# Graphene—Structure, and Synthesis Techniques: A Comprehensive Review

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## Abstract:

Graphene is a one-atom-thick layer of carbon atoms arranged in a two-dimensional honeycomb lattice. Graphene has attracted tremendous attention due to its exceptional mechanical, electrical, and thermal properties. Graphene was considered a "wonder material" immediately after its discovery because it was deemed capable of bringing drastic changes to many fields. This review gives a comprehensive overview of the atomic structure of graphene, its bonding, and the physical characteristics that have positioned this material as one of the most studied during the past two decades. Further, we discuss recent synthesis techniques including CVD and electrochemical exfoliation and detail the advantages and limitations of each with regard to scalable production. The following review further discusses the vast applications of graphene, from electronics to energy storage, involving production challenges and further improvements that could be achieved in the future. This collection is meant to serve as a starting point for researchers interested in the complications and opportunities brought about by graphene in today's technologies.
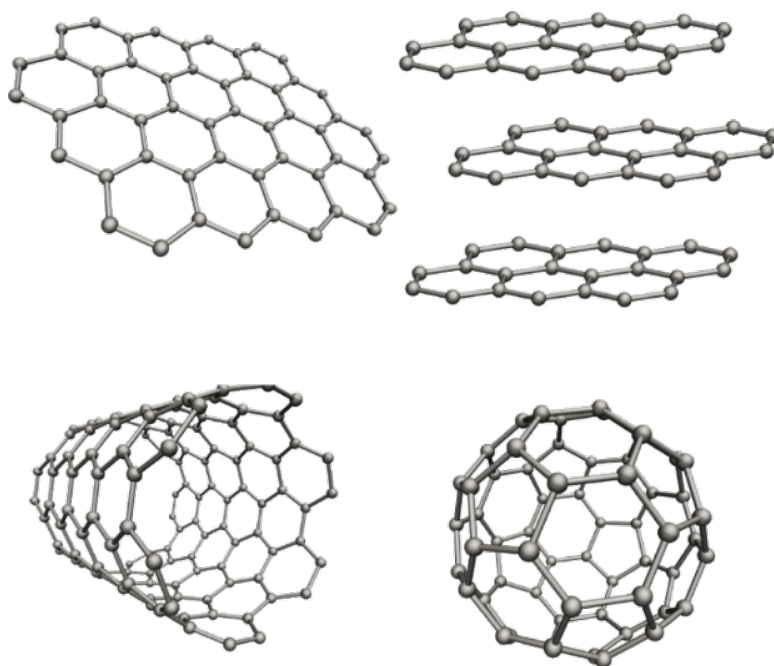
# Introduction

Graphene is a one-atom-thick layer of carbon packed in a two-dimensional honeycomb lattice, serving as the basis for arguably one of the most radical materials of the last decade thanks to its extremely impressive mechanical, electrical, and thermal properties. [28] Graphene was referred to as the "wonder material" and commanded an unusual amount of interest since its first isolation in 2004 by Andre Geim and Konstantin Novoselov, using mechanical exfoliation-more popularly, the "Scotch tape method." Very soon, in 2010, both scientists earned the Nobel Prize in Physics. This discovery singled out intensive research into numerous promising directions relating to graphene electronics, energy storage, and materials science. [12].

Unlike its parent material, graphite, which consists of stacked layers of graphene, monolayer graphene exhibits superior properties such as high electron mobility, exceptional tensile strength, and excellent thermal conductivity. These characteristics make graphene a promising candidate for various advanced technologies. However, challenges remain regarding the scalable and cost-effective production of high-quality graphene, leading to the development of several synthesis methods such as Chemical Vapor Deposition (CVD) and electrochemical exfoliation [38].

# 1 Structure of Graphene

Graphene's atomic structure plays a crucial role in its exceptional properties. The material consists of carbon atoms arranged in a planar hexagonal lattice, where each carbon atom is covalently bonded to three neighboring carbon atoms via sp²-hybridized bonds. This bonding structure forms strong sigma ($\sigma$) bonds, which contribute to graphene's impressive mechanical strength [6]. The carbon atoms are positioned at an approximate bond length of 1.42 Å, creating a highly stable honeycomb pattern.

## 1.1 Bonding and Hybridization

In graphene, each carbon atom is sp²-hybridized, meaning three of its four valence electrons form $\sigma$-bonds with adjacent atoms, creating a planar structure. The remaining p-orbital electron from each carbon atom forms a delocalized $\pi$-bonding network, which extends over the entire sheet. This delocalized $\pi$-electron system is responsible for graphene's exceptional electrical conductivity, allowing electrons to move freely across the lattice with minimal resistance [5].
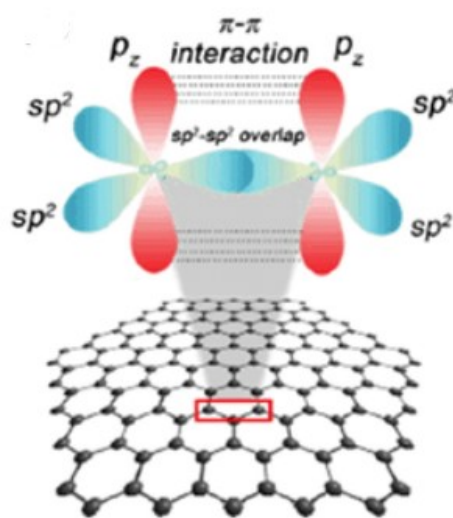


Figure 1: Schematic of sp²-hybridized carbon atoms in graphene, showing the $\sigma$-bonds in the plane and the delocalized $\pi$-bonds above and below the plane.

# 2 Properties of Graphene

## 2.1 Thermal Conductivity

Graphene is renowned for its exceptional thermal conductivity, which results from its unique atomic structure. The material consists of carbon atoms arranged in a two-dimensional honeycomb lattice, with each atom bonded to three others via strong sp²-hybridized bonds. This configuration allows phonons, or quantized vibrations of the lattice, to travel through the material with minimal scattering. As a result, graphene's thermal conductivity can reach up to 5000 W/m·K at room temperature, which is significantly higher than most conventional materials. Such high thermal conductivity makes graphene an excellent choice for thermal management applications in electronic devices, where efficient heat dissipation is crucial for maintaining device performance and longevity [27].

## 2.2 Mechanical Strength

Graphene exhibits extraordinary mechanical strength, making it one of the strongest known materials. Its tensile strength is estimated to be around 130 GPa, which is roughly 100 times greater than steel. This remarkable strength is due to the robust carbon-carbon bonds within its hexagonal lattice structure. These covalent bonds form a stable and rigid network that can endure substantial forces without breaking. Despite

its impressive strength, graphene is also highly flexible, allowing it to be stretched and bent without losing its structural integrity. This unique combination of strength and flexibility makes graphene suitable for a variety of applications, including advanced composites and protective coatings [11].

## 2.3 Electrical Conductivity

The electrical properties of graphene are equally striking. Due to its unique band structure, graphene exhibits exceptionally high electrical conductivity. At the Dirac point, where the conduction band and valence band meet, electrons behave as massless Dirac fermions. This results in extremely high carrier mobility and low electrical resistance. Graphene's electrical conductivity can exceed 200,000 S/cm, making it superior to many conventional conductive materials. This high conductivity, coupled with low thermal noise, positions graphene as a promising candidate for next-generation electronic devices, including high-speed transistors and other advanced components [10].

# 3 Graphene Synthesis

In general, synthesis of graphene follows the two major routeways: top-down and bottom-up techniques. Top-down methods break down bulk graphite into individual graphene layers using various methodologies such as liquid-phase exfoliation [15], electrochemical exfoliation [29], and ball milling [32]. These synthesis routes are scalable and cheaper. However, both these approaches introduce structural defects in graphene and are not suitable for applications that require graphene of a high degree of purity. In contrast to this top-down approach, the bottom-up technique in CVD [42], epitaxial growth [4] will build up graphene from carbon-containing precursors; while yielding high-quality graphene with fewer defects, the process is more expensive and difficult to use in scalable processing. Both techniques have their advantages, and application usually determines which process is followed.

## 3.1 Electrochemical exfoliation

The principle of electrochemical exfoliation is based on the insertion of either cations or anions from the electrolyte solution into the graphite under an applied voltage. These various methods of exfoliation are performed with either an anodic or cathodic potential. In the event of anodic exfoliation, positive charges accumulate at the anode, which in turn favors the insertion of large anions into the graphite, thereby increasing the interlayer spacing of graphite. On the other hand, cathodic exfoliation deals with the application of a negative voltage. This attracts cations onto the graphite electrode. These intercalate between the graphene layers, expanding and separating them.

As presented in Scheme 1, Müllen and co-workers [4] proposed that a positive potential was applied to a graphite anode, and then the $sp^2$ carbon atoms of graphite were attacked by nucleophilic hydroxide ions ($OH^-$) that were generated from water molecules. The C–OH bond and vicinal hydroxyl group formation follows reaction 1. These hydroxyl groups can then further react to form an epoxy group, reaction 2, which in turn can be oxidized into a carbonyl group, reaction 3. Interactions between carbon and water molecules result in the formation of carbon dioxide, reaction 4, while water also self-oxidizes to form oxygen gas, reaction 5.
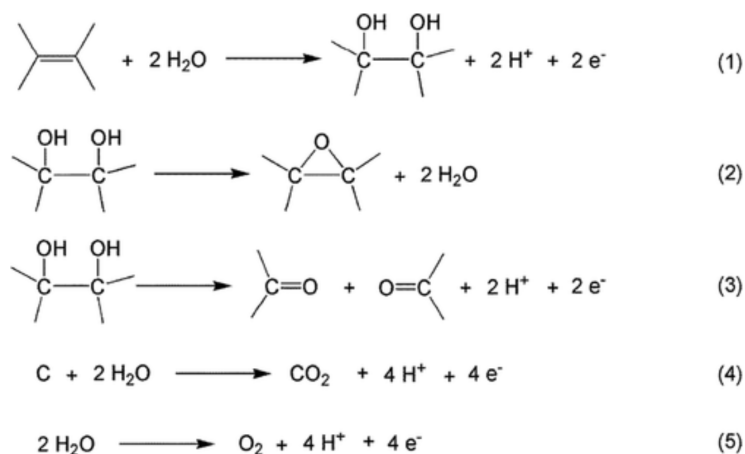


Figure 2: Schematic Representation of the Electrochemical Oxidation Process of Graphite Electrodes

4

### 3.1.1 Effect of Types of Electrolytes

The electrolyte type is one of the most critical factors influencing the yield of graphene oxide (GO). Each electrolyte offers different oxidation capabilities, which results in varying amounts of GO production. Molten salts, ionic, and inorganic solutions are common electrolytes used in the electrochemical process for GO formation. Once a specific oxidation threshold is reached, adding more oxidizing agents does not significantly alter the composition or structure of GO. Sulfuric acid ($H_2SO_4$), a strong proton donor (pKa = -3), is a particularly effective electrolyte as it enhances GO functionality. $H_2SO_4$ is widely used in the exfoliation of graphite and GO synthesis due to its rapid exfoliation rate, the appropriate size of $SO_4^{2-}$ ions relative to the graphite interlayer distance, and the generation of $SO_2$ and $O_2$ gases, which further promote exfoliation [37]. Wu et al. [37] demonstrated that a low concentration of $H_2SO_4$ leads to the production of few-layer graphene with low oxidation due to the rapid expansion of graphite layers caused by gas release during exfoliation. Further studies explored the impact of different acids, such as 1 M $H_2SO_4$, 1 M $HClO_4$, and 1 M $HNO_3$, on GO formation. GO was successfully synthesized using 1 M $HClO_4$ and 1 M $HNO_3$, whereas no GO peak was observed with 1 M $H_2SO_4$ due to the fast electrochemical exfoliation [29]. Parvez et al. [29] demonstrated the electrochemical exfoliation of graphite into low-oxidation graphene sheets, achieving a high yield (85%) with up to three layers and a lateral size of up to 44 $\mu$m when using inorganic salts such as $(NH_4)_2SO_4$, $Na_2SO_4$, and $K_2SO_4$. In contrast, acidic electrolytes produced a mixture of GO and graphene with moderate quality but larger lateral sizes. As such, the oxidation degree of graphite can be controlled depending on the choice of electrolyte: inorganic salts lower the oxidation degree, while acidic solutions tend to enhance it [29].
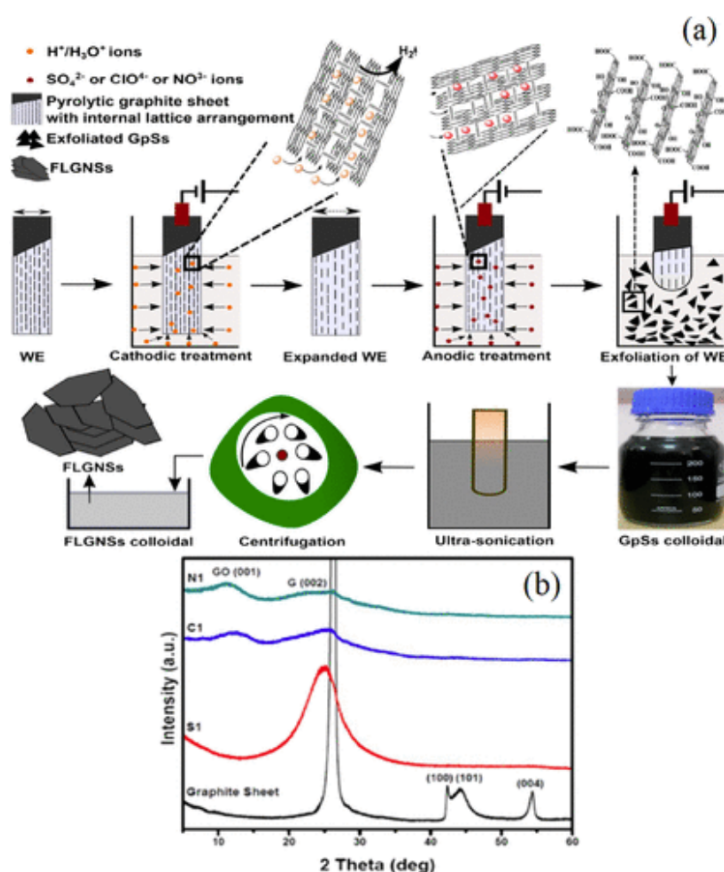


Figure 3: (a) Illustration of electrochemical intercalation and exfoliation by using 1 M H2SO4, 1 M HClO4, and 1 M HNO3. (b) No GO (001) peak was seen in XRD spectrum of 1 M H2SO4 (S1), whereas the GO (001) peak was present in 1 M HClO4 (C1) and 1 M HNO3 (N1). [31]

In addition to sulfuric acid ($H_2SO_4$), cetyltrimethylammonium bromide (CTAB) is frequently used as a cationic surfactant in the electrochemical exfoliation of graphite. CTAB assists in functionalizing graphene oxide (GO) by grafting alkyl chains onto the edges, resulting in a stable colloidal suspension. Another technique involves using a mixture of urea, acetamide, and ammonium nitrate as the electrolyte due to its high viscosity, strong intercalation potential, and slow migration speed. This method has achieved a graphene yield of up to 76%, with one to five layers, and a specific surface area of 878 $m^2/g$.

Ionic solutions are also preferred as electrolytes for GO synthesis due to their superior ionic conductivity and broad electrochemical potential. For instance, triethyl sulfonium bis(trifluoromethyl sulfonyl) imide has been

utilized as an electrolyte, with graphite serving as the anode. The produced GO was applied in surface plasmon resonance (SPR) sensing for the detection of *Salmonella typhi*. It is important to note that ionic solutions and molten salts exhibit different exfoliation mechanisms compared to aqueous electrolytes, due to the absence of water.

Graphite anode oxidation can be accelerated by introducing specific chemicals, such as nitric acid, which was demonstrated by Abdelkader and colleagues. Another method involves coating the anode electrode with p-phthalic acid (PTA) to control the exfoliation rate and enhance oxidation. A two-step electrochemical process has also been developed, where intercalation is performed using concentrated $H_2SO_4$, followed by oxidation with 0.1 M ammonium sulfate (($NH_4$)$_2SO_4$). This approach enables the large-scale production of GO, with a yield exceeding 70%, an oxygen content of 17.7%, and a high proportion of single-layer GO (90%). [21]

Table 1 provides a summary of GO characteristics synthesized using various electrolytes.

| Electrolytes | C/O | ID/IG | GO Yield | Thickness | Lateral Sizes | Synthesis Rate |
|---|---|---|---|---|---|---|
| $H_2SO_4$, $H_3PO_4$ | - | 0.71 | - | 3–9 nm | 1–5 m | - |
| $H_2SO_4$, $HClO_4$, $HNO_3$ | 1.54–1.76 | 1.005–1.072 | 49–50% | 2.7–5.6 nm | 120–220 nm | - |
| ($NH_4$)$_2SO_4$, $H_2SO_4$, $Na_2SO_4$, $MgSO_4$ | - | 0.85 | 80% | 1.08 nm | 0.5–3.0 m | - |
| $HClO_4$ | 1.43–11.55 | 0.16–0.75 | 6.63–34.2% | - | - | - |
| $H_2SO_4$ | - | - | ~5–8 wt% | 3 nm | 1–40 m | - |
| $HClO_4$, $H_2SO_4$ | 3.0–5.7 | - | - | 2 nm | 10 m | - |
| ($NH_4$)$_2SO_4$, $NH_3 \cdot H_2O$ | 7.15 | 1.33 | 34 wt% | 1.9–3.5 nm | - | - |
| Oxone ($KHSO_5 \cdot 0.5KHSO_4 \cdot 0.5K_2SO_4$) | - | ~1.24 | ~60.1% | 2.5 nm | 1–5 m | - |
| 0.2 M sodium citrate (pH 3.7), $HNO_3$ | 4 | - | - | 1.1 nm | - | - |
| NaOH, PTA | 3.15 | - | 99% | 1.8–2.2 nm | 1–50 m | - |
| NaOH, PTA | 4.02 | 0.90 | 87.3% | 2.0 nm | 4.2 m | - |
| 95% $H_2SO_4$, 0.1 M ($NH_4$)$_2SO_4$ | 4.6 | 1.48 | 71% | ¡1.5 nm | - | 10 g, less than 30 min |

Table 1: Summary of types of electrolytes used for GO production [21].

### 3.1.2 Effect of Anodic Voltages/Currents

Electrochemical exfoliation is a widely used method for synthesizing graphene oxide (GO) due to its efficiency and scalability. The application of voltage leads to the intercalation of anions into graphite, causing exfoliation and oxidation. Research has shown that adjusting anodic voltages significantly influences the yield and quality of GO. For instance, Pei et al. demonstrated the effectiveness of water electrolytic oxidation in producing high-quality GO within seconds [30].

Additionally, Chen et al. reported a photosynergetic electrochemical approach that improves GO synthesis by utilizing light to enhance the electrochemical process . Carbon-based fibers derived from electrochemical synthesis are also showing promise for advanced energy storage applications [8]. The use of carbon-based materials as electrodes in supercapacitors has been extensively studied, with excellent results in terms of capacitance and conductivity [42].

Furthermore, the potential of carbon-based electronics has been highlighted, with applications ranging from flexible devices to sensors, as reported by Avouris et al. [3]. Anodic voltages also play a role in controlling the oxidation degree of GO, as demonstrated by Tian et al., who found that varying the applied voltage can fine-tune the chemical properties of the GO produced [33].

Cathodic exfoliation is another method used for GO synthesis. Dalal et al. demonstrated that a minimum of -4 V is required to initiate exfoliation, with higher voltages increasing the yield of graphene sheets. The review by Li et al. also discusses recent advances in the preparation of GO via electrochemical approaches, emphasizing the role of electrolyte choice and applied voltage in determining the final product's properties [18].
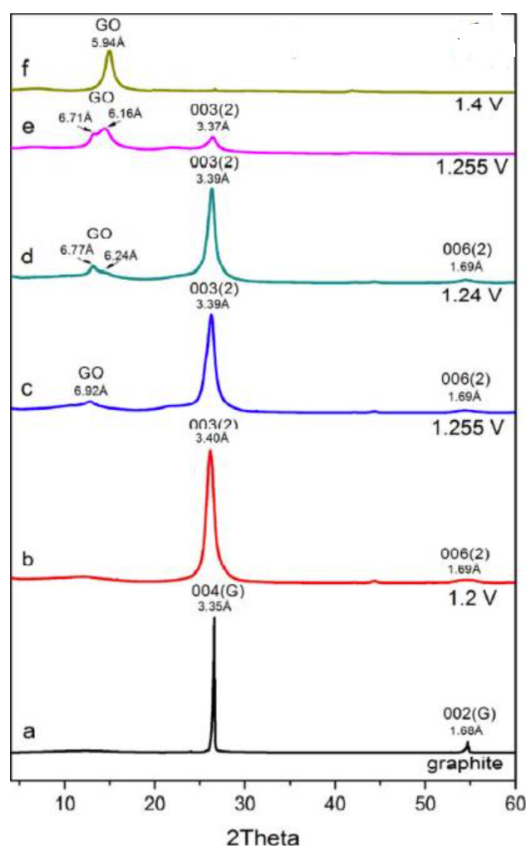
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Figure 4: The GO peak intensities increased significantly with increasing applied voltage, as shown in XRD patterns of graphite oxidized in 8 M HClO4. [13]

## 3.2 Chemical Vapour Deposition

Chemical Vapor Deposition (CVD) is a technique for depositing thin films of material onto substrates through chemical reactions involving vapor species. The specific reactions and processes in a CVD reactor are influenced by various factors, including system setup, reactor design, gas feedstock and ratios, reactor and gas partial pressures, reaction temperature, and growth time. CVD is a widely employed bottom-up method for producing few-layer and single-layer graphene films. The initial use of thermal CVD on metals was reported in 1966, demonstrating the growth of highly crystalline graphite films on nickel substrates. Subsequently, a single layer of graphite was deposited using CVD on a platinum surface through hydrocarbon decomposition at 530 °C [34]. Following the isolation of graphene in 2004, the potential of CVD for graphene film growth was successfully demonstrated with the use of Low-Pressure CVD (LPCVD) to grow graphene on iridium [26]. The popularity of CVD for graphene synthesis is attributed to its straightforward setup in research labs, proven long-term use in industrial settings, and scalability. Moreover, considering ecological and cost factors, CVD is among the most effective methods for synthesizing graphene-based materials. Various CVD methods are now available for synthesizing graphene, categorized based on processing parameters such as temperature, pressure, precursor type, gas flow, wall/substrate temperature, deposition time, and activation method, as illustrated in **Figure 5**

For CVD graphene deposition, a Cu metal substrate is put into the furnace tube, normally made of quartz, and heated under hydrogen flow at low vacuum or atmospheric pressure. The high temperature anneals the substrate and increases its grain size, usually in the range between 1-10 m [40], as well as reduces the metal oxide film on the substrate surface [17]. During growth, carbon is usually provided by mixing a hydrocarbon gas, such as methane ($CH_4$), with hydrogen. The gases are then passed through the reactor at a pre-determined ratio. This can be done by either changing the reactor pressure or by the addition of an inert diluent gas such as argon (Ar) or nitrogen (N). At the end of reaction, the furnace is usually turned off and allowed to cool down to room temperature under a gas flow, such as H2, H2 + Ar. The purpose of this step is to prevent the aggregation of deposited carbon, which may give rise to multi-layer graphene or even bulk graphite. It henceforth plays its role in realizing a continuous graphene monolayer on the surface of metals.

Figure 3 shows diagram of the CVD reaction of graphene from methane and hydrogen - numbered steps are explained in the text for clarity. First, the reactants are transported by convection in the gas flow, step 1, and thermally activated, steps 2. Then they are transported by gas diffusion from the main gas stream through the stationary boundary layer, step 3. These subsequently are adsorbed on the surface of the substrate
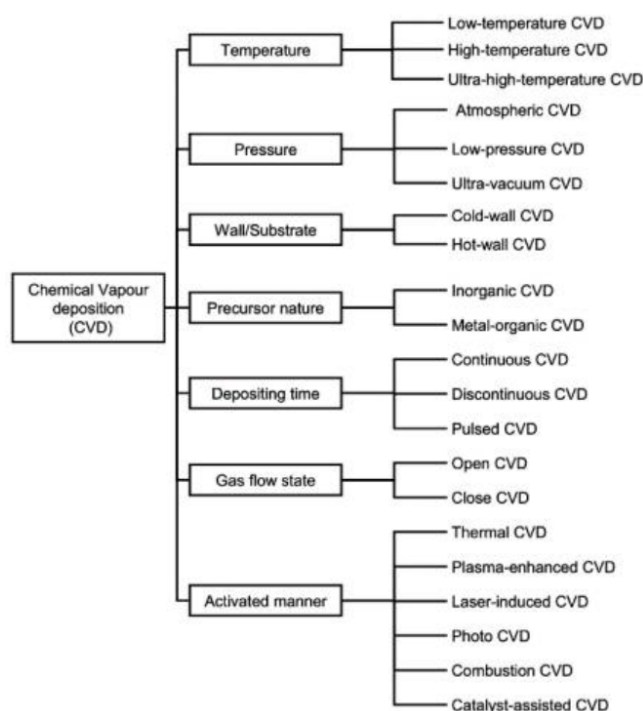
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Figure 5: Classification of CVD methods . [39]

(step 4) and/or diffused into the bulk of the substrate (step 5), depending on the carbon's solubility and the physical properties of the substrate used. In substrates with low carbon solubility, the growth step of graphene occurs at the surface where CH4 catalytic decomposition and adsorption of carbon atoms forming graphene film occur. On the contrary, a substrate of high carbon solubility sees carbon atoms diffracted into the bulk, while the graphene growth step occurs during the cooling process, where carbon precipitates into the surface. The kinetics of formation, therefore calls for the fast cooling in order to suppress the nucleation and growth of graphene multi-layers. During surface processes, step 6, catalytic decomposition of reactive species besides surface migration to the attachment sites, occurs along with other heterogeneous reactions. The by-products are then desorbed from the substrate, step 7, following the film growth. The final steps are diffusing the by-products through the boundary layer to the main gas stream, step 8, to be convected by force to the exhaust system, step 9 [25].
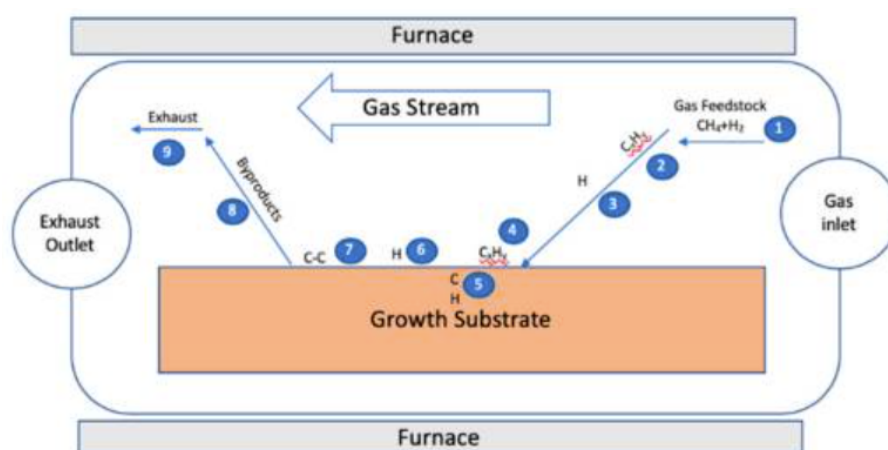


Figure 6: Schematic diagram of thermal CVD growth of graphene.
[21]

### 3.2.1 Role of Hydrogen

Among the CVD conditions, hydrogen ($H_2$) has been commonly adopted in graphene synthesis for its beneficial effects on several aspects during synthesis. One of the major functions of hydrogen is to clean and reduce the

8

substrate surface by removing oxides or impurities that may form barriers to the growth of graphene. In metals like Cu and Ni, there is a natural oxide formation on the surface, wherein hydrogen reacts with the oxides to reduce them into volatile compounds such as water ($H_2O$) which get removed from the system, thereby giving a clean and active surface. This is an important prerequisite for graphene formation [22]. Besides this, hydrogen also controls the dissociation of the carbon precursor-usually methane $CH_4$ which controls the rate at which carbon atoms are released for graphene formation. Without hydrogen, the methane $CH_4$ would decompose too fast, leading to a carbon deposition rate that is too high and which would form multilayer graphene or even amorphous carbon. In this way, hydrogen has controlled the formation of high-quality monolayer graphene through this dissociation. This is because hydrogen maintains the active sites on the metal substrate. For metals like Ni, hydrogen diffusion and desorption enhance surface activity. In this case, increasing hydrogen flow increases the number of active sites for $CH_4$ dissociation, thus facilitating graphene growth with higher efficiency. In contrast, hydrogen can block active sites on Cu at higher flow rates; this reduces the rate of graphene deposition [19]. Hydrogen also acts as a chemical etchant to prevent undue accumulation of carbon through reaction with it in the form of volatile hydrocarbon species, such as $CH_4$, by reducing the likelihood of forming amorphous carbon. Such an etching mechanism participates and ensures that graphene gets deposited uniformly with high crystallinity, without defects, and thereby enhances electrical and mechanical properties. The role of hydrogen is not confined to these tasks; it might also influence graphene growth kinetics and crystal quality. On Ni, higher hydrogen flow increases the growth rate by enhancing the surface activity, while in the case of Cu, high hydrogen flow decreases the growth due to surface site blockage [35]. Finally, in some systems, hydrogen acts like a carrier gas and provides transport for the carbon precursor at the substrate surface, hence assuring uniform carbon deposition. In general, hydrogen presence in the CVD process is necessary in order to control both the quality and kinetics of graphene growth; it therefore is a key factor in the synthesis process itself [14].

### 3.2.2 Role of Growth Temperature

Among the most influential factors on the physicochemical mechanisms of graphene nucleation and growth, including the atomic-level steps, is the CVD growth temperature. In other words, the process of graphene nucleation and the proceeding growth is a result of adsorption, desorption, and adsorbate (active atoms) migration mechanisms, each highly influenced by the process temperature. Reports on surface kinetics that consider the details of surface kinetics give evidence that with the increase in the reaction temperature, the growth rate of CVD graphene film rises. It is generally believed that a higher temperature reduces the nucleation density of graphene, as according to [36]. Lui et al. proposed increasing the CVD process temperature, which would reduce surface roughness of the substrate, decreasing active nucleation sites and increasing the mobility of active species, thereby enhancing growth quality [20]. Growth temperatures for CVD close to or above the melting point of Cu ($T_m$ of Cu = 1084 °C) usually result in high-quality graphene with monolayer, uniform, crystalline, continuous, and low defect density within the graphene film. This is due to a fast dehydrogenation rate of the hydrocarbon feedstock and/or an improved probability that active carbon species have sufficient energy to overcome the energy barrier for attaching to the surface for graphene film growth [16].

Chaitoglou and Bertran studied the influence of temperature on the CVD graphene growth process within the range from 970 to 1070 °C. At temperatures below that value, no nucleation of graphene took place, hence the choice of temperature was made, while the higher limit was close to the Cu melting point. They studied, from SEM images, the effect of temperature on the process kinetics of graphene growth, considering morphological features such as nucleation density, growth rate, and graphene surface coverage. Their findings indicated that the highest nucleation density corresponds to the lowest growth temperature of 75 nuclei/10,000 $\mu m^2$ at 970 °C, while the lowest nucleation density corresponds to the highest temperature of 3.4 nuclei/10,000 $\mu m^2$ at 1070 °C. At higher temperatures, however, the graphene growth rate increased sharply from 144 $\mu m^2$/20 min at 970 °C up to 1369 $\mu m^2$/20 min at 1070 °C .
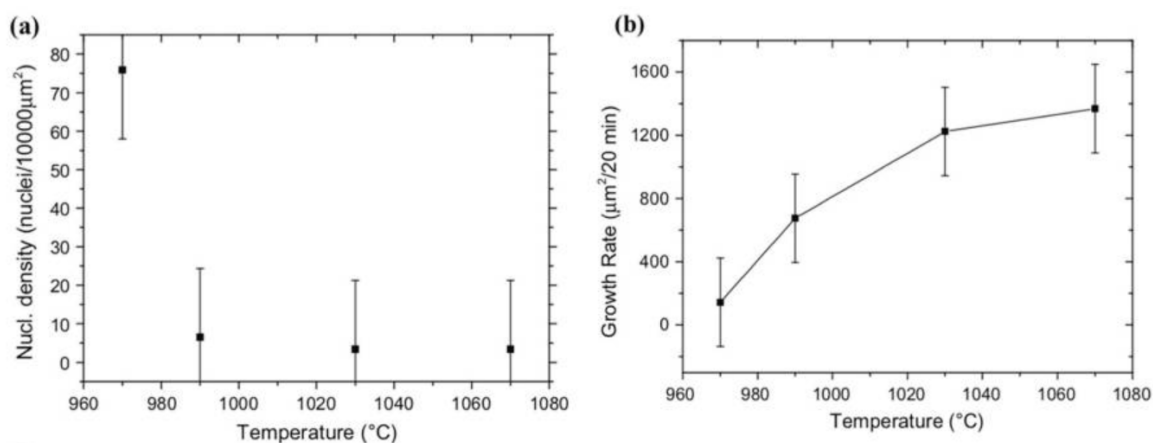
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Figure 7: (a) nucleation density versus growth temperature, (b) nucleus growth rate versus growth temperature [7]

### 3.2.3  Solid Substrates

Transition metals play a pivotal role in catalyzing the growth of graphene through chemical vapor deposition (CVD). Their unique catalytic properties give them an edge over other materials. Extensive research has focused on metals such as nickel (Ni), copper (Cu), palladium (Pd), ruthenium (Ru), iridium (Ir), and platinum (Pt) for facilitating the growth of single-layer graphene. Among these, Ni and Cu are the most frequently employed substrates due to their proven ability to effectively control graphene's growth, making them ideal for scalable production. [2]. Nickel (Ni) has been integral in the growth of graphene layers for over 50 years, with its applications observed in various industrial settings. Among transition metals, Ni(111) is particularly favorable for graphene growth due to its minimal lattice mismatch with graphene, only around (1%). This close alignment makes Ni(111) catalytically superior compared to other metals, allowing for more controlled and uniform growth of graphene layers. This property, combined with its industrial viability, has made nickel a key substrate in the chemical vapor deposition (CVD) process for graphene production. [24].The mechanism of graphene growth on Ni is a bulk diffusion process. Carbon atoms dissolve in the nickel substrate because of the metal carbon solubility. While cooling, these carbon atoms segregate from the bulk, precipitating onto the surface and forming graphene layers. The advantage of this method is that the properties of solubility of Ni enable control of graphene formation during cooling and yield high-quality graphene layers. Grain boundaries and defects on the substrate's surface increase nucleation sites, leading to more heterogeneous graphene growth [2]. Testing different metallic substrates, copper rapidly proved to be an excellent substrate for CVD graphene growth [19]. This is supported by the first works, for instance by Li et al., where they have demonstrated that low carbon solubility of copper at high temperatures decreases the precipitation on the surface and allows more uniform single-layer graphene to grow [19]. Figure 8 is a schematic illustration of the difference in graphene growth process originating between Ni and Cu: Graphene growth on Cu is attributed to the surface adsorption mechanism of carbon atoms on the copper surface. The stable electronic configuration of Cu makes its interaction with carbon atoms in the form of weak forces, which decreases the bulk diffusion of carbon atoms into the Cu substrate. That gives copper an advantage in growing single-layer graphene, as the process mostly proceeds on the surface. [23].
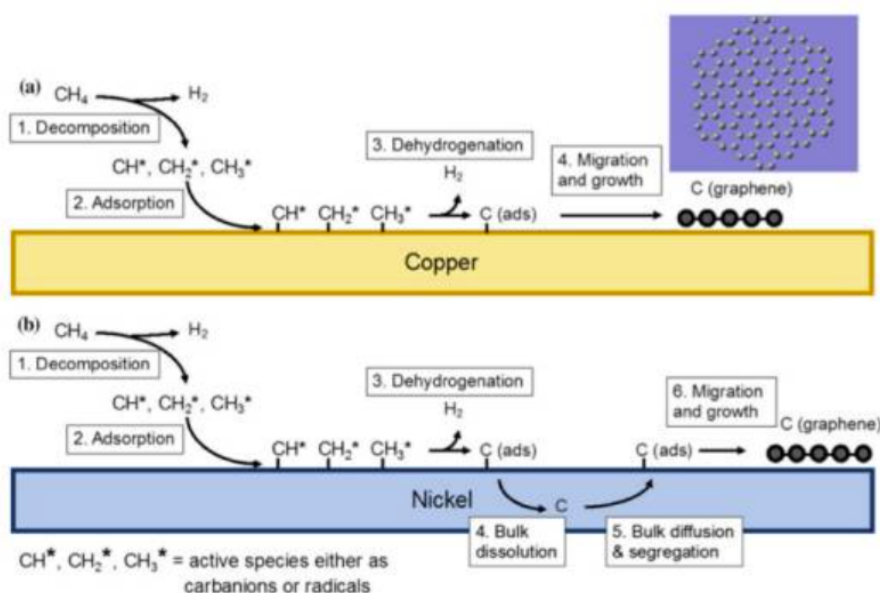
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Figure 8: Difference in graphene growth processes between (a) Cu and (b) Ni substrates. Surface diffusion occurs on Cu substrate while bulk diffusion and precipitation occurs on Ni [2]

In brief, it is now possible to summarize the growth mechanism of graphene on catalytic metal substrates. The decomposition of $CH_4$ in the CVD reactor is highly complex and can involve numerous chain reactions. In the absence of a catalyst, $CH_4$ can react in the gas phase either by pyrolysis or via chain reactions if the temperature is sufficiently high to assist thermal decomposition and when $P_{CH_4}$ is high. Reactions within the gas phase supply $CH_3$, $H_2$, $H$, and $C_2H_x$ (x = 1–6). [19]. In the case of Cu substrate, $CH_4$ is considered to be thermally and catalytically decomposed on the substrate because Cu is a well-known dehydrogenation catalyst. The catalytic decomposition of $CH_4$ involves its initial absorption and the final product in the form of one carbon atom and four hydrogen atoms on the surface of Cu substrate through three kinds of intermediates which are methyl ($CH_3$), methylene ($CH_2$) and methylidyne ($CH$). [41]:

$$CH_4 \rightarrow CH_3^* + H$$
$$CH_3 \rightarrow CH_2^* + H$$
$$CH_2 \rightarrow CH^* + H$$
$$CH \rightarrow C + H$$
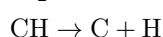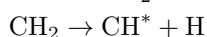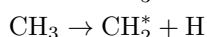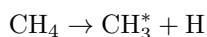
Interestingly, it is found that substrate thickness can affect the number of layers of graphene grown on the substrate. Growing graphene on different thicknesses of Cu substrates, Yilmaz and Eker have shown that the grain size of the substrate decreases with an increase in the substrate's thickness [1]. In the thickness range of 9–250 µm, the results of single-layer graphene grown on all substrates show that 150 µm gave the best quality graphene, while the other substrates had few-layer graphene in addition.

While the authors only show the difference with increasing thickness, they do not explain why the best results were obtained with a substrate at 150 µm rather than the substrate at 250 µm. The authors did mention that the increasing thickness within the substrate corresponds to micro-strain decrease, which was told to be crucial for single-layer graphene growth. Nguyen et al. used a quartz cap to cover the substrate to minimize impurities issuing, as they said, from the bulk of the substrate as well. [9].

# Conclusion:

Graphene stays at the heart of material science research due to its unmatched combination of remarkable properties: exceptionally high electrical conductivity, remarkable mechanical strength, and very good thermal conductivity. In the last two decades, important progress has been made both in the understanding of its atomic structure and in synthesizing high-quality graphene at an industrially relevant scale. Of these, techniques such as CVD and electrochemical exfoliation are among the most promising, yet considerable barriers to manufacturing in a cost-effective, defect-free manner remain. The versatility of graphene, nonetheless, allows for numerous applications: in electronics, energy storage, and composite materials.

In the future, synthesis techniques should be optimized, targeting quality and scalability, reducing production costs. Further research into developing the limitation factors in present methods will enable successful applications based on graphene in the near future. With deeper understanding, graphene is going to revolutionize many industries and therefore stands as one of the most important materials for further technological advancement.

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