

# Advancements In Hydrogenated Diamond-Like Carbon Thin Film Deposition & Surface Modification

Hari Shankar Biswas<sup>1,\*</sup>, Amit Kumar Kundu<sup>2</sup>, Shib Shankar Biswas<sup>3</sup>

## Abstract

*Materials synthesis and processing are pivotal in advancing technologies across domains such as electronics and biomedical applications. This review provides a detailed exploration of recent advancements in thin film deposition techniques, focusing on hydrogenated diamond-like carbon (HDLC) films and various surface modification methodologies. Beginning with an overview of HDLC films, the paper highlights their unique properties and wide-ranging applications, emphasizing their importance in modern materials science. Key sections of the review examine different HDLC film deposition methods, particularly chemical vapor deposition (CVD) and physical vapor deposition (PVD). Additionally, the paper delves into surface modification techniques, including plasma treatment, ion implantation, and laser processing, offering insights into their mechanisms and potential uses. By integrating theoretical concepts with practical applications, this review aims to provide researchers and engineers with a comprehensive understanding of advanced materials synthesis and processing techniques. The synthesis of HDLC films and the application of surface modifications are discussed in detail, demonstrating their impact on enhancing material performance. This paper serves as a valuable resource by encapsulating recent developments and methodologies in thin film deposition and surface modification, fostering innovation, and paving the way for transformative applications across various scientific and technological fields. Through this synthesis of knowledge, the review contributes to ongoing advancements in materials science and engineering, supporting the development of future technologies.*

**Keywords:** HDLC, Thin Film, Surface modification, CVD, PVD

## INTRODUCTION

The importance of nanoscience and nanotechnology as a key driving force for solid-state carbon nanomaterials like Graphene, HDLC, Graphene oxide, Carbon nanotubes, nanocomposite, etc., is globally acknowledged for advancing fundamental scientific research. Materials synthesis and processing stand at the forefront of technological innovation, driving advancements across many

industries ranging from electronics and aerospace to healthcare and renewable energy.<sup>1-3</sup> Central to these advancements are thin film deposition techniques, which have garnered significant attention due to their unparalleled ability to fabricate functional coatings with highly controlled and tailored properties.<sup>4</sup> Among the various types of thin films, hydrogenated diamond-like carbon (DLC) films have emerged as a particularly promising class of materials.<sup>5</sup> Renowned for their exceptional mechanical, tribological, and biocompatible properties, DLC films are finding increasing applications in diverse fields.<sup>6,7</sup> This introduction aims to provide a comprehensive overview of DLC films, delving into their unique

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properties and extensive applications, thereby laying a solid foundation for further exploration into the sophisticated realm of thin film deposition techniques and surface modification methods. Diamond-like carbon films are a subset of amorphous carbon materials that exhibit many of the desirable properties of diamond, such as high hardness and low friction, but can be deposited at much lower temperatures and on a variety of substrates.<sup>7, 8</sup> The "diamond-like" term encapsulates the unique combination of  $sp^2$  (graphitic) and  $sp^3$  (diamond-like) carbon bonding and different phase (Figure 1) within the material's amorphous matrix.<sup>9</sup> Hydrogenated DLC (a-C) films, in particular, incorporate hydrogen atoms into this carbon matrix, which plays a crucial role in stabilizing the film structure and enhancing its properties.<sup>10</sup>

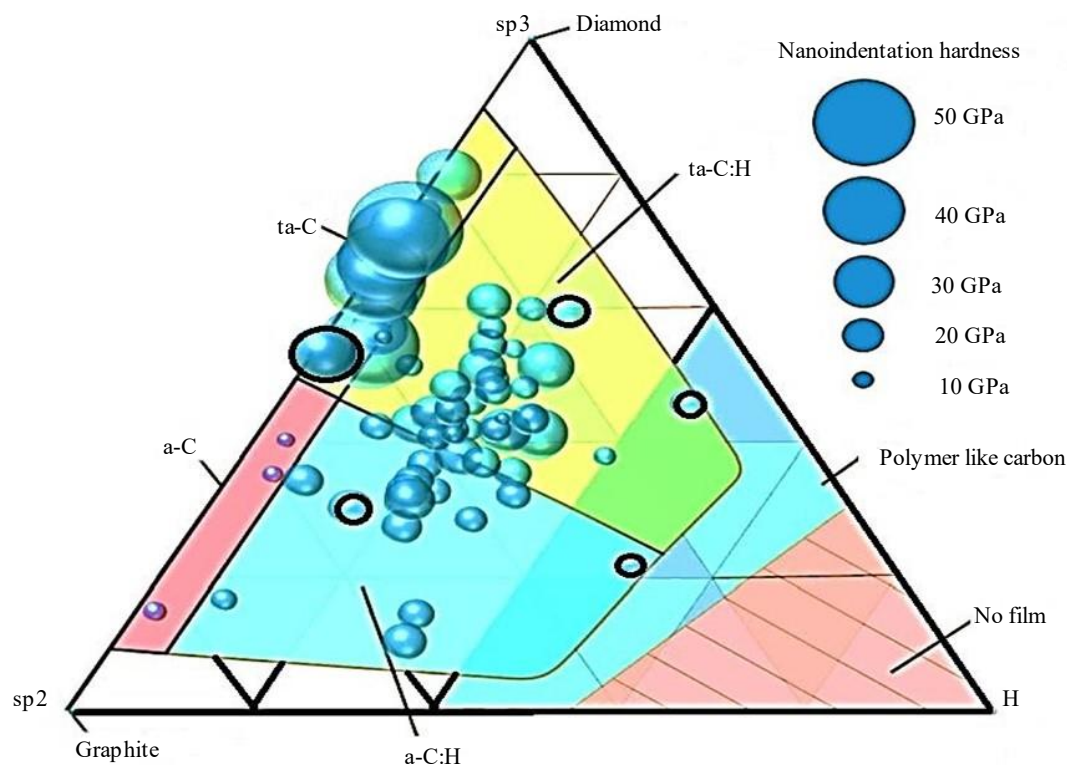
The exceptional mechanical properties of hydrogenated DLC films are among their most celebrated attributes. These films boast a high hardness, often reaching up to 80 GPa, which makes them incredibly resistant to scratching and wear. This hardness is comparable to that of natural diamonds, positioning DLC films as a formidable alternative in applications where wear resistance is paramount.<sup>11</sup> Additionally, the low coefficient of friction, typically in the range of 0.01 to 0.2, significantly reduces wear and extends the lifespan of components subjected to mechanical contact. This tribological excellence makes DLC coatings particularly valuable in the automotive and aerospace industries, where reducing friction and wear can lead to improved performance and energy efficiency.<sup>12,13</sup> Beyond their mechanical robustness, hydrogenated DLC films are also highly biocompatible, making them suitable for medical and biomedical applications.<sup>14</sup> The biocompatibility of DLC films arises from their chemical inertness and the smooth, pinhole-free surface they provide, which resists bacterial adhesion and minimizes the risk of inflammatory responses.<sup>15</sup> This has led to their use in a variety of medical devices, including stents, joint prostheses, and surgical instruments. In dental applications, DLC coatings are used to enhance the durability and biocompatibility of dental implants and tools, ensuring long-term performance and patient safety.<sup>16</sup> The versatility of hydrogenated DLC films extends to their optical properties, which can be finely tuned for specific applications. DLC films are generally transparent to infrared light and can be engineered to exhibit various refractive indices by altering the deposition parameters and the hydrogen content.<sup>17</sup> This tunability makes them suitable for use in optical coatings, such as anti-reflective coatings for lenses and protective coatings for optical components in harsh environments.<sup>18</sup> Additionally, the excellent barrier properties of DLC films prevent the permeation of gases and liquids, which is critical for applications in packaging and protective coatings for electronics.<sup>19</sup>

The synthesis of hydrogenated DLC films involves a range of deposition techniques, each with its unique advantages and limitations. Physical vapor deposition (PVD) and chemical vapor deposition (CVD) are the two primary methods used to create DLC coatings.<sup>20</sup> PVD techniques, such as sputtering and pulsed laser deposition, rely on physical processes to transfer material from a target to the substrate. These methods are capable of producing highly pure films with excellent adhesion to the substrate. However, PVD techniques generally require high vacuum conditions and can be less efficient for coating complex geometries. On the other hand, CVD methods, including plasma-enhanced CVD (PECVD) and hot filament CVD (HFCVD), utilize chemical reactions to deposit the film.<sup>21</sup> PECVD, in particular, has emerged as a popular choice for depositing hydrogenated DLC films due to its ability to operate at lower temperatures and its flexibility in controlling film composition and properties.<sup>22,23</sup> By introducing hydrocarbons and hydrogen into a plasma, PECVD facilitates the formation of a carbon-hydrogen matrix on the substrate surface.<sup>24</sup> This method allows for precise control over the film's hydrogen content and microstructure, enabling the production of coatings with tailored properties.

Surface modification techniques further enhance the functionality of DLC films, extending their applicability across various domains.<sup>25,26</sup> Ion implantation, for instance, is a process where ions are accelerated and implanted into the DLC film to alter its properties. This technique can improve the film's hardness, adhesion, and wear resistance by modifying its atomic structure.<sup>27</sup> Another surface modification approach is the application of top coatings or multilayer structures, where DLC films are combined with other materials to achieve specific performance characteristics.<sup>28</sup> For example, combining DLC with titanium nitride (TiN) can produce coatings with superior wear resistance and

reduced friction, ideal for cutting tools and industrial machinery.<sup>29</sup> Moreover, recent advancements in nanotechnology have opened new avenues for enhancing the performance of hydrogenated DLC films. Incorporating nanoparticles or nanocomposites into the DLC matrix can significantly improve its mechanical and tribological properties.<sup>30</sup> Nanodiamond particles, for instance, can be embedded in the DLC film to increase its hardness and wear resistance further. These nanocomposite DLC coatings offer unprecedented performance, making them suitable for the most demanding applications in aerospace, automotive, and biomedical fields.<sup>31</sup> The ability to fine-tune these properties through advanced deposition techniques and surface modifications underscores the potential of DLC films to revolutionize various technological sectors. As research and development in this field continue to progress, the future promises even more innovative applications and improved performance of hydrogenated DLC films, cementing their role as a cornerstone of modern material science and engineering. This exploration into DLC films sets the stage for a deeper understanding of thin film deposition techniques and the exciting possibilities they hold for future advancements.

The novelty of this review paper lies in its comprehensive exploration of the latest advancements in hydrogenated diamond-like carbon (HDLC) thin film deposition and surface modification techniques, which have not been extensively covered in previous literature. Unlike earlier reviews, this paper highlights emerging deposition methods such as plasma-enhanced chemical vapor deposition (PECVD) and nanocomposite approaches, offering new insights into tailoring the hydrogen content and microstructure of HDLC films for enhanced mechanical, tribological, and optical properties. Additionally, it delves into cutting-edge surface modification techniques, including ion implantation and the incorporation of nanomaterials like nanodiamonds, which significantly boost hardness, wear resistance, and biocompatibility. The review further emphasizes the novel applications of HDLC films in advanced industries like aerospace, automotive, biomedical, and optical technologies, showcasing the transformative potential of these materials in both established and emerging fields. By addressing these innovative developments, the paper provides a forward-looking perspective, positioning HDLC films as a cornerstone for future material science advancements.



**Figure 1.** Schematic Drawing of a ternary phase diagram of 74 types of amorphous carbon thin films with circle diameter to nanoindentation hardness.

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## PROPERTIES OF HYDROGENATED DIAMOND-LIKE CARBON FILMS

Hydrogenated diamond-like carbon (DLC) films, a unique class of amorphous carbon materials, have garnered significant interest due to their exceptional properties and wide-ranging applications.<sup>5</sup> This section delves into the distinct key properties of hydrogenated DLC films, including their mechanical, tribological, optical, and biocompatible attributes (Figure 2). Furthermore, it highlights the various industrial applications of DLC films, demonstrating their versatility and critical importance.<sup>32</sup>

### Mechanical Properties

One of the most celebrated attributes of hydrogenated DLC films is their outstanding mechanical properties.<sup>33</sup> These films exhibit a remarkable hardness, often comparable to that of natural diamond<sup>34</sup> Typically, the hardness of hydrogenated DLC films can reach up to 80 GPa, making them exceptionally resistant to scratching and deformation. This high hardness is primarily attributed to the presence of  $sp^3$  (diamond-like) carbon bonds within the amorphous carbon matrix. In addition to hardness, elasticity is another critical mechanical property of hydrogenated DLC films. These films exhibit a high elastic modulus, which enables them to withstand significant mechanical stresses without permanent deformation.<sup>35</sup> The combination of high hardness and elasticity ensures that hydrogenated DLC films maintain their structural integrity even under harsh operating conditions, which is essential for applications in demanding environments. Wear resistance is another key mechanical property of hydrogenated DLC films. The low wear rates of these films are a result of their robust atomic structure, which resists material loss during mechanical contact.<sup>36</sup> This wear resistance is particularly beneficial in applications where components are subjected to repetitive mechanical motions, such as in cutting tools, bearings, and other mechanical parts. By reducing wear, DLC coatings extend the lifespan of these components, leading to improved reliability and reduced maintenance costs.

### Tribological Properties

The tribological properties of hydrogenated DLC films are equally impressive, with low friction and high wear resistance being the most notable.<sup>37</sup> The low coefficient of friction of hydrogenated DLC films, typically in the range of 0.01 to 0.2, significantly reduces the frictional forces during mechanical contact. This reduction in friction not only enhances the efficiency of mechanical systems but also minimizes energy loss, making DLC films highly desirable for automotive and aerospace applications where energy efficiency is crucial.<sup>38, 39</sup> The high wear resistance of hydrogenated DLC films further enhances their tribological performance. This property ensures that the films can endure prolonged exposure to mechanical stress and friction without significant material degradation. As a result, components coated with DLC films exhibit extended operational lifespans, reduced downtime, and lower maintenance requirements. In the automotive industry, for example, DLC coatings are applied to engine components to reduce friction and wear, leading to improved fuel efficiency and engine performance.<sup>40</sup>

### Optical Properties

Hydrogenated DLC films also possess unique optical properties that can be tailored for specific applications. These films are generally transparent to infrared light, making them suitable for various optical applications.<sup>41</sup> The optical transparency of hydrogenated DLC films can be adjusted by modifying the deposition parameters and the hydrogen content in the film.<sup>42</sup> This tunability allows for the creation of coatings with specific optical characteristics, such as anti-reflective coatings for lenses and protective coatings for optical components used in harsh environments. The refractive index of hydrogenated DLC films can also be precisely controlled, enabling their use in a variety of optical devices. By adjusting the hydrogen content and the  $sp^2/sp^3$  carbon bond ratio, the refractive index of DLC films can be varied to match the requirements of different optical applications.<sup>43</sup> This property is particularly useful in the fabrication of optical coatings that need to exhibit specific reflective or transmissive properties.

### Biocompatibility

Biocompatibility is a critical property of hydrogenated DLC films that has led to their widespread use in medical and biomedical applications.<sup>6</sup> The biocompatibility of these films is primarily due to

their chemical inertness and the smooth, pinhole-free surfaces they provide. These characteristics prevent bacterial adhesion and reduce the risk of inflammatory responses when DLC-coated devices are implanted in the body.<sup>44</sup> In the medical field, hydrogenated DLC films are used to coat a variety of medical devices, including stents, joint prostheses, and surgical instruments. The coatings enhance the durability and biocompatibility of these devices, ensuring long-term performance and patient safety. In dental applications, DLC coatings are applied to dental implants and tools to improve their wear resistance and biocompatibility, leading to better clinical outcomes and patient satisfaction.<sup>45</sup>

## **APPLICATIONS OF HYDROGENATED DLC**

Hydrogenated diamond-like carbon (HDLC) films offer a versatile range of applications across several key industries (Table 1) due to their unique properties, including biocompatibility, hardness, wear resistance, and chemical stability. In biomedical applications, HDLC films are ideal for medical implants and devices, as their biocompatibility and low friction reduce tissue damage, enhancing the longevity of implants such as stents, prostheses, and surgical tools.<sup>46,47</sup> Additionally, HDLC films can be tailored for drug delivery systems, enabling the controlled release of therapeutic agents. In electronics and optoelectronics, HDLC coatings are applied as wear-resistant layers in electronic components, improving device durability. Their optical transparency makes them suitable for anti-reflective coatings and optical filters in optical devices.<sup>8,48</sup> In mechanical and aerospace engineering, HDLC films serve as tribological coatings, reducing friction and wear in mechanical systems, while also providing protective coatings for aerospace components, such as turbine blades, bearings, and other parts exposed to extreme conditions, improving their efficiency and reliability.<sup>49,50</sup> Energy applications also benefit from HDLC films, which are used in photovoltaic devices as protective coatings to enhance solar cell efficiency and reduce reflection losses. They also protect fuel cell electrodes, boosting their performance and lifespan.<sup>51,52</sup> In environmental applications, HDLC films play a role in water purification and air filtration systems, where their hydrophobic properties and chemical inertness improve the filtration process and pollutant removal.<sup>53,54</sup> Furthermore, HDLC films are increasingly utilized in automotive and industrial sectors, where they coat engine and transmission components, cutting tools, and packaging materials, contributing to reduced friction, wear, and contamination. These diverse domain-wise applications highlight the broad utility of HDLC films in enhancing performance across various fields.<sup>55,56</sup>

## **THIN FILM DEPOSITION TECHNIQUES**

Thin film deposition techniques are critical for the synthesis of hydrogenated diamond-like carbon (DLC) films, enabling the creation of coatings with precise control over their properties. The primary methods employed for depositing these films include chemical vapor deposition (CVD) and physical vapor deposition (PVD), each with its variants shown in Figure 3. This section provides an in-depth exploration of these techniques, discussing their principles, advantages, limitations, and recent advancements.

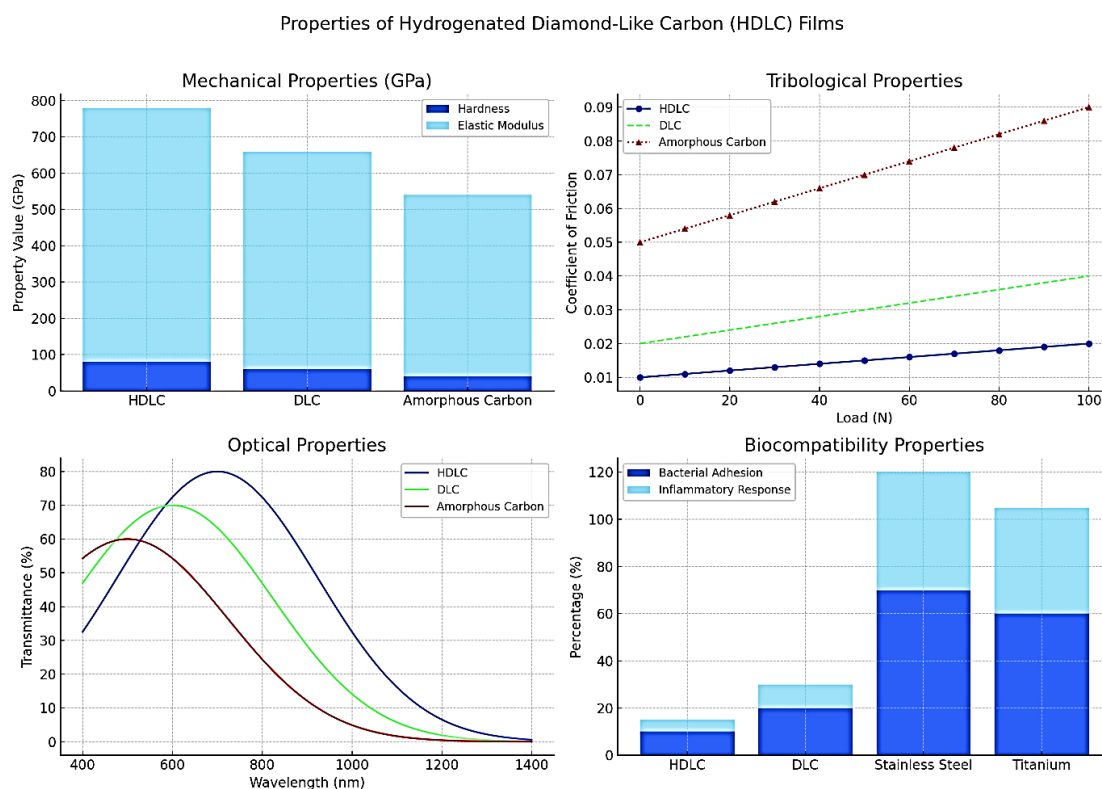
### **Chemical Vapor Deposition (CVD)**

Chemical vapor deposition (CVD) is a widely used method for depositing thin films, including hydrogenated DLC films.<sup>57</sup> In CVD, volatile precursor gases are introduced into a reaction chamber where they decompose or react on a heated substrate surface, forming a solid film. The process typically involves the use of hydrocarbons (such as methane or acetylene) as carbon sources, and hydrogen as a stabilizing agent. The CVD process involves several key steps: gas phase reactions, adsorption of reactants on the substrate, surface diffusion, and film growth.<sup>58</sup> By controlling parameters such as temperature, pressure, gas flow rates, and substrate materials, the properties of the resulting DLC films can be finely tuned. CVD allows for excellent control over film composition and thickness, producing high-purity and uniform coatings. It can deposit films on complex geometries and large areas, making it suitable for a variety of industrial applications.<sup>59</sup> The primary limitations of CVD include the need for high temperatures, which can limit its use with temperature-sensitive substrates, and the potential for hazardous by-products, necessitating stringent safety measures.<sup>60</sup> Recent advancements in CVD

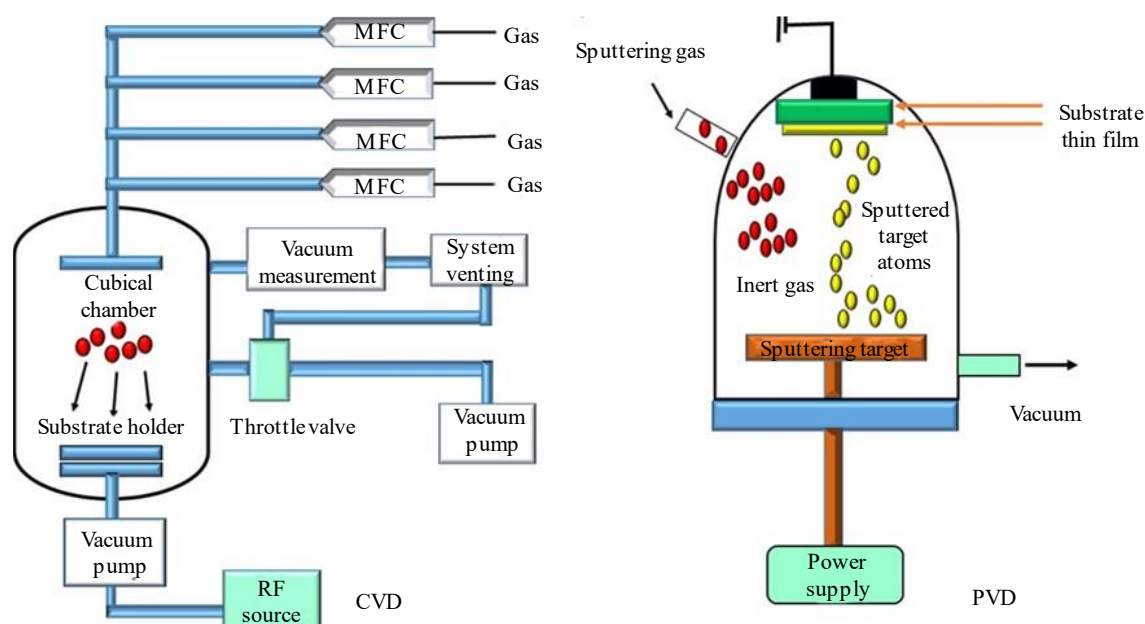
technology have focused on enhancing film quality and uniformity. Plasma-enhanced CVD (PECVD) operates at lower temperatures by using plasma to activate the precursor gases, allowing for deposition on heat-sensitive substrates.<sup>61</sup> Hot filament CVD (HFCVD) and microwave plasma CVD (MPCVD) have also been developed to improve film adhesion and deposition rates.<sup>21</sup> Innovations such as pulsed CVD and atomic layer deposition (ALD) offer even greater control over film thickness and composition, further expanding the applicability of CVD in industrial settings.

### Physical Vapor Deposition (PVD)

Physical vapor deposition (PVD) encompasses a variety of techniques that involve the physical transfer of material from a source to a substrate, typically under vacuum conditions. Common PVD methods for DLC films include sputtering and evaporation.<sup>62</sup> In sputtering, a target material (usually graphite) is bombarded with high-energy ions, causing atoms to be ejected and deposited onto a substrate. Variants such as magnetron sputtering use magnetic fields to enhance ionization efficiency and deposition rates. Evaporation techniques, including thermal evaporation and electron beam evaporation, involve heating a carbon source to its vaporization point, allowing the vapor to condense on the substrate to form a thin film. PVD techniques can produce films with high adhesion and excellent uniformity. They operate at lower temperatures compared to CVD, making them suitable for temperature-sensitive substrates.<sup>63</sup> PVD processes are also cleaner, producing fewer chemical by-products. PVD techniques often require high vacuum conditions, which can increase complexity and cost. They may also struggle with coating large areas or complex geometries uniformly.<sup>64</sup> Advancements in PVD technology have focused on improving deposition efficiency and film properties. Reactive sputtering, which introduces reactive gases into the sputtering chamber, allows for the formation of more complex film compositions. Hybrid PVD techniques, such as pulsed laser deposition (PLD), combine multiple deposition methods to achieve better control over film characteristics.<sup>65</sup> Additionally, the development of high-power impulse magnetron sputtering (HiPIMS) has enhanced the density and adhesion of DLC films, offering improved performance for demanding applications.<sup>66</sup>



**Figure 2.** Schematic graphical representation of the key properties of hydrogenated diamond-like carbon (HDLC) films<sup>48, 49</sup>



**Figure 3.** Schematic drawing of chemical vapor deposition (CVD) and physical vapor deposition (PVD) process.

## SYNTHESIS OF HYDROGENATED DIAMOND-LIKE CARBON FILMS

### Chemical Vapor Deposition of Hydrogenated Diamond-Like Carbon Films

In general, Chemical vapor deposition (CVD) remains a cornerstone technique for the deposition of hydrogenated DLC films. This section explores the intricacies of the CVD process, including the parameters, precursor gases, deposition mechanisms, and growth kinetics, as well as recent technological advancements.<sup>67</sup> Key parameters in CVD include temperature, pressure, gas flow rates, and substrate material. The substrate temperature typically ranges from 300 to 800°C, influencing the decomposition of precursor gases and the mobility of adsorbed species. Pressure is maintained between a few millitorr to several torr, affecting the mean free path of gas molecules and deposition rate. Gas flow rates determine the concentration of reactive species in the chamber, influencing the film's composition and growth rate. Common precursor gases for hydrogenated DLC films include hydrocarbons such as methane (CH<sub>4</sub>) and acetylene (C<sub>2</sub>H<sub>2</sub>), with hydrogen (H<sub>2</sub>) used to stabilize the carbon matrix. The choice of precursors and their ratios significantly impact the film's sp<sup>2</sup>/sp<sup>3</sup> carbon bonding ratio, hydrogen content, and overall properties. The deposition mechanism involves the decomposition of hydrocarbon gases in the presence of hydrogen, forming reactive carbon species that adsorb onto the substrate. Hydrogen atoms play a crucial role in terminating dangling bonds and stabilizing the sp<sup>3</sup> carbon bonds, essential for achieving diamond-like properties. The growth kinetics of DLC films are influenced by the substrate temperature, precursor concentration, and plasma conditions (in the case of PECVD).<sup>68</sup> High temperatures and optimized gas mixtures promote the formation of sp<sup>3</sup> bonds, enhancing film hardness and wear resistance. Understanding these kinetics is essential for tailoring film properties for specific applications. Recent developments in CVD technology have focused on improving film quality, uniformity, and adhesion. PECVD has become a preferred method due to its ability to deposit high-quality DLC films at lower temperatures.<sup>24</sup> Innovations such as pulsed PECVD and the use of advanced plasma sources (e.g., microwave and radio frequency plasmas) have further enhanced the control over film properties.<sup>69</sup> Additionally, the integration of in-situ diagnostic tools allows for real-time monitoring and adjustment of deposition parameters, ensuring consistent film quality.

### Physical Vapor Deposition of Hydrogenated Diamond-Like Carbon Films by Sputtering Method

Physical vapor deposition (PVD) techniques are essential for the synthesis of hydrogenated DLC films, offering unique advantages in terms of film purity and adhesion.<sup>70</sup> This section delves into the

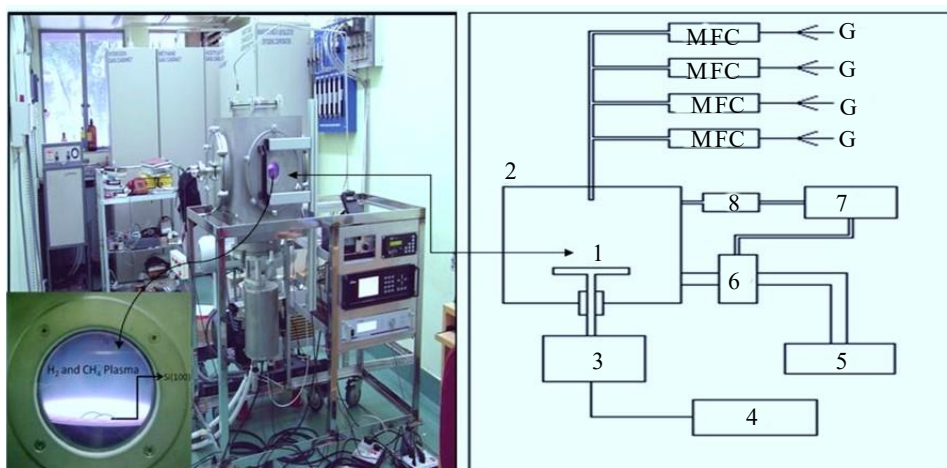
various PVD methods, their advantages and challenges, and recent advancements. Sputtering involves bombarding a graphite target with high-energy ions, typically argon, causing the ejection of carbon atoms that deposit on the substrate. Magnetron sputtering enhances ionization efficiency through the use of magnetic fields, improving deposition rates and film uniformity. Sputtering can produce films with high adhesion and uniformity across the substrate.<sup>71</sup> It operates at lower temperatures, making it suitable for temperature-sensitive substrates. The need for high vacuum conditions increases complexity and cost. Achieving uniform coatings on complex geometries can be challenging. High-power impulse magnetron sputtering (HiPIMS) has improved film density and adhesion, offering enhanced performance. Reactive sputtering introduces reactive gases to form complex film compositions, expanding the range of achievable properties.<sup>34</sup> Evaporation techniques involve heating a carbon source to its vaporization point, allowing the vapor to condense on the substrate. Electron beam evaporation uses an electron beam to heat the source material, providing precise control over the deposition rate. Evaporation methods can produce highly pure films with excellent uniformity.<sup>72</sup> They are well-suited for coating large areas and temperature-sensitive substrates. Maintaining high vacuum conditions is critical, adding to operational complexity and cost. Uniform deposition on complex shapes can be difficult. Hybrid PVD approaches, such as combining evaporation with ion beam assistance, have improved film properties and adhesion. Innovations in deposition sources, such as using carbon nanotubes or fullerene targets, have expanded the range of achievable film characteristics.

## SURFACE MODIFICATION TECHNIQUES

In the realm of material science, surface modification techniques are essential for tailoring the properties of hydrogenated diamond-like carbon (DLC) films to meet specific application requirements.<sup>73</sup> These techniques enhance the performance of DLC films by altering their surface characteristics, thereby improving their mechanical, tribological, and functional properties. This section explores several prominent surface modification methods, including plasma treatment, ion implantation, laser processing, and chemical functionalization, discussing their mechanisms, effects on film properties, and applications.

As an example, Figure 4 illustrates the experimental setup used for synthesizing Hydrogenated Diamond-Like Carbon (HDLC) thin films onto Si(100) substrates at room temperature. This setup includes several critical components designed to ensure precise deposition and control over the film quality. The primary component is the process cubical chamber (2), with each side measuring 33.8 cm. The substrate holder (1), with a diameter of 15 cm, is introduced from the bottom of this chamber to hold the substrate in place during the deposition process. Gas flow lines are introduced from the top of the process chamber to manage the introduction of gases necessary for the film deposition. The vacuum pumping system (5) is crucial for maintaining the appropriate pressure within the chamber. This system includes a roots vacuum pump with a capacity of 253 m<sup>3</sup>/h and a two-stage rotary vane pump with a capacity of 65 m<sup>3</sup>/h. These pumps are connected to the process chamber via a DN 63 ISO-K pumping port. Additionally, the process chamber is equipped with DN 40 KF vacuum ports that facilitate pressure control via a throttle valve (6), vacuum measurement (8), and system venting (7).

To ensure independent control over pressure and gas flow, an MKS system is used. This system comprises four flow controllers, a throttle valve, and a Baratron vacuum gauge. Ion bombardment, necessary for producing high-quality HDLC films at room temperature, is achieved using an RF-biased substrate holder. The separation of biasing and plasma production allows for a balance between the chemical and physical aspects of the process, with the RF bias providing ion bombardment even for insulating surfaces. The biasing is performed using a 13.56 MHz RF source (4) with power up to 0.6 kW. To minimize reflected power, separate impedance matching (3) is used. The substrate holder can accommodate specimens up to 5 inches in diameter and is equipped with water cooling to maintain the substrate temperature between 12°C and 15°C during film deposition. This cooling is important as lower temperatures can increase the deposition rate, and it also allows the use of plastic substrates for HDLC deposition.

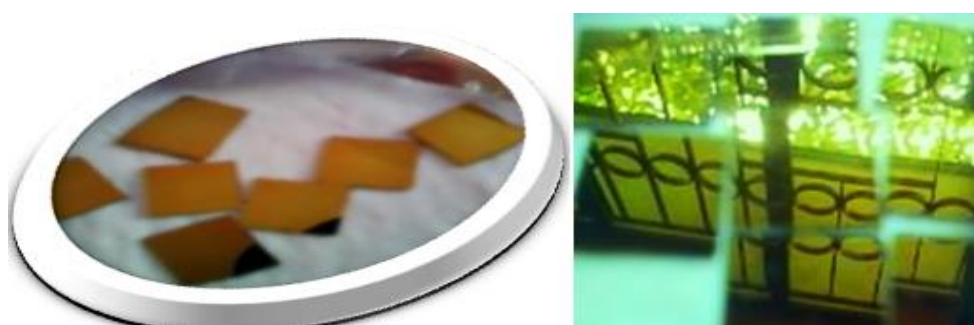


**Figure 4.** Experimental setup for the synthesis of HDLC thin films<sup>74</sup>.

Gas introduction into the vacuum chamber is controlled by Mass Flow Controllers (MFC), allowing precise control over the flow of H<sub>2</sub>, CH<sub>4</sub>, and He gases. The maximum vacuum achievable in the chamber is 0.001 mbar. The RF power applied between the substrate holder and the process chamber can be varied between 0-300W, resulting in a DC self-negative bias of up to -800 volts. The water cooling arrangement ensures that the temperature of the substrate holder remains stable, which is critical for consistent film quality. This setup, with its detailed control over pressure, gas flow, ion bombardment, and temperature, enables the synthesis of high-quality HDLC thin films suitable for various applications, including those requiring insulating surfaces and plastic substrates. The precise control mechanisms and cooling systems are essential for optimizing the deposition process and achieving the desired film properties<sup>74</sup>

### Plasma Treatment

Plasma treatment is a versatile surface modification technique used to modify the surface properties of DLC films. This method involves exposing the DLC-coated surface to a plasma environment, which consists of ionized gases such as argon, oxygen, or nitrogen.<sup>45</sup> Plasma treatment induces physical and chemical changes on the film's surface by bombarding it with high-energy ions and reactive species. This process can clean the surface, remove contaminants, and introduce functional groups that enhance the film's properties.<sup>75</sup> Plasma treatment can significantly improve the adhesion, wettability, and biocompatibility of DLC films.<sup>14</sup> By introducing oxygen or nitrogen plasma, the surface can become more hydrophilic, enhancing its compatibility with biological tissues.<sup>76</sup> Additionally, plasma treatment can increase surface roughness, which can be beneficial for certain applications requiring enhanced friction or mechanical interlocking.<sup>77</sup> Plasma-treated DLC films are widely used in biomedical applications, such as coatings for implants and surgical instruments, where enhanced biocompatibility and adhesion are crucial. They are also employed in microelectronics to improve the adhesion of subsequent layers in multilayer structures.



**Figure 5.** Picture of Prepared HDLC films and the typical mirror image of objects due to the reflection of light from the film.<sup>74</sup>

### Ion Implantation

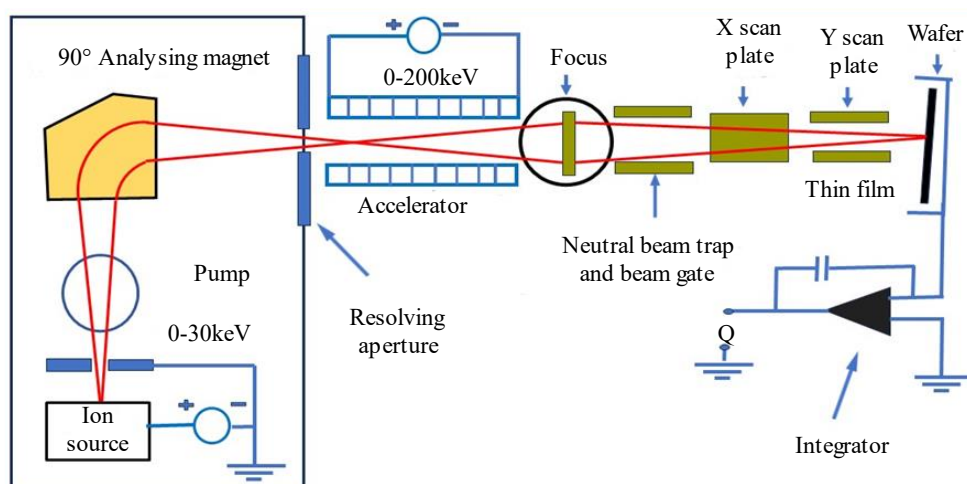
Ion implantation is a powerful technique used to modify the surface composition and structure of DLC films by embedding ions into the film's surface.<sup>27</sup> This process involves accelerating ions (such as nitrogen, boron, or silicon) to high energies and directing them onto the DLC-coated surface (Figure 6).<sup>28</sup> The ions penetrate the surface, creating defects and altering the film's microstructure and chemical composition. Ion implantation can enhance the hardness, wear resistance, and thermal stability of DLC films.<sup>78</sup> For instance, nitrogen implantation can increase the film's hardness and reduce internal stresses, while silicon implantation can improve its thermal stability and oxidation resistance.<sup>79</sup> Ion-implanted DLC films are used in cutting tools and mechanical components where enhanced hardness and wear resistance are required. They are also employed in electronic devices to improve the thermal stability and durability of protective coatings.

### Laser Processing

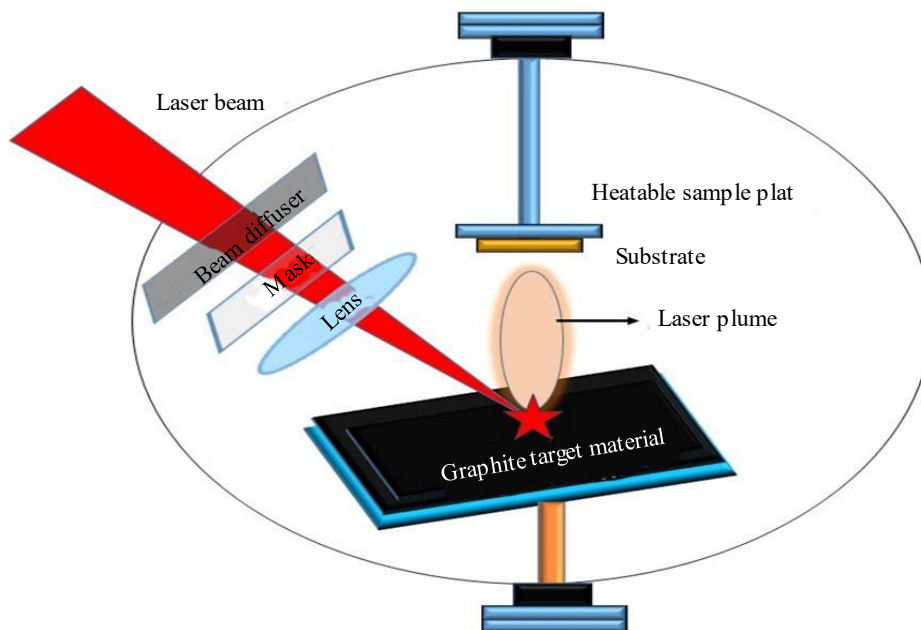
Laser processing is a precise surface modification technique that uses laser beams to alter the surface properties of DLC films.<sup>80</sup> Laser processing involves focusing a high-energy laser beam onto the DLC-coated surface, causing localized heating, melting, or ablation. This process can modify the surface morphology, introduce microstructures, or create patterns on the film (Figure 7).<sup>80, 81</sup> Laser processing can improve the surface hardness, reduce surface roughness, and create micro-patterns that enhance the film's tribological performance. It can also be used to anneal the DLC film, relieving internal stresses and improving adhesion. Laser-processed DLC films are used in advanced manufacturing and microelectronics, where precise surface patterning and improved mechanical properties are essential. They are also employed in biomedical devices to create textured surfaces that promote cell adhesion and tissue integration.<sup>82</sup>

### Chemical Functionalization

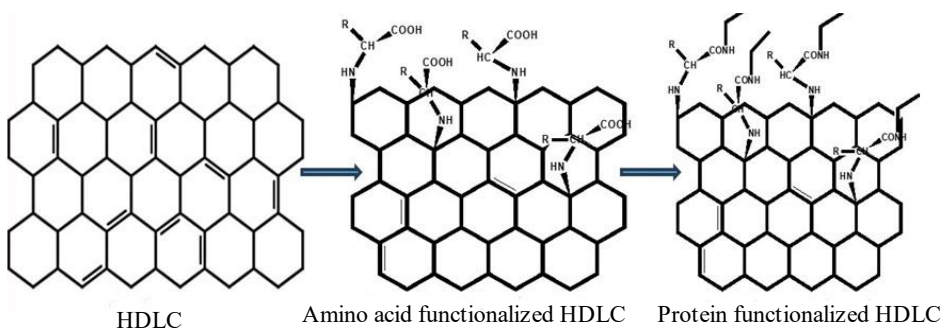
The chemical functionalization of hydrogenated diamond-like carbon (HDLC) typically involves modifying the surface to enhance its properties for specific applications, such as biocompatibility, adhesion, or reactivity. The functionalization process generally includes the introduction of functional groups (e.g., amine, carboxyl, hydroxyl) onto the HDLC surface, which can serve as active sites for subsequent chemical reactions (like Figure 8).<sup>74,83</sup> Chemical functionalization can enhance the hydrophilicity, biocompatibility, and chemical reactivity of DLC films.<sup>84</sup> Functional groups can provide binding sites for biomolecules, improve lubrication properties, or enhance corrosion resistance.<sup>85</sup> Chemically functionalized DLC films are extensively used in biomedical applications, such as biosensors, drug delivery systems, and tissue engineering scaffolds. They are also applied in tribological systems to improve lubrication and reduce wear.



**Figure 6.** The schematic diagram for the description of the Ion Implantation synthesis process of HDLC thin film



**Figure 7.** The schematic diagram for the description of the Laser Processing synthesis process of HDLC thin film



**Figure 8.** Schematic drawing of HDLC, amino acid, and protein functionalized HDLC.

### CHALLENGES AND FUTURE PERSPECTIVES

The synthesis and application of hydrogenated diamond-like carbon (DLC) films, while highly promising, face several challenges that must be addressed to fully realize their potential:

- *Scalability of thin film deposition methods:*
  - Optimization of techniques like CVD and PVD for large-scale production.
  - Development of cost-effective processes to produce uniform and high-quality films over large areas and complex geometries.
- *Understanding fundamental mechanisms:*
  - Need for a deeper understanding of atomic-level interactions during deposition.
  - Precise control of film properties, such as  $sp^2/sp^3$  carbon bonding ratios, hydrogen content, and thickness uniformity.
- *Advanced In-situ diagnostic tools:*
  - Implementation of tools and simulation techniques to elucidate film growth mechanisms.
  - Enabling precise control over film characteristics.
- *Exploring novel surface modification strategies:*
  - Refinement of techniques like plasma treatment, ion implantation, laser processing, and chemical functionalization.
  - Research into hybrid approaches and integration of multiple modification techniques to enhance surface properties.

- *Emerging applications:*
  - Potential for flexible and durable DLC coatings in wearable electronics to protect delicate components.
  - Advanced DLC-coated implants and drug delivery systems in biomedicine to revolutionize patient care.
  - Enhancements in renewable energy technologies, such as next-generation solar panels and wind turbines, leveraging the durability and efficiency of DLC films.

**Table 1.** A comparative table representing applications of DLC and HDLC.

	DLC Applications	HDLC Applications
Industry	DLC-coated engine components (pistons, camshafts, fuel injectors) reduce friction and wear, enhancing fuel efficiency and performance. DLC on fuel injectors improves combustion efficiency and reduces emissions. <sup>86</sup>	- HDLC coatings on automotive parts offer enhanced wear resistance and lower friction, ensuring greater longevity. Plasma-treated HDLC surfaces provide improved adhesion and wear resistance under harsh conditions. <sup>55</sup>
Automotive	DLC coatings on turbine blades improve wear resistance and high-temperature oxidation resistance. Ion-implanted DLC films on bearings increase hardness and durability, ensuring reliable performance in extreme environments. <sup>87</sup>	HDLC films provide superior mechanical stability under extreme temperatures. Nanocomposite HDLC films enhance tribological performance for critical aerospace components such as turbine blades and landing gear. <sup>56</sup>
Medical Devices	DLC coatings on implants and joint prostheses reduce wear and inflammation, improving patient outcomes. DLC on surgical instruments increases durability and biocompatibility. <sup>46</sup>	HDLC films exhibit enhanced biocompatibility, making them suitable for long-term implants and prostheses. Chemically functionalized HDLC surfaces promote better cell adhesion, ideal for biosensors and tissue engineering. <sup>47</sup>
Electronics	DLC films provide abrasion resistance for optical lenses and protect microelectronic components from moisture and contamination. DLC-coated sensors offer improved durability in harsh conditions. <sup>48</sup>	HDLC films improve protective coatings for electronics, providing superior barrier properties against environmental factors. HDLC's tunable optical properties make them ideal for anti-reflective coatings and high-precision electronics. <sup>8</sup>
Renewable Energy	DLC coatings on photovoltaic cells increase durability by protecting from environmental degradation. DLC-coated wind turbine blades reduce friction and improve wear resistance, enhancing energy conversion efficiency. <sup>17</sup>	HDLC films provide better surface protection for solar panels, improving efficiency under varying environmental conditions. Nanocomposite HDLC films on wind turbine blades enhance wear resistance and extend operational life. <sup>52</sup>

## CONCLUSION

- *Exceptional material properties:* Hydrogenated diamond-like carbon (DLC) films demonstrate outstanding mechanical strength, wear resistance, optical transparency, and biocompatibility.
- *Diverse applications:* DLC coatings are crucial in various industries, including automotive, aerospace, medical devices, electronics, and renewable energy, enhancing performance, durability, and efficiency.
- *Cost-effectiveness and scalability:* Addressing scalability challenges is essential for developing cost-effective deposition methods that produce uniform films over large areas and complex geometries.
- *Understanding film growth mechanisms:* A deeper understanding of the mechanisms governing film growth is critical for controlling properties such as carbon bonding ratios and hydrogen content.
- *Surface modification techniques:* Refining surface modification techniques can tailor DLC surfaces for specific applications, enhancing their efficiency and effectiveness.

- *Research into hybrid approaches*: Investigating hybrid methods and integrating multiple modification techniques can lead to the creation of DLC surfaces with unprecedented properties.
- *Future innovations*: Hydrogenated DLC films and their surface-modified variants are poised to drive advancements in emerging fields, such as wearable electronics, biomedicine, and renewable energy.
- *Collaboration and ongoing research*: Continued research, innovation, and collaboration will be key to unlocking the full potential of DLC materials and their transformative impact on various industries.
- *Sustainable technological advancements*: By addressing current challenges, DLC materials can contribute significantly to sustainable technological developments and improve the quality of life.

### Conflict of Interest

There is no conflict of interest

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