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Carbon nanotubes are of wide interest due to their excellent properties such as tensile strength and electrical and thermal conductivity, but are not, when placed alone on a substrate, well resistant to mechanical wear. Diamond-like carbon (DLC), on the other hand, is widely used in applications due to its very good wear resistance. Combining the two materials could provide a very durable pure carbon nanomaterial enabling to benefit from the best properties of both carbon allotropes. However, the synthesis of high-quality diamond-like carbon uses energetic plasmas, which can damage the nanotubes. From previous works it is neither clear whether the quality of the tubes remains good after DLC deposition, nor whether the DLC above the tubes retains the high $sp^3$ bonding fraction. In this work, we use experiments and classical molecular dynamics simulations to study the mechanisms of DLC formation on various carbon nanotube compositions. The results show that high-$sp^3$-content DLC can be formed provided the deposition conditions allow for side-wards pressure to form from a substrate close beneath the tubes. Under optimal DLC formation energies of around 40–70 eV, the top two nanotube atom layers are fully destroyed by the plasma deposition, but layers below this can retain their structural integrity.

I. INTRODUCTION

Single-walled carbon nanotubes (SWCNTs) and their networks are promised as materials which have potential applications as optically transparent conductive electrodes, thin-film field transistors and sensors,1 due to their unique electrical conductivity and optical transparency.2 However, the SWCNT-networks cannot resist mechanical damage from scratching and wear,3 which makes them challenging to use in mechanical applications. It has been reported that a carbon coating could improve the mechanical properties of the SWCNT networks, i.e., improved elasticity and better nanowear resistance.4

By using vacuum arc discharge, fully ionized carbon plasma with controllable energy and flux are deposited on the nanostructures, where amorphous diamond-like carbon (DLC) has been reported to grow on top, resulting in enhanced mechanical strength.5–10 In DLC films, carbon atoms are bonded together mainly in the form of $sp^2$ and $sp^3$ hybridizations. Because DLC films are well known for their high hardness and high elastic modulus, they are utilized in a wide range of applications to improve properties such as high wear resistance, chemical inertness, high electrical resistivity, and low friction coefficients.11 This has led to practical applications such as antireflective and scratch-resistant wear-protective coating for IR optics,12,13 wear and corrosion protection of magnetic storage media,14 and coating and protecting biological implants against corrosion as diffusion barriers.15,16 DLC-CNT composites could be formed by doing vacuum arc deposition on CNTs with an average energy of carbon ions about 30–70 eV. The functional SWCNT-networks could then be covered by the amorphous DLC matrix, while the electrical conductivity and optical transparency are preserved with enhanced mechanical properties.4

It is still challenging to characterize the structure of DLC films because of their complicated amorphous morphology. There are some experimental techniques for characterization of DLC, for example, Fourier transform infrared spectroscopy (FTIR), high resolution nuclear magnetic resolution (NMR), electron energy loss spectroscopy (EELS), X-Ray Photoelectron Spectroscopy (XPS), Auger spectroscopy, etc. It also has been reported that by either thermal activation17,18 or low energetic ion irradiations,19 the structure of the metastable DLC materials will convert some $sp^3$ bonds to $sp^2$ bonds towards graphite-like carbon.11 Thus a fundamental understanding of carbon hybridization under low energetic carbon atom bombardments is of great interest. In this paper, experimental details of SWCNT network synthesis and amorphous carbon deposition on it are given. The $sp^2$ and $sp^3$ hybridizations are quantized by XPS. Classical molecular dynamics (MDs) simulations were performed to examine ion beam deposition of such DLC films on SWCNTs, carbon foams, multi-walled carbon nanotubes (MWCNTs) SWCNT bundles, with and without diamond substrates, as well as temperature effects on DLC films growth. The atomic structures of...
II. EXPERIMENTAL METHOD

SWCNTs were synthesized by a high temperature floating catalyst CVD process, based on thermal decomposition of ferrocene to form iron nanoparticles.\textsuperscript{20–22} Following this catalytic decomposition of carbon monoxide via Bouduard reaction on the iron nanoparticle surfaces leads to nucleation and growth of SWCNTs in gas phase, inside a quartz walled laminar flow reactor, maintained at 880°C based on previous optimization.\textsuperscript{20} The SWCNTs can aggregate in gas phase forming bundles, consisting of several parallel SWCNTs due to surface energy minimization.\textsuperscript{23} SWCNTs were collected on nitrocellulose membrane filters (Millipore, 0.45 μm pore size) at the outlet of the reactor to form randomly oriented SWCNT networks. These SWCNT networks are subsequently transferred onto Si substrates using a room temperature press transfer method described in detail elsewhere.\textsuperscript{22,24}

Tetrahedral amorphous carbon (ta-C) coating was deposited onto the press transferred SWCNT networks using a pulsed Filtered Cathodic Vacuum Arc (p-FCVA) deposition system at Aalto University. A pulse forming network, charged to 400 V (pulse current 650 A) was used to strike the triggerless arc\textsuperscript{25} with a frequency of 1 Hz and a knee filter with 45° bend was utilized to filter out macro-particles. The working pressure during depositions was 2 × 10⁻⁶ Torr and the substrates were at floating potential and room temperature (300 K). The cathode to substrate distance was maintained at 110 mm and substrates were rotated to ensure homogeneous film deposition. The deposition rate of the ta-C coating was around 0.1 nm/pulse (on silicon), for a cathode to substrate distance of 110 nm, as measured by a contact profilometer (Dektak 6 M). 20 nm thick ta-C coating was deposited onto Si substrates (reference sample) and on the SWCNT networks (test sample).

XPS was performed by an Axis Ultra electron spectrometer (Kratos Analytical) using monochromatic Aluminium Kα (E = 1487 eV) irradiation. Low resolution survey scans were recorded in hybrid mode, together with high resolution C1s spectra using 5 eV pass energy and 50 meV energy step with X-Ray power of 150 W. In all XPS measurements the area of analysis was 700 μm × 300 μm.

These experimental observations clearly show that high-\textsuperscript{sp}³ content DLC can be formed on carbon nanotube networks. However, the mechanism is not obvious. Previous work on DLC formation\textsuperscript{26–28} has explained the formation of the DLC to be due to a “subplantation” effect, i.e., that the carbon atoms stop inside a material where a transient high pressure and temperature can promote formation of high \textsuperscript{sp}³ fractions. However, the density of the nanotubes is very low, and hence it is not a priori clear how a high \textsuperscript{sp}³ content can be produced when the carbon is landing on top of them. To understand how and under which conditions the DLC can be formed, we utilize here MDs computer simulations of DLC deposition on various carbon nanotube morphologies.

III. EXPERIMENTAL RESULTS

SWCNT samples were imaged by S-4700 (Hitachi) Scanning Electron Microscopy (SEM) pre (Fig. 1(a)) and post (Fig. 1(b)) ta-C deposition. Image analysis, using ImageJ software shows areal coverage density of SWCNTs on the substrate is an average of 40%. Post deposition, the presence of coating thickens individual SWCNT bundle and network morphology, is different in comparison to an uncoated network (Fig. 1(a)).

Fig. 2 shows the XPS C1s high resolution spectra for un-coated SWCNTs, ta-C reference sample, and ta-C coated SWCNT sample with curve fitting for different components. The C1s spectrum for un-coated SWCNTs only (Fig. 2(a)) was fitted with an asymmetric Doniach-Sunjic\textsuperscript{33} profile after removal of Shirley background, to fit conductive \textsuperscript{sp}² bonded carbon due to its semi-metallic behavior\textsuperscript{34} and a Gaussian component. The Doniach-Sunjic fit peak at 284.4 eV is identified as \textsuperscript{sp}² bonded carbon\textsuperscript{35–38} and the uncoated SWCNT network has a dominant \textsuperscript{sp}² carbon bonding fraction (around 82% of C1s spectrum area). The Gaussian component at 285.5 eV is attributed to defects in the nanotube structure as shown in literature\textsuperscript{39,40} and minor surface contamination.

The C1s spectra for reference ta-C sample (Fig. 2(b)) and ta-C coated SWCNT sample (Fig. 2(c)) were fitted with

![FIG. 1. SEM image of SWCNT bundles (a) pre-deposition; (b) post deposition of 20 nm taC.](image)

![FIG. 2. XPS C1s high resolution spectra for un-coated SWCNTs, ta-C reference sample, and ta-C coated SWCNT sample (Fig. 2(c)) were fitted with](image)
mixed Gaussian-Lorentian components after removal of Shirley background. The \( sp^2 \) component in ta-C coating is not fitted by the Doniach-Sunjic component as the \( sp^2 \) phase is disordered and ta-C is insulating in nature. The reference ta-C spectrum (Fig. 2(b)) has primary peaks at 284.4 eV and 285.3 eV corresponding to \( sp^2 \) and \( sp^3 \) bonded carbon, respectively, and a secondary peak at 286.5 eV, attributed to C-O contamination, due to air exposure. The peak fits match well with similar studies in literature and show a significant \( sp^3 \) bonding fraction (around 76\% of C1s spectrum area). The ta-C coated SWCNT sample also shows a significant \( sp^3 \) bonding fraction (around 75\% of C1s spectrum area), similar to reference ta-C sample. This indicates that the coating on the SWCNT network is good quality ta-C.

**IV. SIMULATION METHOD**

The deposition processes were simulated by using the classical MD method with the PARCAS code. For modelling the C-C interactions, the analytic bond-order potential of Brenner with extended cutoff parameters was used. The original form of the cut-off function, which describes the range of the local atomic orbitals, was only limited to the first neighbors with the cutoff parameters \( R = 1.7 \, \text{Å}, S = 2.0 \, \text{Å} \), which allows the existence of compressed graphite structures with even higher densities than the diamond. It has been reported by Jäger and Albe that by adjusting the cutoff parameters to \( R = 1.95 \, \text{Å} \) and \( S = 2.25 \, \text{Å} \) much higher \( sp^3 \) fractions could be achieved.

The quality of the deposited films were analysed by the coordination numbers, which were calculated by the radial distribution function (RDF) within the first cutoff length of 1.9 Å. The threefold atoms were considered as \( sp^2 \) hybridization, while the fourfold atoms were considered as \( sp^3 \) hybridization. Meanwhile, depth profiles were calculated with the depth interval of 2.05 Å, indicating the dependence of DLC quality on the deposition depths. Mass densities were also calculated compared to pure diamond and graphite. Furthermore, the overall RDF, and the RDF calculated only at \( sp^2 \) or \( sp^3 \) sites with the contributions of \( sp^2 \) and \( sp^3 \) coordinated neighbours, were compared to study the short range order of the deposited films. Ring analysis was applied to quantify the overall disorder of the grown films.

*FIG. 2. XPS high resolution C1s spectra with peak fits: (a) Un-coated SWCNTs with 82\% \( sp^2 \) bonding fraction; (b) 20 nm thick reference ta-C coating with 76\% \( sp^3 \) bonding fraction; (c) SWCNT network with 20 nm thick ta-C deposited showing 75\% \( sp^3 \) bonding fraction.*

A diamond \{111\} substrate with a box size of about \( (30, 30, 20) \, \text{Å} \) was used as the substrate. Periodic boundary conditions were used at the lateral directions of the diamond substrate, while the top surface was kept open. To prevent the entire system from moving during the irradiation, two atomic layers were fixed at the bottom. The incoming carbon atoms with the energies of 30, 40, 50, and 70 eV bombarded perpendicular to the open surface. A random cell shift in the lateral direction was used for each ion bombardment with periodic boundary conditions. The entire deposition process was simulated at 100 K and 300 K or at temperatures of 100–1000 K in one case. During each bombardment within the time scale of 15 ps, the heat dissipation from the impact region to the rest of the system was modelled by Berendsen temperature scaling, by which the periodic boundaries within a thickness of 7 Å were immersed in a heat bath at 100 K and 300 K. A relaxation time of 5 ps between every two impacts was used to linearly cool down the entire system to 100 K and 300 K.

**A. The effect of electronic stopping power**

Electronic stopping refers to the slowing down process of a projectile ion because of the inelastic collisions between bound electrons and the energetic ion. When the impacting energy is high, the ion is slowed down mainly by electronic stopping. To test whether the electronic stopping power positions...
We first carried out simulations of C deposition on a pristine diamond (with no nanotube on top) to get a point of comparison with the NT systems. Fig. 3 shows the simulation results on a pristine diamond with deposition energy of 70 eV at 100 K and 300 K, without electronic stopping power. The negative deposition depth is the growing direction, and the positive depth of the substrate with the interface at 0 Å. At both temperatures, the $sp^3$ fractions went down from 100% to very low values at the surface of the growing films. It is shown that at 100 K the fractions of $sp^3$ hybridizations decreased at the near diamond grown layers from 100% to 45% gradually within the depth of 20 Å, while at 300 K, lying closer to the density of diamond (3.52 g/cm$^3$) than graphite (2.09–2.27 g/cm$^3$).

**B. Radial distribution function**

To study the short order of the grown amorphous film, RDF was calculated for two samples with 37.2% and 48.4% $sp^3$ coordinated atoms excluding the diamond substrate as shown in Fig. 4. The top panel shows the overall RDF for all the atoms, as well as the contributions of $sp^2$ and $sp^3$ neighbours. The lower panel explains the RDF calculated only at $sp^2$ sites with the corresponding $sp^2$ and $sp^3$ contributions, and the RDF calculated only at $sp^3$ sites. It can be seen that for the case of 48.4% $sp^3$ film, the $sp^2$ and $sp^3$ neighbours made the same amount of contributions at the first peak of the overall RDF, which was corresponding to the same percentages of $sp^2$ and $sp^3$ coordinated atoms. However, when calculated only at $sp^2$ sites compared to the overall RDF, the contribution of $sp^2$ neighbours shows a big increase, while the contribution of $sp^3$ neighbours also increased comparatively when calculated only at $sp^3$ sites. This interesting feature can be explained by the separation of $sp^2$ and $sp^3$ sites. In other words, $sp^3$ sites tend to grow close to the diamond substrate, while $sp^2$ sites were mostly near the surface due to the lack of atoms to form bondings at the top.

**C. Ring analysis**

To characterize the amorphous films and quantify the overall disorder, ring analysis$^{32}$ was used to study the films with varied densities and $sp^3$ hybridizations grown at different deposition energies. This method analyses the number of prime rings, which were defined in Ref. 32 as rings without any shortcut. The diamond substrates and the surfaces with a thickness of 20 Å were not included in the studied films. As shown in Fig. 5, the films with lower densities and lower $sp^3$ coordination reveal a relatively more disordered ring analysis when compared to the film with a higher 3.11 g/cm$^3$ density and 58.2% $sp^3$ coordination. The more ordered of ring analysis of this film approaches more closely to the ideal diamond structure, where a six-membered ring is the only prime ring configuration.

**V. SIMULATION RESULTS**

To determine the atomic structures of the deposited films, we simulated the impinging carbon atoms bombarding the SWCNT with a diamond substrate, nano foam with a diamond substrate, suspended SWCNT bundle, and MWCNTs,
as well as MWCNTs with a diamond substrate, as presented in Figs. 6(a)–6(e). For the systems in Figs. 6(a), 6(b), and 6(e), periodic boundary conditions were applied on the two lateral directions of the diamond substrate, including the direction of the tubes or the foam length.

In Fig. 6(a), the chosen CNT with the length of about 26 Å consisting of 450 atoms, was a zigzag SWCNT with the chiral index of (19,0), which gave the diameter of about 15 Å. Meanwhile, the size of the diamond substrate was about (30, 26, 12) Å, which consisted of about 6 atomic layers of the ideal diamond [111]. Before the irradiation, the system was built by connecting the tube on the middle surface of the diamond [111] cell with a distance of 2.0 Å in between, followed by a relaxation at 100 K and 300 K for 100 ps.

In Fig. 6(b), a nano foam which had a similar size as the CNT (Fig. 6(a)) but with the same density as graphite, is shown. The nano foam was formed by amorphous carbon with the mass density of 2.09 g/cm³ with a slow annealing from 5000 K to 100 K and 300 K over 1 ns. Then the nano foam with the size of (15.0, 15.0, 30.6) Å consisting of 721 atoms was connected on top of the diamond with a distance of 2.0 Å in between, followed by a relaxation for 1 ns at 100 K and 300 K.

The deposition processes on the SWCNT bundles and MWCNTs with carbon ion energies of 40, 50, 70 eV were also studied, visualized in Figs. 6(c) and 6(d). In Fig. 6(c), the SWCNT bundles consisting of 11704 atoms were obtained by connecting 7 zigzag (19,0) SWCNTs together with the distance of 3.4 Å between each other at the sides. In Fig. 6(d), the MWCNTs composed of (5,5), (10,10), (15,15) armchair SWCNTs, gave the diameter of 6.8 Å, 13.6 Å, and 20.3 Å, with the inter-shell distance of 3.4 Å. The lengths of the bundle and the MWCNTs were about 100 Å at the periodic boundary condition, within which the middle parts of
The depth profiles for the fractions of \( sp^3 \) hybridization and mass density at 100 K and 300 K were calculated in Fig. 7(f), where a CNT region, a stable inner film region, and a surface region can be clearly identified. In the CNT region, at the energy of 70 eV the structure of the three-fold coordinated SWCNT was completely damaged and transformed to four-fold coordination, while at 40 eV the structure at this region was still identified as three-fold hybridization. Hence, the fractions of \( sp^3 \) bonded atoms at 70 eV was relatively higher than those at 40 eV, where the fractions were 0%–10% in the CNT region. In the inner films, the fractions of \( sp^3 \) hybridization became stable, lying at about 50%–60% at 100 K, and 30%–55% at 300 K, which were quite close to those directly deposited on the pure diamond substrate. At the surface region, the \( sp^3 \) fractions decreased to 0 due to the domination of the \( sp^2 \) bonded atoms. Hence, at the beginning of the deposition, the \( sp^3 \) bondings were hardly constructed because of the existence of the CNT, while when the films were further deposited to a stable level, significant percentages of the \( sp^3 \) configurations would be created. Meanwhile, the mass density of the stable inner film was again lying in the middle of the densities of diamond and graphite. Fig. 7(g) shows the result of ring analysis studied on the obtained samples at 100 K and 300 K. When compared with other films, the sample with irradiation energy of 40 eV at 100 K, which had the highest density of 3.10 g/cm³ and highest \( sp^3 \) fraction of 52.7%, showed the most oriented order ring analysis with the most common ring configurations being six-ring and seven-ring sizes.

To illustrate the temperature effect on \( sp^3 \) hybridization, the deposition processes were simulated with the irradiation energy of 40 eV at 100 K, which had the highest density of 3.10 g/cm³ and highest \( sp^3 \) fraction of 52.7%, showed the most oriented order ring analysis with the most common ring configurations being six-ring and seven-ring sizes.

A. Deposition on SWCNT with diamond substrate

We found that at the low energy of 40 eV, the structure of the SWCNT can still be identified under such irradiations, with only the top two atomic layers of the diamond substrate damaged. Meanwhile, as the impact energy went higher to 70 eV, the SWCNT was completely destroyed together with the damaged top four atomic diamond substrate layers. The overall RDF of the deposited films of each case illustrated quite well the contribution amounts of \( sp^2 \) and \( sp^3 \) neighbours, where the higher fraction of \( sp^3 \) hybridization resulted in a higher contribution of \( sp^3 \) neighbours at the first peak of the overall RDF.

The depth profiles for the fractions of \( sp^3 \) hybridization and mass density at 100 K and 300 K were calculated in Fig. 7(f), where a CNT region, a stable inner film region, and a surface region can be clearly identified. In the CNT region, at the energy of 70 eV the structure of the three-fold coordinated SWCNT was completely damaged and transformed to four-fold coordination, while at 40 eV the structure at this region was still identified as three-fold hybridization. Hence, the fractions of \( sp^3 \) bonded atoms at 70 eV was relatively higher than those at 40 eV, where the fractions were 0%–10% in the CNT region. In the inner films, the fractions of \( sp^3 \) hybridization became stable, lying at about 50%–60% at 100 K, and 30%–55% at 300 K, which were quite close to those directly deposited on the pure diamond substrate. At the surface region, the \( sp^3 \) fractions decreased to 0 due to the domination of the \( sp^2 \) bonded atoms. Hence, at the beginning of the deposition, the \( sp^3 \) bondings were hardly constructed because of the existence of the CNT, while when the films were further deposited to a stable level, significant percentages of the \( sp^3 \) configurations would be created. Meanwhile, the mass density of the stable inner film was again lying in the middle of the densities of diamond and graphite. Fig. 7(g) shows the result of ring analysis studied on the obtained samples at 100 K and 300 K. When compared with other films, the sample with irradiation energy of 40 eV at 100 K, which had the highest density of 3.10 g/cm³ and highest \( sp^3 \) fraction of 52.7%, showed the most oriented order ring analysis with the most common ring configurations being six-ring and seven-ring sizes.

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To test the idea that sidewards pressure is crucial for building up \( sp^3 \) configurations, the same MWCNT system on top of the diamond \{111\} substrate with 6 ideal atomic layers was also used to grow the films on. The visualization of the system is in Fig. 6(e).

FIG. 6. (a) and (b) Front views and three-dimensional views of the deposited system of the SWCNT and nano foam on the top of the diamond \{111\} substrate before carbon ion irradiations. (c) and (d) The cross sections and side views of the SWCNT bundle and MWCNTs after relaxation. (e) Front view and three-dimensional view of the deposited system of MWCNTs on the top of the diamond \{111\} substrate before irradiation. The periodic boundaries in the three-dimensional views and side views are marked with red atoms.
B. Deposition on carbon foam with a diamond substrate

The same method as for the SWCNT was used to simulate the deposition processes with the impacting energies of 40 eV and 70 eV. We found that $sp^3$ fractions at 100 K (up to $sp^3$ at 70 eV) were relatively higher than those at 300 K ($sp^3$ at 70 eV) at the inner stable film region. Ring analysis shows more six-ring ordered rings with the higher $sp^3$ fractions.

C. Deposition on SWCNT bundle

The fractions of the $sp^3$ configurations for the deposited films on the SWCNT bundles were also calculated. However, only a small amount of $sp^3$ bondings could be observed from

FIG. 7. (a) Front view and three-dimensional view of the deposited system of the SWCNT on the top of the diamond $[111]$ substrate before carbon ion irradiations. (b)–(e) The first panels are the visualizations of the composited films on the deposited systems at 100 K and 300 K with the irradiating energies of 40 eV and 70 eV, respectively, after about 10 000 irradiations. The blue atoms stand for $sp^2$ bonded atoms, while the green atoms stand for $sp^3$ bonded atoms. The second panels are the overall RDFs and its $sp^2$ and $sp^3$ contributions of the corresponding grown films, calculated at all atoms of the deposited films only which exclude the atoms of the diamond substrates. (f) Depth profiles of $sp^2$ fractions and mass density of the deposited films. The vertical dashed lines mark the CNT region, the stable inner film region, and the surface region. (g) Ring analysis of the four deposited films which exclude the atoms of the diamond substrates.

FIG. 8. Depth profiles of $sp^3$ fractions of the deposited films on SWCNT on top of the diamond $[111]$ substrate with the deposition energy of 30 eV, at 100, 300, 600, 800, and 1000 K, respectively.
the pure $sp^2$ system at both temperatures. At the low irradiation energy, the top CNTs survived and stayed almost intact, while at the energy of 70 eV the carbon atoms penetrated into 1–2 CNTs and started to grow inside the tubes. The lack of side pressure, due to the suspension at both ends of the bundle, as well as the curvature of the bundle surface, would be the possible reasons causing the low $sp^3$ fractions.

D. Deposition on MWCNTs

We found that at the irradiation energy of 40 eV, only the outermost shell was damaged and the incoming carbon atoms started to grow on top of the substrate, leaving the 2 inner shells structurally and functionally intact. Meanwhile, at the energy of 50 eV, the impacts penetrated into the two outer shells and the atoms started to fill the space between the shells, while the top half of the MWCNT was completely destroyed at the energy of 70 eV. By analysing the depth profiles of $sp^3$ fractions of the growing films, we found that the $sp^3$ fractions of the deposited films at both 100 K and 300 K were still very low, compared to the pure $sp^2$ system.

E. Deposition on MWCNTs with a diamond substrate

Visualization of the structures of the system and the growing films with the deposition energy of 50 eV and 70 eV at 100 K and 300 K is shown in Figs. 9(a)–9(e). It can be seen that at 50 eV the inner two tubes stayed almost intact embedded in the grown films, while at 70 eV the innermost tube and the lower half part of the MWCNT can survive at...
both temperatures. As usual, the overall RDF, as well as the densities and $sp^3$ fractions of each corresponding films are also presented, illustrating that at the first peak of the overall RDF, the contribution of the $sp^3$ coordinated neighbours was proportional to the overall $sp^3$ fraction and the density of the studied film. By analysing the depth profiles of $sp^3$ fractions of the growing films in Fig. 9(f), we found that the depth of the MWCNT region was about (~25, 0) Å, where $sp^3$ hybridizations were barely observed because of the curvature of the MWCNT. However, beyond this region, the $sp^3$ fractions increased gradually to more stable values. For example, at 100 K with 50 eV, the $sp^3$ fraction continuously increased to ~75% with the increasing grown depth, indicating very good DLC quality. The $sp^3$ fraction at 300 K went steady up to 40% in the inner stable film region. Again in Fig. 9(g), the higher fractions of the six-ring illustrated the higher $sp^3$ hybridization and higher density.

VI. DISCUSSION

We have studied the structural configurations of $sp^2$ and $sp^3$ bondings of vacuum arc deposition on carbon nano hybrid materials with experiments and MD simulations. The experimental results show that high quality ta-C can be formed on SWCNT bundles on Silicon substrate. From the MD simulation results of deposition of ta-C on the SWCNT bundle and MWCNTs without diamond substrate, we found that only a small amount of $sp^3$ bondings were observed due to the fact that there was no sideward confinement, and that the curvature of the CNTs made $sp^3$ bonding creation difficult. For the cases with diamond {111} substrates, like pure diamond, SWCNT, nano foam as well as MWCNT, at 100 K DLC films of good quality could be obtained at the inner stable films where the $sp^3$ fractions can reach up to 70% with 70 eV irradiation energy. At 300 K the fractions of four-fold coordination were slightly lower than those at 100 K in all cases. In general, at 300 K, very high percentages of $sp^3$ configurations (50%–100%) were obtained near the diamond substrate within the distance of 20 Å with good DLC quality. However, this value dropped to stable values at 30%–50% with further depositions. The quantitative details of the average $sp^3$ fractions and mass densities for the grown inner stable films at 100 K and 300 K are shown in Table I. The fractions of $sp^3$ configuration could not reach very high values at the stable inner films in all cases because the $sp^2$ bondings are more energetically favorable and stable. The temperature effect was also simulated in the deposition process. $sp^3$ configurations were observed at lower temperatures than those at higher temperatures, and $sp^3$ hybridizations were hardly observed at all above 600 K, which agrees with the experiment by Koskinen.43

It must be noted that the experimentally deposited ta-C film is much thicker (around 10 times thicker) than the ta-C deposited by simulation. We believe this has an effect on the results, wherein during experimental deposition enough film is deposited to ensure sidewall pressure and form high quality ta-C. Hence the simulated results do not show high enough quality of ta-C when deposited on suspended SWCNT/MWCNT or when they are on substrate.

The fact that our simulations predict the formation of high $sp^3$ contents at 100 K, but lower at 300 K, while in the room-temperature experiments the $sp^3$ content is quite high, indicates that the temperature-dependence of the material properties of the potential is not fully correct. Nevertheless, we emphasize that this does not affect the main point of the current work, i.e., the side pressure from the substrate and the two dimensional boundary confinement can lead to the formation of high DLC contents.

Furthermore, at the first peak of overall RDF, the amount of contributions of $sp^2$ and $sp^3$ neighbours were roughly proportional to the overall fractions of three-coordinated and four-coordinated atoms in the studied films. When calculated only at $sp^2$ (or $sp^3$) sites compared to the overall RDF, a big increase of the $sp^2$ (or $sp^3$) neighbours contribution revealed the separation of $sp^2$ and $sp^3$ sites, where $sp^2$ sites were mostly near the surface because of the lack of atoms to form bondings at the top. It is found that the films with higher $sp^3$ fractions and higher density had relatively more ordered ring analysis results, where the ideal diamond has the most ordered configuration with the most popular six-ring size.

VII. CONCLUSIONS

In conclusion, using experiments and molecular dynamics simulations of C deposition on carbon nanotube and nanofoam systems, we find that high-$sp^3$-content (≥50 eV) diamond-like carbon films can, under certain conditions, be formed on top of carbon nanostructures. Above 600 K, DLC formation does not occur, in agreement with experiments. Moreover, we found that to get the high $sp^3$ contents, it is necessary that there is also deposited material on the sides of the nanotubes. Without this condition (i.e., if deposition is carried out on a nanotube system without a substrate close beneath) there is no possibility to maintain a high pressure

<table>
<thead>
<tr>
<th>Samples</th>
<th>$sp^3$ (%)</th>
<th>Densities (g/cm$^3$)</th>
<th>$sp^3$ (%)</th>
<th>Densities (g/cm$^3$)</th>
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<tr>
<td>Pure</td>
<td>30 eV</td>
<td>52.6</td>
<td>3.07</td>
<td>40.6</td>
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<tr>
<td>diamond</td>
<td>40 eV</td>
<td>51.7</td>
<td>3.09</td>
<td>42.4</td>
</tr>
<tr>
<td>50 eV</td>
<td>61.5</td>
<td>3.15</td>
<td>42.6</td>
<td>3.01</td>
</tr>
<tr>
<td>70 eV</td>
<td>61.1</td>
<td>3.13</td>
<td>52.4</td>
<td>3.06</td>
</tr>
<tr>
<td>SWCNT</td>
<td>30 eV</td>
<td>43.0</td>
<td>3.02</td>
<td>27.5</td>
</tr>
<tr>
<td>40 eV</td>
<td>49.0</td>
<td>3.08</td>
<td>35.6</td>
<td>2.97</td>
</tr>
<tr>
<td>50 eV</td>
<td>51.1</td>
<td>3.10</td>
<td>32.5</td>
<td>2.96</td>
</tr>
<tr>
<td>70 eV</td>
<td>56.3</td>
<td>3.11</td>
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<tr>
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<td>36.2</td>
<td>2.86</td>
<td>21.9</td>
</tr>
<tr>
<td>foam</td>
<td>40 eV</td>
<td>36.7</td>
<td>2.92</td>
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<tr>
<td>50 eV</td>
<td>44.7</td>
<td>2.96</td>
<td>32.2</td>
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<tr>
<td>70 eV</td>
<td>48.1</td>
<td>3.04</td>
<td>36.1</td>
<td>2.92</td>
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<td>MWCNT</td>
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</table>
and the growing film relaxes to an almost graphitic condition. In other words, the possibility to form a “sideways pressure” is a prerequisite for forming DLC films on top of the nanostructures. The simulations also showed that for typical DLC cathodic arc deposition energies around 40–70 eV, two carbon layers in the nanotube are destroyed by the deposition, but nanotubes below these layers can remain virtually undamaged.

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29 K. Nordlund (2006), parcas computer code. The main principles of the molecular dynamics algorithms are presented in Refs. 44 and 45. The adaptive time step and electronic stopping algorithms are the same as in Ref. 46.