or any other transition metals are absent in the tube-end nanoparticles, indicating

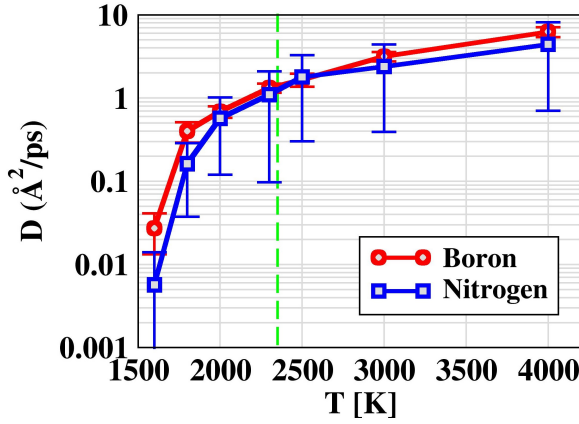


FIG. S3. The diffusivity (D) of boron and nitrogen atoms parallel to the surface computed from DFT-PBE simulations as a function of temperature. The green dashed line indicates the bulk melting temperature of boron.

that transition metals are not crucial for the synthesis of BNNTs using arc discharge.

A3. DIFFUSIVITY OF BORON AND NITROGEN

We perform ab initio MD simulations of nitrogen in liquid boron at 1600–4000 K. In these simulations, the liquid slab contains 101 boron atoms and one nitrogen atom in the periodic unit. Each trajectory is at least 210 ps long. The diffusivity of boron and nitrogen atoms parallel to the surface is computed from the mean squared displacement (MSD) of the particles in a direction parallel to the surface of the slab. The entire trajectory was divided into sections of 20 ps each separated in time by 10 ps. In each section of the trajectory, the slope of the MSD is obtained from linear fitting and is set to be equal to $4D$, as appropriate for two-dimensional diffusion. Then the average diffusivity and the standard deviation are computed from the values obtained from all sections of the trajectory. The temperature dependence of the diffusivity of boron and nitrogen is shown in Fig. S3. The statistical error is much larger for nitrogen than boron since the statistics are obtained from one nitrogen atom as opposed to 101 boron atoms.

A4. TEMPERATURE DEPENDENCE OF BN STRUCTURES

We randomly place 12 nitrogen atoms on the surface of a liquid boron slab with periodic unit having surface area equal to $9.1 \times 9.1 \text{ Å}^2$. Simulations at 3000 K produce a disordered BN mixture whereas at 2300 K they produce an ordered BN island, as shown in Fig. S4.

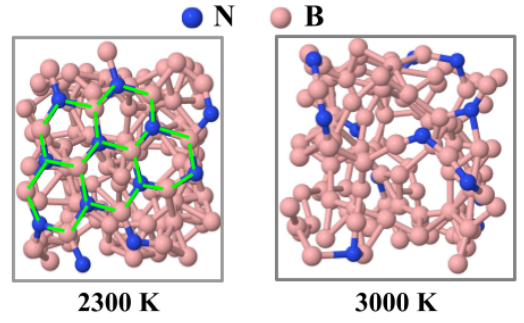


FIG. S4. Comparison of the BN structures at two different temperatures. The green lines highlight the hexagonal BN rings.

A5. LOCAL ORDER PARAMETER (S)

In order to distinguish different BN structures we use a local order metric (LOM) that measures the degree of order in the neighborhood of an atomic site. The LOM maximizes the overlap between the spatial distribution of sites belonging to that neighborhood and the corresponding distribution in a suitable reference system.³ The LOM takes a value close to zero for completely disordered environments and equal to one for environments that match perfectly with the reference. The site averaged LOM defines a scalar order parameter, S . To characterize the BN systems of interest here, we consider nitrogen sites only. The reference system is chosen to be the second coordination shell of a nitrogen atom in a perfect h-BN planar sheet, as shown in Fig. S5(a). This order parameter is able to distinguish different BN structures on the surface of liquid boron, as shown in Fig. S5.

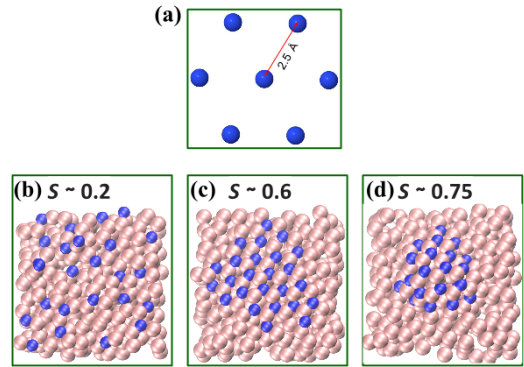


FIG. S5. (a) Reference system for the local order metric. The order parameter (S) in different structures: (b) randomly distributed nitrogen atoms on the boron surface, (c) a BN island on the surface, and (d) a BN cap on the surface. Each structure contains 25 nitrogen atoms.

A6. STABILITY OF A BN CAP ON THE SURFACE OF LIQUID BORON

A (5,5) BN cap (containing 50 atoms) placed on a liquid boron surface (containing 100 atoms) floats on the surface and remains stable till the the entire time span of our simulation lasting more than 200 picoseconds at 2000 K, as shown in Fig. S6.

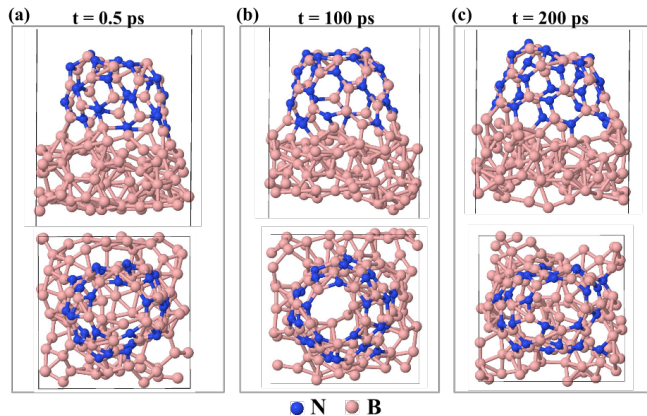


FIG. S6. Snapshots at different times (t) of a simulation in which a (5,5) BN cap is placed on a liquid boron surface at 2000 K. Top and bottom panels are side and top views, respectively. See main article for further description.

Similarly, a (6,0) capped short BN nanotube (containing 58 atoms) placed on the same liquid boron slab remains stable till the the entire time span of our simulation lasting more than 150 picoseconds at 2000 K, as shown in Fig. S7.

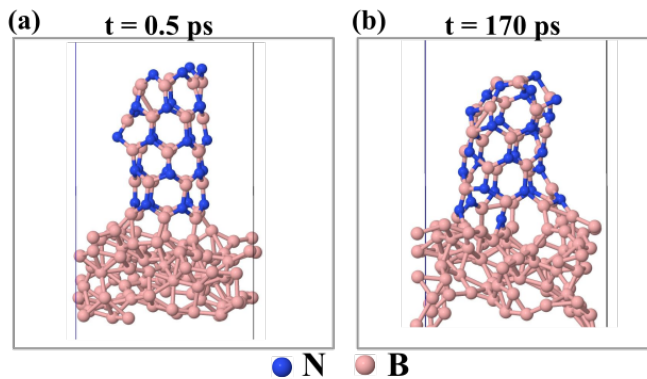


FIG. S7. Snapshots at different times (t) of a simulation in which a (6,0) capped short BN nanotube is placed on a liquid boron surface at 2000 K. Top and bottom panels are side and top views, respectively.

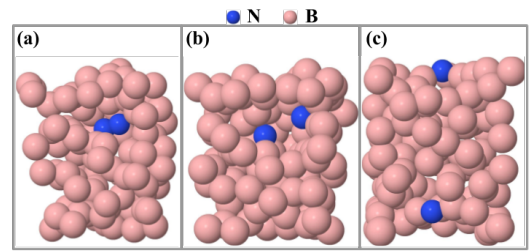


FIG. S8. Snapshots depicting the dissociation of an N_2 molecule initially located in a subsurface layer of a liquid boron slab at 2500 K. (a) Initial configuration showing an intact N_2 molecule. (b) Dissociation is already evident after 0.3 ps. (c) Both nitrogen atoms precipitate on the surface after ~ 6.5 ps. A side view of the slab is shown in all the images.

A7. POSSIBLE ORIGIN OF THE NITROGEN ATOMS IN THE BORON DROPLETS

In the high-temperature synthesis of BNNTs, boron droplets form in the condensation of vapor containing boron and nitrogen atoms. Nitrogen atoms initially present in the vapor may condense to form N_2 molecules or other molecular species, such as BN and BN chains. In order to confirm that such BN molecular species appear in arc, *in situ* spectroscopic measurements are required, which are beyond the scope of this work. In a study conducted previously during laser ablation of boron nitride in N_2 environment, the emission spectra showed signatures of BN in the ablated plasma plume.⁴ This finding indicates that BN can also be present in arc plasma. These molecular species may get trapped into the boron droplets during their condensation, or they can get absorbed by droplets that are already formed. Inside the droplets all these nitrogen containing species dissociate quickly, as shown in Fig. S8 for N_2 . BN chains hitting the surface of the droplet are easily adsorbed and dissociate quickly, as shown in Fig. S9 for a $(BN)_2$ molecule. A few trajectories similar to the one of Fig. S9 but involving an N_2 molecule indicate that this molecule is not easily adsorbed but tend to scatter off the droplet. This is a consequence of the weak interaction of N_2 with the boron surface. N_2 molecules would dissociate quickly if they could penetrate into the subsurface region (Fig. S8). Subsurface penetration of N_2 is a rare event on the time scale of our simulations and we are unable to quantify its likelihood by direct simulation.

A8. BULK LIQUID BORON BENCHMARK

In order to assess the predictive power of our ab initio MD approach, we model bulk liquid boron and compare the simulated structure with x-ray diffraction experiments.⁵ The simulation in the NVT ensemble uses a periodic simple cubic box containing 100 atoms. The

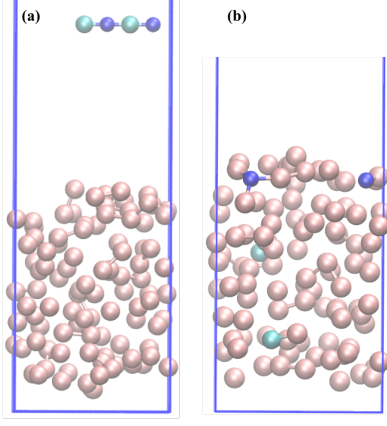


FIG. S9. Snapshots depicting the dissociation of a $(\text{BN})_2$ chain that hits the surface of a liquid boron slab at 3000 K. (a) The $(\text{BN})_2$ molecule moves towards the surface of the slab with thermal velocity. (b) The molecule dissociates within ~ 0.5 ps as it hits the slab; the nitrogen atoms (blue) remain on the surface while the boron atoms (cyan) diffuse throughout the slab, shown in a side view.

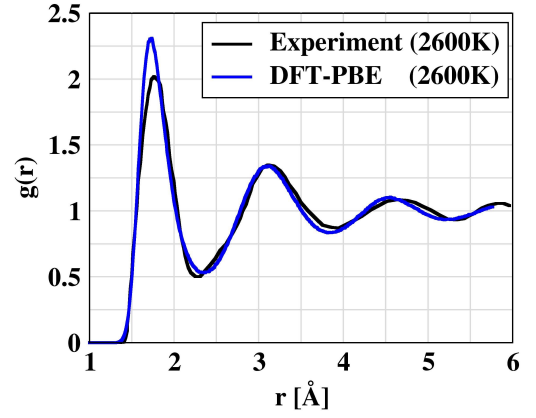


FIG. S10. A comparison of the radial distribution function, $g(r)$, of liquid boron obtained from DFT-PBE simulation and from scattering experiment.

lattice parameter is set equal to 11.5 \AA to reproduce the experimental density (2.3 g/cm^3) of liquid boron at the melting temperature (2350 K) and standard pressure using 200 boron atoms in the unit cell. The simulation runs for 50 ps following 10 ps of equilibration. The radial distribution function (RDF) at 2600 K agrees well with experiment at the same temperature, as shown in Fig. S10. The most notable difference between theory and experiment is a small discrepancy in the height of the first peak. This discrepancy may be due to the inaccuracy of the adopted DFT approximation but may also result from the experimental resolution (the highest momentum transfer was $\sim 11 \text{ \AA}^{-1}$). Notice that the RDF has not yet reached the asymptotic value of 1 at the boundary of our cell, suggesting that some size effects may affect our simulation.

* biswajit.santra@gmail.com

† rcar@princeton.edu

¹ J. Cumings and A. Zettl, Chem. Phys. Lett. **316**, 211 (2000).

² Y.-W. Yeh, Y. Raites, B. E. Koel, and N. Yao, Sci. Rep. **7**, 3075 (2017).

³ F. Martelli, H.-Y. Ko, E. C. Oğuz, and R. Car, Phys. Rev. B **97**, 064105 (2018).

⁴ C. Dutouquet, S. Acquaviva, and J. Hermann, Spectrochimica Acta Part B: Atomic Spectroscopy **56**, 629 (2001).

⁵ S. Krishnan, S. Ansell, J. J. Felten, K. J. Volin, and D. L. Price, Phys. Rev. Lett. **81**, 586 (1998).