Etching of photon energy into binding energy in depositing carbon films at different chamber pressures

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ABSTRACT

A hot filament chemical vapor deposition is an attractive technique to deposit carbon films of different applications. In this technique, it is also feasible to study the influence of chamber pressure in the deposition of carbon films. In the deposition chamber, having dissociated from the methane precursor, gaseous carbon atoms first convert into the graphite state atoms and then into the diamond state atoms. An increase in the chamber pressure changes the morphology and structure of the deposited carbon films. The deposited carbon films increase the growth rate by increasing the chamber pressure from 3.3 to 8.6 kPa. The rate of converting gaseous carbon atoms into diamond atoms also increases. At 11.3 and 14 kPa chamber pressure, gaseous carbon atoms convert into graphite state atoms at a high rate. The gas activation and gas collision processes vary broadly at varying chamber pressure. The morphology and structure of carbon films got deposited at different growth rates. The dissociation of molecular hydrogen into atomic hydrogen varies by varying the chamber pressure. The etching of photons (released from the hot filaments) into the dash-and golf-stick-shaped energy bits is from the atomic hydrogen. Thus, bits of differently shaped energy result. Gaseous carbon atoms convert into graphite and diamond state atoms depending on the set value of chamber pressure. Graphite state atoms bind under the same involved energy bits while conversion, which is not the case when the diamond state atoms bind. Carbon films in different phases have emerged with many applications: cutting tools, field emitter devices, heat sinks for electronic equipment, electrode materials, biological sensors, infrared imaging technology, etc. Such applications are well-suited to carbon-based materials compared to other materials. So, the study sets a new trend in depositing, characterizing, and analyzing carbon films.
1 Introduction

1.1 Motivation behind the research

Many research groups around the globe researched carbon films. The carbon films can deposit by employing various vapor deposition techniques. Some studies show the handling of deposition at low chamber pressures. Some studies show the selection of high chamber pressures. Carbon films deposited by hot filament chemical vapor deposition (HF-CVD) are considered strong candidates for Hi-Tech and advanced engineering applications. An HF-CVD is simple for synthesizing carbon films.

1.2 Literature survey

There are many studies on carbon films, and some of them are cited here [1–8]. Carbon films with higher diamond content discussed some exciting aspects [9–14]. In the deposition of carbon films, switching dynamics under different conditions have been discussed [6]. The low growth rate of diamond film in HF-CVD has been the main drawback compared to the flame jet technique [15]. By employing the HF-CVD system, a carbon film was deposited by retaining with *40 μm thickness [16].

A key parameter in the CVD diamond process is the system pressure, as it regulates the overall features of a carbon film. A systematic study on the influence of chamber pressure in depositing carbon films is yet not performed. Studies have reported that diamond film deposited at a low pressure contained more non-diamond components than those deposited at high pressure [17, 18]. Kang et al. [18] deposited well-faceted diamond cubes over silicon by keeping the 0.13 kPa chamber pressure at the nucleation stage and the 2.7 kPa chamber pressure during the growth period. At different pressures, different diamond growth surfaces were studied [19].

Heimann et al. [20] studied the influence of different parameters on the deposition of carbon films. The growth rate of the carbon film at 200 kPa chamber pressure was about four times higher than the carbon film deposited at 50 kPa chamber pressure [21]. The set residence time also affects the growth rate [21, 22]. A faceted morphology is developed at 1.3 kPa, and 2.7 kPa chamber pressures, whereas poor crystallinity at 0.7 kPa and 6.7 kPa chamber pressures [23]. The growth rate of diamond film increased between 1.2 and 2.7 kPa [24].

Wan et al. [25] found that CVD diamond synthesis restricts by the gas phase composition, temperature, and pressure. Brunsteiner et al. [26] investigated the dependence of the growth rate on chamber pressure and found the maximum growth rate at chamber pressure was 2.7 kPa.

1.3 Objective of the research

The deposition of carbon films can emerge with several applications. When the deposited carbon films are in the high-quality diamond phase, they can work efficiently for abrasive, cutting tool, and heat sink applications. When the deposited carbon films are rich in the graphite phase, they can work efficiently for electrode and field-emission applications. When the deposited carbon films are equally good in diamond and graphite phases, they can work efficiently for the hybrid application. A carbon film in its high-purity form can show unique performance for the related application.

The growth of carbon films, mostly diamond films, has been studied for decades. However, underlying science and engineering remained largely unaddressed. Again, there is incomplete information explaining the underlying science of carbon films. The discussion based on the influence of chamber pressures to deposit carbon films strikingly demands a comprehensive study. This study also discusses the etching of photon energy into binding energy in the deposition of carbon films at various chamber pressures.

2 Experimental details

A Chinese-made HF-CVD system was employed to deposit the carbon films. The system is HFCVD-450, Beijing Technol Science Co., Ltd. The Schematic of the HF-CVD system is given in the previous studies [27].

In this research, a tantalum wire designs the filaments. The diameter of the wire is 0.5 mm and the length of the wire is 13 cm. The distance between the substrate and filaments was ~ 7 mm. The distance between the parallel wires is ~ 10 mm.

In each experiment, the base pressure was around 3 ×10⁻³ Pa. A turbo-molecular pump maintains the base pressure.
However, a vane pump-2 drains the gaseous species and maintains the pressure at each set value. The study investigates the influence of varying chamber pressure from 3.3 to 14 kPa. The total mass flow rate of the H₂ and CH₄ was 304.5 sccm during each experiment. Built-in mass flow controllers controlled the flow of H₂ and CH₄ gases. A methane concentration is 1.5% in each experiment. The approximate volume of the chamber was 2.9 cubic ft. Table 1 shows the detail of the chosen parameters in the deposition of different carbon films.

Polished p-type (100) silicon substrates with an area of 2 × 2 cm² and thickness of 400 µm were agitated ultrasonically. Substrates mechanically scratched for 5 min with suspension. The suspension prepared with diamond powder has a mesh size of *30–40 (~28 µm) and acetone. The silicon samples were scratched again for 10 min with the suspension prepared from acetone and diamond powder, a mesh size of ~5 µm. The samples were washed with acetone to remove any debris from the substrate.

Input power of ~3.3 kW set to maintain the temperature of the filaments. There was no separate heater. The temperature of the substrates is well maintained by the heating effect of filaments. Temperature is approximately measured. Both the optical pyrometer and K-type thermocouples were adjusted to measure the temperature. There is a need to perform more research to measure the temperature. The rotational speed of the substrate holder was 5 rpm.

The processing time in each experiment was 10 h. The chamber pressure reached the set value in an initial 13 min. The X-ray reflectometer determined structural regularity in different carbon films (Philips PW3710). A copper line-focused X-ray tube having Kα radiation wavelength of 1.541874 Å is used here. The X-ray reflectometer is also known as an X-ray diffractometer.

The field-emission scanning optical microscope was used to analyze the surface and interface studies, FE-SOM (JEOL Model: JSM-7000F). The FE-SOM is also known as FE-SEM. In this study, the spectroscopic analyses of the carbon films performed by the micro-Raman spectroscope model HR800 UV have a He–Ne Red Laser wavelength of 632.8 nm.

### Results and discussion

#### 3.1 Structural examination of carbon films by x-ray analysis

Figure 1a–f shows the X-ray patterns of the carbon films deposited at different chamber pressures. Carbon films show peaks at 2θ ~ 43.9°, ~75.3°, ~91.5°, and ~119.5°. Peaks studied related to the (111), (220), (311), and (400) planes, respectively. However, the peak at 2θ ~ 43.9° relates to the X-ray reflection from the outer ring electrons of the diamond atoms denoted by D (OR-R). The peak at 2θ ~ 75.3° relates to the X-ray reflection from the zeroth ring electrons of the diamond atoms denoted by D (ZR-R). The peak at 2θ ~ 91.5° labeled by D (ZR-IR) relates to the inverse reflection of X-rays from the zeroth ring electrons of the diamond atoms as denoted by D (ZR-R). The peak at 2θ ~ 119.5° labeled by D (OR-IR) relates to the inverse reflection of X-rays from the outer ring electrons of the diamond atoms.

Figures 1a and d–f also show a peak at 2θ ~ 56.1°. It is related to the graphite phase in deposited carbon films. The peak at 2θ ~ 56.1° has a very high density in carbon films deposited at chamber pressures of 11.3 kPa and 14.0 kPa. It means the deposition of

| Chamber pressure (kPa) | Filament temperature (°C) | Current (in amp)/ voltage (in volts) | Substrate Temperature (°C) | The flow rate of gases (sccm) |
|------------------------|---------------------------|------------------------------------|---------------------------|-------------------------------|
| 3.3                    | 2100                      | 255/12                             | 895                       | CH₄: 4.5, H₂: 300             |
| 6.0                    | 2050                      | 255/14                             | 880                       | CH₄: 4.5, H₂: 300             |
| 7.3                    | 2030                      | 255/16                             | 905                       | CH₄: 4.5, H₂: 300             |
| 8.6                    | 2030                      | 255/14                             | 925                       | CH₄: 4.5, H₂: 300             |
| 11.3                   | 1800                      | 255/12                             | 820                       | CH₄: 4.5, H₂: 300             |
| 14.0                   | 1765                      | 255/12                             | 795                       | CH₄: 4.5, H₂: 300             |
carbon films in the graphitic phase. The peaks of the diamond phase almost diminish in the carbon films deposited at 11.3 kPa and 14.0 kPa.

The peak at \(2\theta \approx 56.1^\circ\) is related to the reflection of X-rays from the zeroth ring electrons of the graphitic carbon atoms, as denoted by G (ZR-R) in Fig. 1.

In earlier studies, the peaks of an X-ray pattern relate to the Bragg peaks or Bragg planes. However, these peaks do not study the planes discussed under the Miller Indices Formulation. New insights into the atomic structure reveal that these peaks relate to the electronic rings of atoms incorporated. Further detail can refer to the study given elsewhere [28]. X-ray analysis is beneficial in studying the structure for practical applications.

The peaks found in different patterns are related to the interaction of X-rays with atomic electrons belonging to the top-layered surface of carbon films [28]. The less-intensive graphitic peak appears in the patterns of carbon films deposited at the chamber pressures of 3.3 kPa and 8.6 kPa.

Carbon film deposited at 7.3 kPa chamber pressure keeps the highest structural regularity in terms of the diamond phase. The deposited carbon film does not show the peak of a graphite phase at \(2\theta \approx 56.1^\circ\).

The less-intensive graphitic peak at low pressure is due to the few carbon atoms in the graphite state at the top-layered surface of the sample.

The non-presence of the graphitic peaks at 6 kPa and 7.3 kPa is due to the entire diamond state of the carbon atoms at the top-layered surface. At 8.6 kPa, the graphite state of the carbon atoms exists up to some extent resulting in a less-intensive graphitic peak in the pattern as well.

However, reflected X-rays from the tiny grains, grains, and particles containing diamond and graphite phases originate the associated peaks in the X-ray reflection (XRR) part and the X-ray inverse reflection (XRIR) part of the X-ray pattern in different ways. Further details on a structural determination by XRIR analysis will be discussed in a separate study.

### 3.2 Surface morphology and interface study of the carbon films

The carbon film grown at the lowest chamber pressure (3.3 kPa) shows consistent morphology. The surface morphology of the carbon film in Fig. 2a shows no specific shape of tiny grains, grains, and particles.

The morphology of the carbon film shows uniform distribution of tiny-sized grains, grains, and particles. Some grains and particles grow with the smooth faces in the carbon film. Many grains and particles also show their non-uniform growth behaviors. In Fig. 2A, many nucleated grains do not grow further. Secondary nucleation starts.

At chamber pressure of 6.0 kPa, the dynamics of carbon atoms become favorable to grow tiny-sized grains and grains into the size of particles. Figure 2b shows that the morphology of tiny grains, grains, and particles deviated toward the cubic growth. In Fig. 2B, cubic growth was more evident. Grains and particles were amalgamated in one region at a very high rate, as shown in Fig. 2B.

At chamber pressure of 7.3 kPa, the growth behavior of grains and particles was in pyramid-shaped morphology. The growth behavior is uniform at a later stage, in Fig. 2c. The pyramid-shaped grains and particles nucleated at the start of the process. It is evident in the interface image, as shown in Fig. 2C.

At chamber pressure of 8.6 kPa, growth behavior is more dominant in the pyramid-shaped morphology of grains and particles. In Fig. 2d, the carbon film shows a tilted position. The morphology of grains and particles develops from the surface of the substrate, which could also be verified from the fractured cross-sectional view of the carbon film, as shown in Fig. 2D.
At 11.3 kPa chamber pressure, grains and particles have dome-like shapes. It is evident in the fractured cross-sectional view of the carbon film shown in Fig. 2E. The thickness of the carbon film synthesized at chamber pressure 11.3 kPa decreased several times compared to the carbon film deposited at chamber pressure 8.6 kPa. The thickness of the carbon film is even less than that of the carbon film deposited at a chamber pressure of 3.3 kPa. As labeled in the fractured cross-sectional view of Fig. 2E, the thickness is less than one micron.

Grains and particles again show dome-like shapes at 14.0 kPa chamber pressure. The thickness of the carbon film deposited at chamber pressure 14.0 kPa is the same as in the case of a carbon film deposited at chamber pressure 11.3 kPa. The labeled thicknesses keep slightly different values in the fractured cross-sectional views of the carbon films shown in Fig. 2E and F.

A tiny grain or tiny-sized grain is smaller than the size of a grain. A grain is smaller than the size of a particle. A particle is related to the size in the sub-micron or micron range. A crystallite is more related to the shape of the particle.

Size of the diamond grain increases by increasing the chamber pressure up to 8.6 kPa. However, it drastically decreases upon reaching the chamber pressure at its maximum value. At 14 kPa, the size of the graphitic grain becomes the maximum rather than the diamond.

By increasing the chamber pressure from 5.3 to 39.5 kPa, the morphology of the carbon film varied [20]. However, the primary mechanism of the change of morphology remained unclear. Schwarz et al. [22] observed the pressure-dependent growth rate of diamond coatings at a substrate temperature of 850 °C. On the other hand, the growth rate was 0.2 μm/h at a chamber pressure of 5.0 kPa. At 0.7 kPa chamber pressure, a bit lower growth rate was noted [26].

At low chamber pressures, our results agree reasonably with the chamber pressures 2.0 kPa to 5.0 kPa as given elsewhere [22]. At the highest value of the chamber pressure, the growth rate decreased below 0.05 μm/h [26]. In the present study, the highest growth rate is at 8.6 kPa chamber pressure, i.e., ~ 0.4 μm/h, and drastically decreases at 11.3 kPa and 14.0 kPa chamber pressures, i.e., ~ 0.1 μm/h. The concentration of atomic hydrogen near the filament surface was discussed in the earlier works [22, 29]. The results of Brunsteiner et al. [26] contradict the growth rates of carbon films found in the results of Schwarz et al. [22]. The growth rate and quality of the diamond at 1059.1 kPa atmospheric pressure was noted [26].
pressure were better than the 5.0 kPa chamber pressure [30].

3.3 Raman spectroscopic analyses of the carbon films

In different Raman spectra of the deposited carbon films, the recorded intensity of the Raman signals reveals the morphology and structure of tiny grains, grains, and particles. In Fig. 3, the Raman peak near wave number 1332.1 cm$^{-1}$ corresponds to the diamond peak.

In Fig. 3, the peaks at wave number 1332.1 cm$^{-1}$ show different features in each carbon film. The Raman line width varied from the mode of the deposited diamond [31]. At wavenumber 1581 cm$^{-1}$, an additional peak originated in Fig. 3. It relates to the G-peak due to the highly orientated graphitic phase in CVD diamond coatings [32]. A review discussed the structure of carbon films by Raman spectroscopy [33].

The Raman spectra of carbon films deposited at lower pressure (3.3 kPa to 8.6 kPa) keep nearly identical content under the laser beam as these show similar patterns.

The Raman spectra of carbon films deposited at higher pressure (11.3 kPa and 14.0 kPa) have similar patterns due to having nearly identical content under the laser beam. The carbon films synthesized at different chamber pressures are sensitive to the energy signals shown in Fig. 3. A pronounced peak at wave number 1100 cm$^{-1}$ is found in the carbon films deposited at 11.3 kPa and 14.0 kPa chamber pressures, indicating the presence of an increased graphitic phase. There is a need to re-investigate the Raman spectroscopy of the carbon films.

3.4 Some aspects of nucleation and growth mechanisms of carbon films

Graphitic carbon atoms might not adhere to the seed-ded species. Thus, when the carbon atoms deposit in the graphite state, they can detach from the substrate surface. Graphitic carbon atoms might not stick to the prepared substrate surface. There is a probability of detachment of graphite state atoms from the substrate, so nucleation of tiny-sized grain either in graphite state atoms or in diamond state atoms starts from the preferred sites of the substrate. By fully covering the substrate, depositing carbon atoms in different states is a grand challenge.

The mean free path of active species is inversely proportional to the pressure as per the kinetic theory of gases.

The mean free path of active species decreases by increasing the chamber pressure. At the start of the process, the set parameters fluctuate in each process. It is mainly due to gaining the set conditions of the process. Again, fluctuation in parameters can be due to the water circulation. It can be due to the change in the positions of filaments. They can influence the initial nucleating layer of the carbon film. A different time duration to achieve set chamber pressure can cause a different nucleation rate.

Lee et al. [17] predicted the concentration of active species first increases exponentially and decreases by decreasing the pressure finally. The carbon atoms, which survive, reach the substrate surface to deposit. So, carbon atoms, which do not deposit at the substrate surface, either become part of the drain or contaminate the process of nucleating tiny-sized grains. The nucleation of tiny-sized grains also depends on the rate of releasing bits (pieces) of energy from the gas collision. Keeping the same nucleation rate in depositing carbon films is a great challenge.

An increase in the mean free path leads to partial control of the dynamics in the depositing carbon atoms. It is mainly in the case of low chamber pressures. Therefore, a deposited carbon film keeps the growth partially diamond-specific and partially graphite-specific. At fixed input power, Table 1 has the

![Fig. 3 Raman spectra of carbon films deposited at different chamber pressures](image-url)
temperature of the filaments decreased at high chamber pressure.

There is no separate heater to heat the substrate. So, the substrate temperature also decreases. It is a cause of enhancement of the secondary nucleation. Thus, the thicknesses of the deposited carbon films decreased, as shown in Fig. 2E and F. Figure 2D shows that the carbon film thickness deposited at a chamber pressure of 8.6 kPa remains the highest. The conversion rate of molecular hydrogen into atomic hydrogen increases at 8.6 kPa chamber pressure. More gaseous carbon atoms convert into a diamond state. However, the conversion rate of molecular hydrogen into atomic hydrogen decreases at 11.3 kPa and 14.0 kPa chamber pressures. So, carbon atoms convert into diamond state atoms at a low rate. The growth rates of carbon films decrease along with the deteriorating quality of the diamond content.

Under the commonly employed conditions of the HF-CVD process, the transportation of atomic hydrogen for the growing surface is a diffusion-limited process [34]. Diamond grown by HF-CVD investigated the growth mechanism from the surface topography [35]. The growth of diamond is a sliding scale between atomic hydrogen and hydrocarbon radical [36]. Substrate temperature and pressure jointly influence the growth rate of diamond films [37].

At high chamber pressures, the dissociation of methane into carbon atoms is high compared to the low and intermediate chamber pressures. However, dissociated carbon atoms frustrate as a sufficient amount of carbon atoms remain in the gaseous state. So, the depositing rate of carbon atoms in the graphite state atoms becomes low. Consequently, the rate of converting carbon atoms into diamonds becomes low.

3.5 Growth rate versus chamber pressure

Figure 4 shows the growth rates of diamond and graphite phases in deposited carbon films at different chamber pressures. The estimated zone of the depositing carbon film at a nearly equal growth rate of diamond and graphite is also labeled by (1) in Fig. 4.

The maximum growth of diamond appears at 8.6 kPa. Label (2) in Fig. 4 indicates it.

The maximum growth of graphite appears at 14.0 kPa chamber pressure. Label (3) in Fig. 4 indicates it. The dynamics of carbon atoms work in different manners at 3.3 kPa chamber pressure. Many gaseous carbon atoms get converted into diamond state atoms at intermediate chamber pressures, i.e., 7.3 kPa and 8.6 kPa. At high chamber pressures, the morphology of grains and particles develops in the dome shape. However, the growth rates of carbon films are low. The gaseous carbon atoms mainly get converted into graphitic carbon atoms. At 11.3 kPa, the morphology of grains is more like the dome shape. On increasing the chamber pressure up to 14.0 kPa, the morphology of grains is again like the dome shape.

At high chamber pressures, locally engaged forces synchronize to preserve the bits of shaped energy required to form tiny grains, grains, and particles with graphitic structures. However, locally engaged forces synchronize at intermediate chamber pressures to preserve the bits of shaped energy required to form tiny grains, grains, and particles with diamond structures.

3.6 Dissociation of \( \text{H}_2 \) and \( \text{CH}_4 \) gases—a gas activation process

The dissociation rates of \( \text{H}_2 \) and \( \text{CH}_4 \) gases determine the gas activation process. In the HF-CVD reactor, molecules of methane and hydrogen dissociate to convert into atomic states. Molecular hydrogen converts into hydrogen atoms under the thermal activation of hot filaments.

In converting the methane molecule into the carbon component and the four hydrogen atoms, the hydrogen atoms detach from the carbon atom. On detachment of the four hydrogen atoms, the states of
their binding with a carbon atom become unfilled, enabling its conversion to either graphite or diamond state atom.

In the dissociation of the CH₄ molecule, expansion and contraction behaviors of two different natures trigger, where the carbon component gives away four hydrogen atoms. CH₄ dissociates into carbon and hydrogen atoms. In the process of dissociation of the CH₄ molecule, four hydrogen atoms separate at the same time. However, a hydrogen molecule requires activation energy up to a higher level to convert into hydrogen atoms. A study on diamond films discusses the temperature of hot filaments in the deposition [38]. Further research requires to understand the dissociation of CH₄ and H₂.

The dissociation rate of molecular hydrogen is varied at different chamber pressures. Again, the conversion rate of methane molecules into gaseous carbon and hydrogen atoms becomes different under the varying chamber pressure. The gas activation process varies at each chamber pressure. The rate of etching photon energy also varies at each chamber pressure.

There is a need to study the dissociation rate of H₂ and CH₄ gases at varying chamber pressure. Again, to find out the different species of gas activation processes at different chamber pressures, there is also a need to study the optical emission spectra. Some other qualitative and quantitative analyses can be employed to investigate the rate of gas dissociation and the gas activation process.

3.7 Etching of photon energy into bits of dash- and golf-stick-shaped energy

Figure 5a shows a photon of short length called an overt photon. On traveling oppositely to the atomic hydrogen, an overt photon can etch precisely into bits (pieces). A description mechanism of the hydrogen atom under the new insight is given elsewhere [39]. For the etching of a short-length photon, both electronic tips of the atomic hydrogen involve. As a result, that overt photon converts into pieces or bits of dash-shaped energy, Fig. 5a shows it.

In Fig. 5b, parabola-shaped energy bits form. Atomic hydrogen utilizes one electronic tip to etch the overt photon converting it into parabola-shaped energy bits, Fig. 5b shows it.

Etching the parabola-shaped energy bit into two golf-stick-shaped energy bits, the hydrogen atom also utilizes its one electronic tip. The bits of parabola-shaped energy convert into bits of golf-stick-shaped energy. Figure 5c shows the etching of a parabola-shaped energy bit from one electronic tip of atomic hydrogen in each case. Thus, hydrogen atoms involve etching photon energy rather than etching carbon atoms.

Dash-shaped energy bits enable the conversion of gaseous carbon atoms for graphite and diamond state atoms [40]; graphite state atoms bind under the previously involved dash-shaped energy. Therefore, it is not correct carbon etching is from atomic hydrogen. Etching photon energy is from hydrogen atoms. Figure 5a shows the etching of photon energy into dash-shaped energy. Figure 5b shows the etching of photon energy into parabola-shaped energy.

Dash-shaped energy of two bits involves transferring the electrons converting the carbon atom into another state [40]. Gaseous carbon atoms get converted into graphite and diamond state atoms in the region close to the hot filaments. The distance between the substrate and hot filaments is a few millimeters. The etching of parabola-shaped energy bits is further from the suitable interaction of atomic hydrogen. The shape of a new bit of energy becomes like a golf stick.

A filament becomes hot due to the dissipated heat of the propagating photons. In the deposition chamber, hot filaments release photons of short and long lengths called overt photons. Under a

![Fig. 5](image-url)
suitable interaction of atomic hydrogen, a photon is etched into the bits of energy, having the shape of a dash, parabola, and golf stick. A separate study has detailed the photon generation by a silicon atom [41].

3.8 Gas collision and releasing different-shaped bits of energy

The etching of photon energy into the golf-stick-shaped energy bits increases up to 8.6 kPa chamber pressure. It decreases by increasing the chamber pressure up to 14.0 kPa, shown in Fig. 6a by the solid curve. The etching of photon energy into dash-shaped energy bits remains moderate, low, and high at the lowest, intermediate, and high chamber pressure. In the dotted curve, Fig. 6b shows the etching of photon energy into dash-shaped energy at different chamber pressures.

In Fig. 6a, label (1) shows the point of gas collision. At the point of the dotted line, there is a minimum disruption to form the parabola- and golf-stick-shaped energy bits. Therefore, gas collision is more favorable at intermediate chamber pressures to release bits of golf-stick-shaped energy. Hence, carbon films have a higher growth rate than the diamond phase.

In a gas collision, atomic hydrogen and gaseous carbon are involved, but molecular hydrogen and methane are also involved. The collision rate of gases varies largely at varying chamber pressure, as shown in Fig. 6 in estimation. However, the collision rate of different gases should first depend on the process of gas activation.

In Fig. 6b, label (2) shows the point of gas collision. At the point of the dotted line, there is a minimum disruption to form dash-shaped energy bits. The gas collision is favorable to release the bits of dash-shaped energy.

The deposition chamber has less photon energy at 11.3 kPa and 14.0 kPa chamber pressures. It is due to the excessive contamination of filaments. So, the conversion of atomic hydrogen remained at a lower rate. Thus, the rate of converting gaseous carbon atoms into diamond atoms remained minimum. At high chamber pressures, there is more dissipation of heat energy instead of dealing with the more releasing of photon energy. The presence of heat energy inside the reactor affects the process.

3.9 General discussion

In studies given elsewhere [2, 9], the role of atomic hydrogen remained crucial in determining the content-specific growth of a carbon film. Increasing a small amount of CH₄ in the total mass flow rate lowers the quality of diamond film [2]. These studies validate the crucial role of gas collision.

In Fig. 2c and d, the tilted microscopic images show the pyramid-shaped morphology of large diamond crystallites. Many diamond crystallites are grown by retaining their roots in contact with the substrate surface. Figures 2c and d show an almost similar trend of growth behavior of grains and particles, such kind of growth behavior discloses the stinging nature of diamonds. Diamond growth is south to ground, but the structure of diamond is tetra-electron ground to south topological structure [40]; diamond atoms bind by the involvement of golf-stick-shaped energy bits.

Under different arrangements of hot filaments, the growth rate of the carbon film may differ from the one discussed here. In microwave-based chemical vapor deposition, the structure of tiny grains of carbon films explained the nucleation behavior with some essential detail and how secondary nucleation was initiated [42]. More work is required in the HF-CVD technique to understand the nucleation and growth mechanisms.

Several studies in the literature discuss the applications of carbon films as given elsewhere [43–46]. The ratio of sp² to sp³ is low at the intermediate chamber pressures. This ratio is high at high chamber pressures. In the current study, sp² relates to the...
graphitic phase, whereas sp\(^3\) relates to the diamond phase. Earlier studies discuss the ratio of sp\(^2\) to sp\(^3\) in carbon films [47, 48].

Keeping a constant temperature is quite a difficult task. A different design of the chamber affects the pressure differently. There is a need to discuss the kinetics, dynamics, mass spectroscopy, computational modeling of gas dissociation, and the gas activation of the process. Atomic hydrogen production on the filament and its diffusion to the substrate surface need to explore further. The chemical kinetics of the process at different steps also need to explore further.

4 Conclusion

Tiny carbon grains nucleate at different rates for different chamber pressures. At low chamber pressures, the rate of converting gaseous carbon atoms into graphite and diamond state atoms is moderate. At intermediate chamber pressures, gaseous carbon atoms at a high rate convert into diamond atoms. The conversion rate of gaseous carbon atoms for graphite state atoms increases at high chamber pressures. Nucleations of the diamonds start at the feasible sites of the roughened substrate. In the carbon film, tiny grains grow, reaching the size of grains and particles.

Grains and particles of carbon films show mixed, pyramid, and dome-like shapes at low, intermediate, and high chamber pressures, respectively. The thickness of carbon films depends on the rate of converting gaseous carbon atoms into different states. The morphologies of the grains and particles are sensitive to the Raman signals giving information about the shapes. Grains and particles show high-purity diamond-wise at chamber pressures 6.0 kPa, 7.3 kPa, and 8.6 kPa, whereas high-purity graphite-wise at chamber pressures 11.3 kPa and 14.0 kPa. X-ray analyses of the carbon films agree with the information provided by the spectroscopic and FE-SOM investigations.

Dissociating CH\(_4\) molecules and molecular hydrogen varies at different chamber pressures. A CH\(_4\) molecule simultaneously dissociates into a carbon atom and four hydrogen atoms. The rate of dissociation of gases determines the gas activation process. The rate of the gas activation process determines the gas collision process.

The hot filaments release the photons at different rates for set chamber pressures. Due to the varying gas activation and collision processes at each chamber pressure, the amount of photon energy etched into bits of the dash- and golf-stick-shaped energy is also varied. The conversion rate of the gaseous carbon atoms into graphite and diamond state atoms depends on the dissociation rate of hydrogen. The gas activation and collision processes at different chamber pressures influence the binding rate of carbon atoms. At intermediate chamber pressures, more hydrogen dissociates into atomic hydrogen. So, more photon energy converts into golf-stick-shaped energy bits. At chamber pressures 6.0 kPa, 7.3 kPa, and 8.6 kPa, the gaseous carbon atoms also convert into diamond state atoms at a high rate. So, the binding rate is also high.

The graphite state atoms bind under the same bits of dash-shaped energy, and the diamond state atoms bind under the bits of golf-stick-shaped energy [40]. At intermediate chamber pressures, a gas collision process favors the etching of photon energy into the golf-stick-shaped energy bits. At 3.3 kPa, the etching photon energy in parabola- and golf-stick-shaped energy is moderate. It is high at 6.0 kPa, 7.3 kPa, and 8.6 kPa. At 11.3 kPa and 14.0 kPa, etching photon energy in the dash shape is high.

The work provides insight into problem-based solutions. It can enable one to explore cutting-edge technologies. There is vast room to synthesize carbon films with different applications in the hot-filaments reactor. New designs of the deposition systems can provide further opportunities to synthesize carbon films. In new depositions, resource utilization can minimize, leading to the building of a clean environment.

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