Graphene Synthesis and Its Implications on Electrical Properties: A Comparative Study

Síntese de grafeno e suas implicações nas propriedades elétricas: Um estudo comparativo

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ABSTRACT

Abstract: This study investigates the impact of graphene synthesis techniques such as chemical exfoliation, chemical vapor deposition (CVD) and liquid phase exfoliation (LPE) on electrical conductivity. The objective is to understand how variations in synthesis methods influence the morphology of graphene and, consequently, its electrical characteristics. Synthesis techniques are explored in detail to identify how each process affects the structure and electrical performance of graphene. The results indicate that chemical exfoliation introduces more defects into the graphene structure, potentially reducing its electrical conductivity, while the CVD method tends to produce graphene with greater uniformity and superior conductivity. LPE, on the other hand, offers a balance between quality and production efficiency, making it particularly promising for large-scale applications. The study provides valuable information for selecting synthesis methods based on specific graphene application requirements. The findings could facilitate the development of more efficient materials for advanced electronics, contributing to the optimization of industrial graphene production processes and promoting significant advances in materials technology.

Keywords: Graphene; Graphene oxide; Graphene film; Electrical conductivity.

RESUMO

Resumo: Este estudo investiga o impacto de técnicas de síntese de grafeno, como esfoliação química, deposição química de vapor (do ingês, Chemical Vapor Deposition CVD) e esfoliação em fase líquida (do ingês, Liquid Phase Exfoliation - LPE) na condutividade elétrica. O objetivo é compreender como variações nos métodos de síntese influenciam a morfologia do grafeno e, consequentemente, suas características elétricas. Técnicas de síntese são exploradas detalhadamente para identificar como cada processo afeta a estrutura e o desempenho elétrico do grafeno. Os resultados indicam que a esfoliação química introduz mais defeitos na estrutura do grafeno, reduzindo potencialmente sua condutividade elétrica, enquanto o método CVD tende a produzir grafeno com maior uniformidade e condutividade superior. O LPE, por outro lado, oferece um equilíbrio entre qualidade e eficiência de produção, tornando-o particularmente promissor para aplicações em larga escala. O estudo fornece informações valiosas para a seleção de métodos de síntese com base em requisitos específicos de aplicação de grafeno. As descobertas poderão facilitar o desenvolvimento de materiais mais eficientes para eletrônica avançada, contribuindo para otimização dos processos industriais de produção de grafeno e promovendo avanços significativos na tecnologia de materiais.

Palavras-chave: Grafeno; Óxido de grafeno; Filme de grafeno; Condutividade elétrica.

INTRODUÇÃO

The process of obtaining graphene is a critical factor that directly influences its electrical properties and the viability of its application on an industrial scale (Neto et al., 2009). Methods such as chemical exfoliation, chemical vapor deposition (CVD), and liquid phase exfoliation have been extensively studied to optimize the quality and characteristics of the produced graphene. Each technique has specific advantages and limitations that affect the structure, purity, and consequently, the electrical properties of the final material (Li et al., 2009). The electrical conductivity of graphene, in particular, is of great interest as it can be extensively modified and adapted through different synthesis methods and post-synthesis treatments (Novoselov et al., 2004).

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This article provides a comparative review of the most common methods of obtaining graphene, focusing on the relationship between synthesis techniques and the resulting electrical properties. Through the analysis of conductivity, resistance, resistivity, and other electrical metrics, we seek to establish a clear understanding of how different processes impact graphene's performance e (Rezaei; Kamali; Kamali, 2020). Additionally, we will discuss the measurement and characterization techniques that are crucial for assessing these properties. The in-depth understanding gained from this study aims to provide guidelines for choosing suitable synthesis methods for specific graphene applications, as well as to promote the development of more efficient and economical manufacturing processes.

BACKGROUND

Mechanical and Chemical Exfoliation

Mechanical and chemical exfoliation are two fundamental methods for obtaining graphene and graphene oxide from graphite (Stankovich et al., 2006). Each method has

specific variations, such as the Brodie, Staudenmaier, and Hummer methods, which mainly differ in the chemical reagents used and the subsequent treatment of the graphite.

The Brodie method, developed in 1859, was one of the first techniques for oxidizing graphite, using nitric acid and potassium chlorate. This method was less efficient compared to later developments, but it laid the groundwork for modern techniques of chemical exfoliation of graphite (Ikram & Jan, 2020).

Introduced by Hummer and Offeman in 1958, the Hummer Method is widely used due to its efficiency and relative safety. It uses a mixture of sulfuric acid, sodium nitrate, and potassium permanganate to oxidize the graphite. This method not only improved the efficiency of oxidation but also significantly reduced the risks associated with handling chemical reagents (Ikram & Jan, 2020).

Chemical methods, such as the Hummer method, tend to introduce more defects due to oxidation, while mechanical exfoliation can better preserve the structure of the graphene, although the distribution of sheet sizes may be less controllable. The detailed analysis by Casallas-caicedo et al. (2019) on different exfoliation methods highlights the importance of selecting the appropriate method based on the desired final application of the graphene.

Chemical Vapor Deposition (CVD)

Chemical Vapor Deposition (CVD) is one of the most effective methods for producing high-quality graphene on an industrial scale. Figure 1 illustrates the process of obtaining graphene by CVD. Hydrocarbon precursor gases enter the equipment and, in the internal chamber, are decomposed under heat. The resulting carbon atoms reorganize and deposit themselves on a heated metallic substrate (usually copper or nickel), catalyzing the formation of a graphene monolayer. The quality of graphene produced by CVD depends on several process parameters, including deposition temperature (Pedrazzetti, et al., 2017), system pressure and gas composition (Ta et al., 2017); (Cho et al., 2019), (Sirat et al., 2017), deposition time (Liu et al., 2011) and substrate.

**Figure 1.** Schematic diagram of the CVD system and growth mechanism of graphene on metallic substrate.

Source: Yao et al., (2022)

Variations in CVD parameters have a significant impact on the electrical properties of graphene. The crystalline quality of graphene, which is strongly influenced by temperature and gas conditions, determines electron mobility, a key metric for electronic applications. Graphene with low levels of defects and atomic disorder exhibits superior electron mobility, which is crucial for high-performance electronic devices.

Liquid Phase Exfoliation (LPE)

Liquid Phase Exfoliation (LPE) is a versatile and promising method for the production of graphene, notable for its ability to produce large quantities of graphene efficiently and at relatively low cost. This method involves dispersing graphite in appropriate solvents to mechanically or chemically exfoliate the layers of graphene (Lotya, et al., 2009). The figure below illustrates the steps for obtaining graphene by exfoliation in the liquid phase. As illustrated in the ultrasonic exfoliation step (Figure 2).

Figure 2. Stages of obtaining graphene in liquid phase.
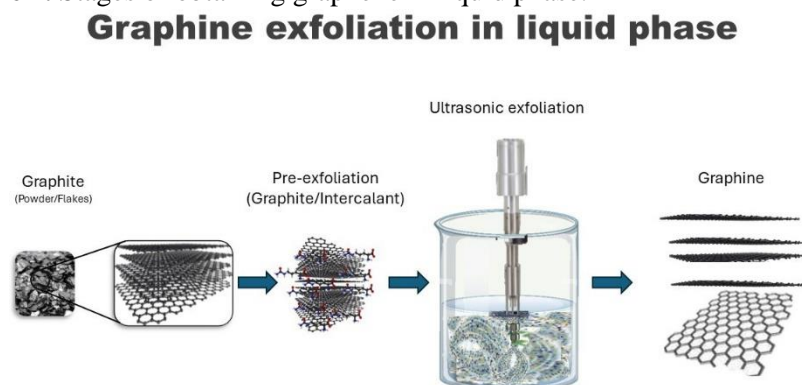
Source: Simao; Neves (2018)

The effectiveness of LPE in graphene production is significant, offering several advantages over other synthesis methods. In this sense, Figure 3 evaluates some of the general aspects of graphene obtained by exfoliation in the liquid phase, among these aspects were evaluated: in terms of graphene quality (G), cost aspect (C; a low value corresponds to high production cost), scalability (S), purity (P) and yield (Y) of the overall production process (Y) (Xu, et al., 2018).

Figure 3. Pentagonal radar plot of LPE method: quality (G), cost (C), scalability (S), purity (P) and yield (Y).
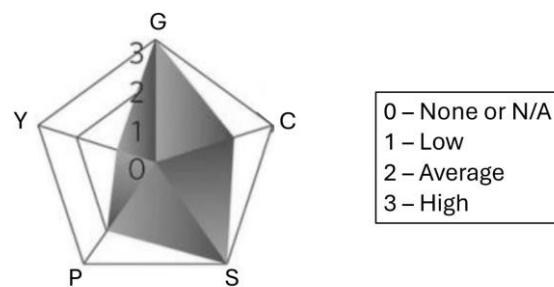
Source: Xu, et al. (2018)

The studies analyzed demonstrate that, although LPE offers a promising pathway for graphene production, the selection of suitable solvents and the optimization of processing conditions are essential to maximize the quality and yield of the produced graphene. These advancements continue to open new possibilities for the application of graphene in various fields, from electronics to advanced composites and new materials (Alaferdov et al., 2014; Li et al., 2020).

Graphene structure

The structure of graphene (monolayer) consists of a single plane of carbon atoms positioned at the vertices of hexagons. Each atom forms covalent bonds with three other atoms, sharing three of the four electrons from their 2s and 2p orbitals. These bonds are extremely robust, giving graphene remarkable structural stability. The fourth electron of each atom can occupy positions above or below the plane, allowing for great mobility in two dimensions. These free electrons have the ability to conduct heat and electricity (Hashimoto et al., 2004).

-The method used to obtain graphene can influence the generation of defects in its structure and, consequently, its electrical, optical, thermal, and mechanical properties

(Hernandez et al., 2008), as the method of graphene production affects the final sp^2 structure. To achieve better properties, graphene needs to be obtained in one or few layers. However, conventional methods for obtaining graphene inevitably introduce defects in its structure.

-Some of these defects are 'intrinsic' ripples with dimensions between 8-10 nm laterally and 0.7-1.0 nm in height on the graphene sheet observed by transmission electron microscopy (TEM) (Inkson, 2016). Other defects such as pentagons, heptagons and their combinations, vacancies, adatoms, edge dislocations, grain boundaries, cracks, surface impurities, presence of functional groups on the flakes, among others, can also be found (Jiang et al., 2014).

In the production of graphene by mechanical or chemical exfoliation techniques, there is typically a variation in the thickness and diameter of the flake. This prevents the production of graphene with small areas and often results in folds at the edges (Johra; Lee; Jung, 2014). In these areas, there is a deviation in the coordination number of the crystal arrangement, resulting in excess energy and stress in the structure (MA et al., 2022a). In this type of preparation, environmental conditions may result in the presence of air-transported impurities. Meanwhile, the CVD method can generate many wrinkles, vacancies, and grain boundaries, which limit the electrical conductivity of graphene (Zhang; Xin; Ding, 2013a).

Electrical Properties

High Electronic Mobility: Electrons in graphene move with exceptional mobility, 100 times greater than in silicon (Novoselov et al., 2004). This property makes it ideal for high-speed, low-power electronic devices (Geim; Novoselov, 2007).

Adjustable Semibandgap: Unlike other semiconductors, graphene has an adjustable semibandgap, which means its electrical conductivity can be modulated through chemical doping or an electric field (Ma et al., 2022b; (Han et al., 2017). This property makes it ideal for a wide range of electronic devices, such as transistors and diodes (Xu; Cao; Heath, 2009).

Optical Transparency: Graphene is a transparent material, transmitting up to 97% of visible light (Novoselov et al., 2004). This property makes it ideal for transparent touch screens and transparent electrodes in solar cells (liu2020, han2017).

Chemical Properties

Chemically Stable: Graphene is chemically stable and corrosion-resistant, making it ideal for applications in harsh environments (Zhang et al., 2010), Biocompatible (Xu et al., 2009); Versatile Functionalization (Liu, 2019).

The exceptional properties of graphene make it a promising material for various innovative applications across different fields, such as electronics, nanotechnology, biomedicine, and energy. The combination of its unique mechanical, electrical, chemical, and optical properties open up a range of possibilities for the development of new devices and materials with innovative and revolutionary features.

Main Characterizations

Raman

Raman spectroscopy is a widely used technique for characterizing graphene and graphene oxide, identifying bond types, and determining crystal lattice disorder. The Raman spectra of carbonaceous materials show characteristic peaks between 1000 and 1800 cm^{-1}, dominated by three main bands: G, D, and D' bands, with visible and infrared excitation energy peaks (Camargos et al., 2017). As illustrated in Figure 4.

Figure 4. Raman spectra and typical graphene bands.
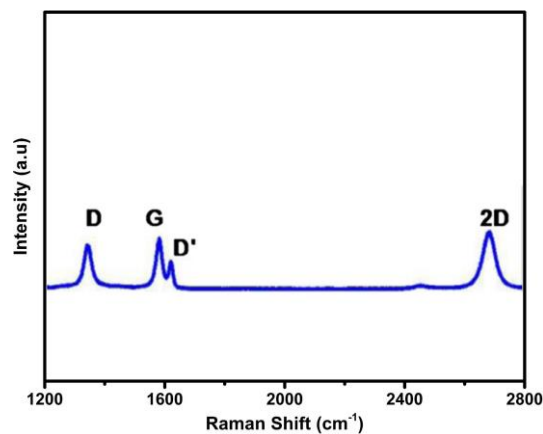
Source: Zafar (2013)

The G band in Raman spectroscopy indicates the type of graphene, while the D band indicates disorder due to defects in the carbon ring structure. The D' band provides additional information about the material's structure and defects. Other peaks, such as the 2D band, reveal the number of graphene layers. Analyzing these bands provides detailed information about the structural and electronic properties of graphene. (Lobo et al., 2005).

With the power of Raman spectroscopy, scientists continue to uncover the secrets of graphene and its derivatives, paving the way for a future filled with technological innovations and transformative applications across various fields of knowledge (Nanda, et. al., 2016).

Electron Microscopy

Electron Microscopy (EM), including Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM), are widely used techniques for the characterization of various materials, particularly graphene (Bachmatiuk et al., 2015; Inkson et al., 2016).

Figure 5. (a) MEV da estrutura da folha de grafeno. (b) TEM da estrutura hexagonal da nanofolha de grafeno. (c) Micrografias HRTEM da estrutura multicamadas.
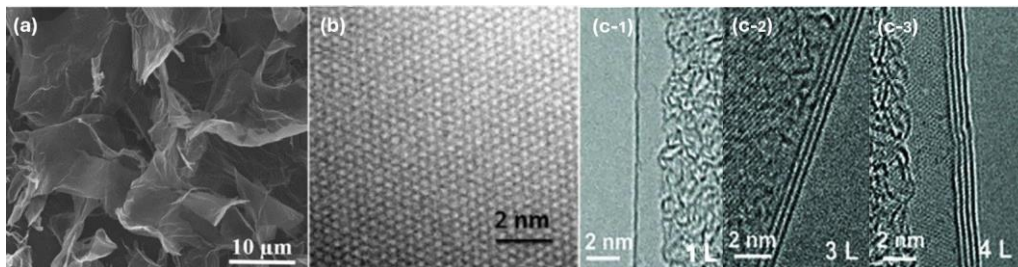
Source: Yasin (2018); Zafar (2013); Adetayo; Runsewe, et al. (2019)

SEM provides high-resolution images of the graphene surface, revealing details of the topography, roughness, and presence of defects such as folds, wrinkles, and holes (Figure 5 (a)). On the other hand, TEM enables a more detailed analysis of the internal structure and thickness of graphene sheets and their structures (Figure 5 (b and c)). This technique allows for the visualization of defects, folds, and multilayers in graphene sheets and their variations (Mbayachi, et al., 2021).

TEM is commonly employed in conjunction with SEM to obtain a comprehensive morphological and structural characterization of graphene-based materials. In summary, SEM and TEM are essential tools for the detailed characterization of the morphology, structure, and composition of graphene and its derivatives, providing crucial information for the development and application of these advanced materials (Shen; Oyadiji, 2020).

X-Ray Diffraction (XRD)

X-ray diffraction (XRD) is a non-destructive analytical technique used to characterize crystalline materials. It allows the determination of atomic and molecular

structures, phase identification, and detection of defects in the crystal lattice. This versatile technique plays a fundamental role in various fields of knowledge, from materials science to chemistry, being used for the study of defects and imperfections, phase and compound identification (Silva, 2020).

Figure 6. XRD spectra: (1) Graphite; (2) Graphene oxide(GO); (3) Reduced graphene oxide (rGO) and (4) Graphene.
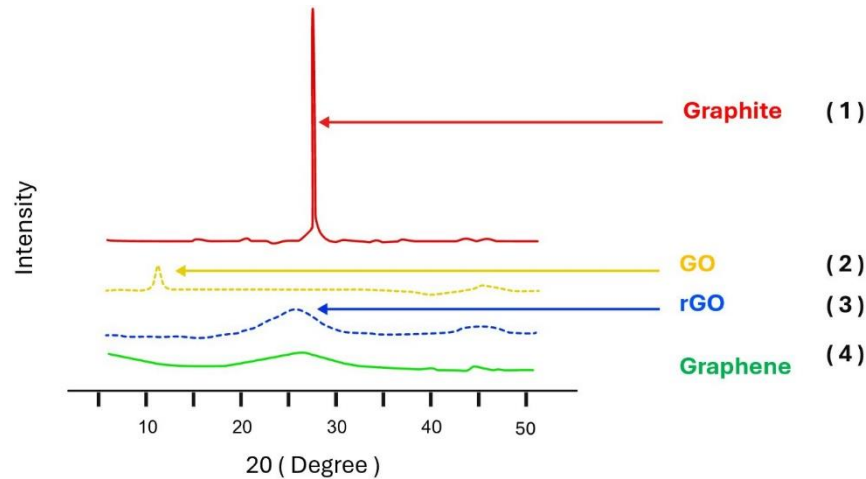
Source: Johra, Lee, Jung, (2014); Tiwari et al. (2020)

Pure graphene has a weak XRD signal, which makes it useful for studying the stacking order in multilayer graphene and graphene films. Figure 6 shows the XRD spectrum of graphite, GO, rGO and graphene. The diffractogram reveals a sharp diffraction peak at 26.6°, indicating a well-defined crystalline structure of graphite (Figure 6 (1)), GO shifts to 10° (Figure 6 (2)), the rGO is observed at the position of 24.8° (Figure 6 (3)) and graphene has a peak at 25.4° (Figure 6 (4)) with lower intensity (Yasin, 2018).

Methods for obtaining graphene and its influence on electrical properties

The production of graphene from graphite by chemical exfoliation or by oxidation-reduction is referred to by the methods of Brodie (Chernova et al., 2023), Staudenmaier (Sheshmani; Fashapoyeh, 2013), and Hummer (Hack et al., 2018). All three methods involve varying levels of graphite oxidation. Brodie and Staudenmaier used a combination of potassium chlorate ($KClO_3$) with nitric acid (HNO_3), while the Hummer method involves treating graphite with potassium permanganate ($KMnO_4$) and sulfuric acid (H_2SO_4).

In addition to the chemical exfoliation method for obtaining graphene, other methods are reported in the literature, such as chemical vapor deposition (CVD) and liquid phase exfoliation (LPE) (Liu et al., 2022). Compared to the other two methods (CVD and liquid exfoliation) for obtaining graphene, the Hummer method stands out for its relatively low production cost, simple operation, speed, safety, lower pollutant generation, and high yield of around 92.2% graphite powder mass (Zhu et al., 2010; (Alshamkhani et al., 2021).

The reduction process of oxidation begins with the reaction of natural graphite with strong acid and powerful oxidizing agents while in ultrasonic dispersion. Subsequently, the oxygenated groups of graphene oxide are removed from the surface through the addition of a reducing agent, resulting in the production of reduced graphene (Kavyashree et al., 2020). Figure 7 shows the forms of graphene.

Figure 7 – (a) Graphene, (b) Oxide graphene, (c) Reduced graphene.
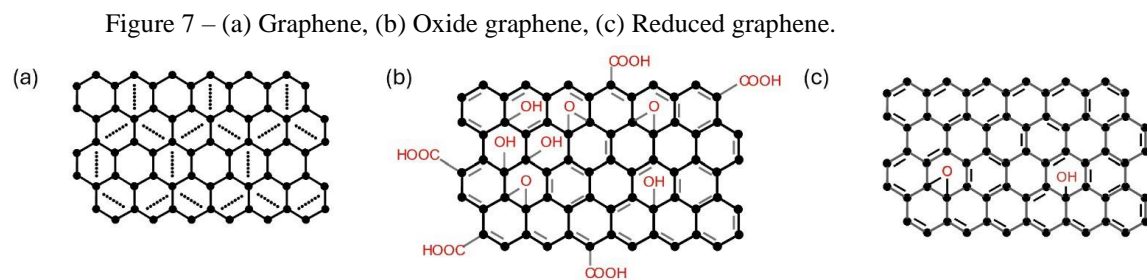
Source: Lalire; Longuet; Taguet, (2024)

The structure of monolayer graphene consists of a single carbon atom positioned on hexagonal vertices. Each atom forms covalent bonds with three other atoms, sharing four electrons in their orbits. These strong bonds provide structural stability, with the fourth electron occupying positions above or below the plane (Rezende, 2014).

Figure 8. Defects in the graphene sheet structure.
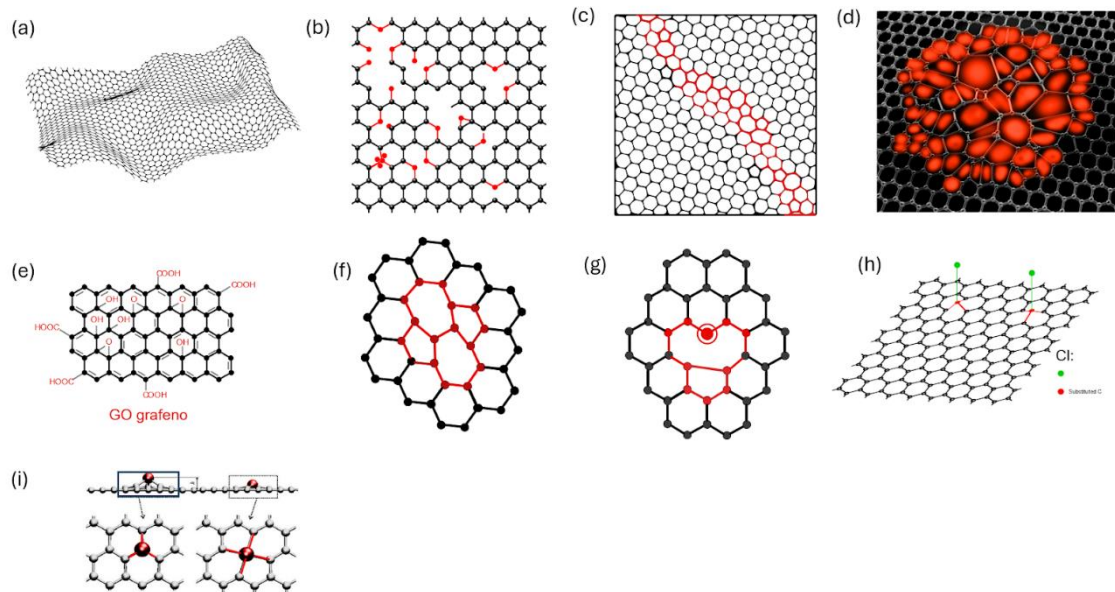
Source: Biró; Lambin (2013); Andrei; Li, Du (2013); Yang, et al. (2018); Bhatt; Kim; Kim (2022)

In Figure 8 (a) Edges of graphene sheets show folds and wrinkled sheets. (b) Formation of a hole in a suspended graphene layer. (c) Graphene sheets displaying grain boundaries. (d) Nanobubbles are present in graphene sheets. (e) GO consists of a random distribution of oxidized areas with oxygen-containing functional groups combined with non-oxidized regions where most carbon atoms maintain sp^2 hybridization. (f) Stone-Wales defect (SW), formed by the rotation of a carbon-carbon bond by 90. (g) Single vacancy (SV) in the lattice refers to a single missing atom. (h) sp^3 defects produced by graphene chlorination. (i) Transition-metal (TM) atoms adsorbed on a perfect graphene sheet (adatoms).

In the process of obtaining graphene through mechanical or chemical exfoliation, there is typically variation in thickness and flake diameter. This results in graphene with small areas and folds at the edges (Jiang et al., 2014). These areas exhibit a deviation in the coordination number of the crystal arrangement, leading to excess energy and structural stress (Qi; Cao; Park, 2013). In such preparations, environmental conditions can result in the presence of airborne impurities. On the other hand, the CVD method can generate wrinkles, vacancies, grain boundaries, which limit the electrical conductivity of graphene (Zhang; Xin; Ding, 2013b).

Influence of the Chemical Exfoliation Method on Graphene Conductivity

Boychuk et al. (2019) studied the structure, morphology, and electrical conductivity of graphene oxide using Hummer GO(H) and Marcano-Tour GO(MT) methods. The electrical conductivity of GO(H) graphene was 0.02 S m^{-1} and 0.08 S m^{-1} at room temperature and 1000 Hz. The change in conductivity corresponds to charge hopping transfer mechanisms.

The study by Clifford et al. (2024) used the liquid phase exfoliation (LPE) method to produce graphene. The product was then centrifuged at different speeds, with the lowest speed yielding smaller nanosheets (200 nm). The conductivity of the graphene was measured, with the lowest speed resulting in a maximum conductivity value of 2.8 x 10^4 S m^{-1}. The research highlights the potential of LPE in producing graphene.

Xiong and colleagues' (2017) study on chemical exfoliation of graphene revealed that agitation during the process affects the efficiency of sulfuric acid intercalation between layers of graphite in the oxidation of potassium permanganate and the reducing agent graphene oxide. They produced graphene oxide dispersion using stirring at 100, 300 and 500 r min^{-1} and measured its electrical resistivity. The study found that the speed of 300 r min.$^{-1}$ showed better electrical conductivity (47.8 .m / 0.0209 S m^{-1}).

Deemer et al. (2017) also studied the influence of functionalization and the diameter of the precursor graphite on the exfoliation and conductivity of the graphene obtained by the modified Hummer and Marcano-Tour methods. Both methods used ascorbic acid (L-AA) and aqueous ammonia for pH adjustment as reducing agents.

Table 1, the conductivity of GO by the modified Hummer and Marcano-Tour methods is shown, taking into account the diameter of the precursor graphite (diameters Ø <100 m and Ø >420 m). Using FTIR and TGA characterization, they observed that the precursors with larger diameters (Ø >420 m) exhibited greater oxidized regions of the flakes and less resistance between the sheets.

Tabela 1 – Conductivity of GO obtained by modified Hummer and Marcano-Tour methods.

Synthesis Method	recursor graphite diameter (Ø / μm)	Conductivity (S cm⁻¹)
Modified Hummer	<1000	0,51
Modified Hummer	>420	52,6
Marcano-Tour	<100	0,53
Marcano-Tour	>420	16,7

Source: Deemer et al. (2017)

Ridzuan et al. (2021) produced graphene oxide using the modified Hummer method for sensor applications. They mixed graphene oxide with silver nanoparticles in a PMMA matrix, producing PMMA-GO and PMMA-Ag-GO nanocomposites. PMMA-Ag-GO nanocomposites showed higher electrical conductivity (3.71×10^{-10} S cm^{-1}).

Influence of Thermal Reduction on the Conductivity of Graphene via Chemical Exfoliation

The study by Acik and Chabal (2013) found that annealing heat treatment significantly reduced the oxygen content in graphene oxide (GO) structure. Yong-zhen et al. (2012) used the modified Hummer method to produce graphene oxide films with controllable size. They used vacuum annealing heat treatment, placing the GO film in a quartz tube under vacuum and maintaining a constant temperature for 1 hour. The heat treatments were carried out at temperatures ranging from 200 to 1100 °C, as indicated in Table 2.

Table 2 – Effect of heat treatment on conductivity of GO film.

Condition (No.)	recursor graphite diameter (Ø / μm)	Conductivity (S cm⁻¹)
1	200	$1{,}94 \times 10^{-1}$
2	300	$2{,}00 \times 10^{0}$
3	400	$7{,}91 \times 10^{0}$
4	500	$6{,}58 \times 10^{0}$
5	600	$6{,}33 \times 10^{0}$
6	700	$9{,}98 \times 10^{0}$
7	800	$2{,}57 \times 10^{1}$
8	900	$2{,}78 \times 10^{1}$
9	1000	$1{,}43 \times 10^{2}$
10	1100	$5{,}36 \times 10^{2}$

Source: Yong-zhen et al. (2012)

In Table 2, it is observed that conductivity increases as the temperature of the heat treatment increases. This behavior in conductivity was attributed to the removal of some oxygen-containing functional groups in the film, which led to the reduction of some sp^3 carbon atoms to sp^2 carbon atoms.

Other studies have utilized the reduction of GO by heat treatments and have examined its influence on conductivity, such as the work of (Vianelli et al., 2015) who produced OG by the modified Hummer method. They conducted high vacuum annealing heat treatments at various annealing temperatures for 1 hour. The conductivity values are shown in Table 3, in ascending order of temperature and conductivity, it is noted that with the increase in annealing, the conductivity of GO increased. With reduced GO, the sp^2 conjugated network is restored, but high temperatures can induce structural defects.

Table 3. Effect of Annealing Temperature on GO Conductivity.

Condition (No.)	recursor graphite diameter (Ø / μm)	Conductivity (S cm⁻¹)
1	200	27.24
2	300	282.48
3	500	943.39
4	600	2.994.01
5	700	5.874.95
6	940	9,803.92

Source: Vianelli et al. (2015)

Maraschin et al. (2018) obtained graphene oxide from graphite powder using a modified Staudenmaier method. They used sulfuric acid, nitric acid, potassium chlorate, and hydrochloric acid to remove sulfate ions. The suspension was dried in a muffle furnace and heated to 1000 °C. The electrical conductivity of graphene oxide and reduced graphene oxide was measured, with higher conductivity for rGO due to the reduction process, and results of 60 S cm^{-1} were obtained. Table 4 presents a summary of the electrical conductivity values obtained by the chemical exfoliation method.

Table 4. Data from work on obtaining graphene by chemical exfoliation

Obtaining method	Condutividade (S m^{-1})	Author
Chemical exfoliation (Hummer)	2.0×10^{-2}	Boychuk et al. (2019)
Chemical exfoliation (Marcano-Tour)	8.0×10^{-2}	Boychuk et al. (2019)
Liquid phase exfoliation (LPE)	2.8×10^{4}	Clifford et al. (2024)
Chemical exfoliation (Hummer)	2.0×10^{-2}	Xiong; Huang; Wei, (2017)
Chemical exfoliation (Hummer)	1.5×10^{-3}	Zapata-hernandez et al. (2022)
Chemical exfoliation (modified Staudenmaier Method)	9.8×10^{3}	Ridzuan et al. (2021)
Obtaining method	**Condutividade (S cm^{-1})**	**Author**
Chemical exfoliation (Marcano-Tour)	1.6×10^{1}	Deemer et al. (2017)
Chemical exfoliation (Hummer)	5.2×10^{1}	Deemer et al. (2017)
Chemical exfoliation (modi-fied Stau-denmaier Method)	6.0×10^{1}	Maraschin et al. (2018)

Influence of the Chemical Vapor Deposition (CVD) method on graphene conductivity

CVD is the most effective method for producing high-quality graphene films, but challenges remain in synthesis and transfer methods to maintain film quality.

Vassiouk et al. (2011) studied graphene production using CVD, focusing on thermal and electrical properties and disorder. They found that low deposition temperature significantly affects disorder, despite its gradual increase, it exhibits high thermal conductivity (10^2-10^3 W K^{-1} m^{-1}) and low electrical resistivity (10^3−3 x 10^5).

Cao et al. (2019) found that incorporating graphene into metals such as Cu, Al and Ag found to have an electrical conductivity 3000 times higher than most pure metal conductors at room temperature. The graphene used as reinforcement had a conductivity of 117%, 58.1 x 10^6 S m^{-1} for the Gr/Cu composites with the thinnest Cu layers.

Park et al. (2016) presented a way to improve the electrical performance of graphene by controlling the density and height of wrinkles after transferring to SiO$_2$/Si substrates, varying the cooling rates during manufacturing. This route improved the electrical properties, such as higher electron/hole mobility, in addition to reducing the sheet resistance.

Table 5. Property data of graphene obtained by CVD.

Obtaining method	Properties	Author
CVD	Conductivity = 10^{-1} - 10^{-3} S m^{-1} S m^{-1}	Ramiréz et. al. (2023)
CVD	Electrical conductivity of xy = $58,1 \times 10^6$ S m^{-1}	Cao et. al. (2019)
CVD	High thermal conductivity = 10^2-10^3 W K^{-1} m^{-1}; Low electrical resistivity = 10^3-3 x 10^5	Vlassiouk et. al. (2011)
CVD	Electrical conductivity of monolayer graphene flakes = $1,46 \pm 0,82 \times 10^6$ S m^{-1}; Condutividade elétrica de flocos de rGO = $2,3 \pm 1,0$ S m^{-1}	Lim et. al. (2021)
CVD	Sheet resistance = 600 sq^{-1}; Transmittance (550 nm) = 96,5%; Carrier mobility = 5080.5 cm^2 V^{-1} s^{-1}	Zhang et. al. (2012)

DISCUSSIONS

Perspectivas Futuras:

– New synthesis techniques: Vlassiouk et al. (2011), (Cao et al., 2019), and Alshamkhani et al. (2021) suggest the development of new graphene synthesis techniques, such as methods based on ionic liquids or plasma synthesis, which can overcome the limitations of current methods and enable large-scale production of high-quality material.

– Improvement of transfer techniques: Park et al. (2016) propose the enhancement and development of more efficient transfer techniques, such as dry methods or polymer-based methods, which can minimize damage to the graphene structure and facilitate its integration onto various substrates.

– Interface engineering: Vlassiouk et al. (2011) highlights that engineering the interfaces between graphene and other materials can significantly improve its properties and pave the way for new applications.

– Advanced functionalization: Park et al. (2016) suggest the development of new functionalization strategies, such as click chemistry or in-situ polymerization, which can

provide greater control over graphene's properties and adapt it to even more demanding applications.

– Comprehensive safety evaluation: Cao et al. (2019) emphasize the importance of in-depth studies on the long-term safety and toxicity of graphene, which are essential to ensure its safe use in products and devices.

Regarding the methods of obtaining graphene, CVD is the most efficient method for producing high-quality graphene, but concerns about toxicity, stability, and environmental impact need to be addressed. Research is ongoing to optimize growth methods for large-scale applications in electronic devices, such as ultra-thin flexible screens, smartphones, biosensors, nanorobots, and light cables in aircraft and satellites. The industry's high demand for graphene in these applications makes it a promising area of study.

Despite challenges in achieving graphene's full potential, continuous research and development can unlock its transformative potential in various sectors, including electronics, medicine, and energy, paving the way for a sustainable, technological, and prosperous future.

Conclusion

Graphene emerges as a revolutionary material, opening doors to a future filled with promising possibilities. Through a thorough analysis of the methods of obtaining it and their impacts on electrical conductivity, this work offers a comprehensive view of graphene's potential to transform various areas. Chemical exfoliation, a traditional method, has advantages such as simplicity and low cost, but faces challenges in the homogeneity and control of the graphene structure. On the other hand, chemical vapor deposition (CVD) stands out to produce high-quality films but requires improvements in synthesis and transfer to preserve the material's integrity. The search for optimized methods and the exploration of innovative applications are crucial areas for the advancement of graphene. The incorporation of graphene into metals demonstrates the potential to significantly increase electrical conductivity, paving the way for a new era of energy efficiency. Precise control of graphene's structure allows the improvement of its electrical properties, paving the way for next-generation electronic devices. However, there are still challenges to be overcome, such as the large-scale production of high-quality graphene and the economic viability of its application in various areas. Continuous

research and development are essential to overcome these obstacles and unlock the full potential of graphene. The future of graphene is promising, with applications extending from electronics and photonics to medicine and energy. It is crucial to continue investing in research and innovations to explore the full potential of this revolutionary material and build a more sustainable and technological future.

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