

Monolayer Amorphous Carbon: Synthesis, Properties, and Emerging Applications of a Novel Two-Dimensional Carbon Allotrope

Chen Meng ^{1,†}, Jiarui Zhang ^{1,†} and Jing Li ^{2,*}

¹ State Key Lab of New Ceramic Materials, School of Materials Science and Engineering, Tsinghua University, Beijing 100084, China

² Beijing Building Materials Academy of Sciences and Research, Beijing 100041, China

* Correspondence: lj02041988@163.com

† These authors contributed equally to this work.

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Abstract: Monolayer amorphous carbon (MAC) has emerged as a novel two-dimensional carbon allotrope with unique structural and functional properties, distinguishing it from crystalline counterparts like graphene. Unlike conventional carbon materials, MAC exhibits an atomically thin yet disordered atomic arrangement, offering tunable mechanical, electronic, and thermal properties. This review comprehensively summarizes recent advancements in MAC research, covering its synthesis strategies, fundamental characteristics, and diverse applications. Key synthesis methods, including chemical vapor deposition and solution-phase approaches, enable precise control over the disorder degree and functionality of MAC, while its exceptional toughness, adjustable conductivity, and thermal stability position it as a promising material for next-generation electronics, flexible devices, and nanofiltration technologies. Challenges and future directions, such as elucidating structure-property relationships and scalable production, are also discussed.

Keywords: monolayer amorphous carbon; disorder engineering; tunable properties

1. Introduction

Carbon materials have long occupied a central position in materials science, from graphite and diamond to fullerenes, carbon nanotubes, and the two-dimensional material graphene (Figure 1). Each of these allotropes exhibits distinct physicochemical properties that enable diverse applications, including battery electrodes [1], semiconductor devices [2] and biosensors [3]. In recent years, with the rapid advancement of material synthesis techniques, a novel carbon allotrope—monolayer amorphous carbon (MAC)—has emerged as a promising frontier in nanomaterials research. Unlike graphene, MAC features atomic-level thickness but possesses an amorphous atomic arrangement rather than a crystalline structure. This subtle yet critical structural distinction endows MAC with fundamentally different material characteristics, offering unique advantages in electronic devices, energy storage, and flexible electronics.

The emergence of MAC is an important event in materials science. While two-dimensional material studies have traditionally focused on crystalline systems such as graphene and transition metal dichalcogenides, amorphous 2D materials have remained relatively unexplored. The discovery of MAC has challenged this paradigm, not only expanding the family of 2D materials but also providing an unprecedented platform for investigating the fundamental properties of non-crystalline systems. Compared to three-dimensional amorphous carbon, the monolayer structure of MAC offers purer, more easily characterized properties [4]. In contrast to



graphene, its disordered atomic arrangement confers distinct properties, particularly in terms of tunable conductivity [5], adjustable ion transport [6], and mechanical resilience [7].

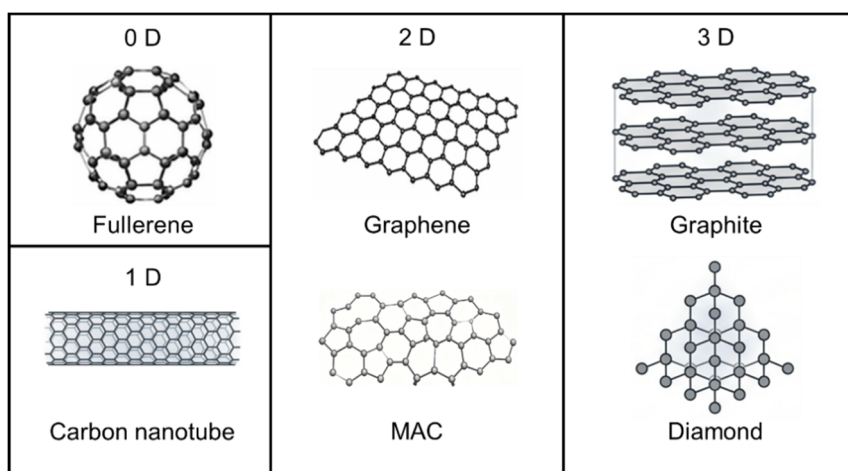


Figure 1. Carbon materials of different dimensions.

Various synthesis methods have been developed for MAC fabrication, including chemical vapor deposition (CVD) and solution-phase approaches, each offering distinct advantages for structural control and property optimization. The degree of disorder in MAC can be systematically modulated through precise tuning of growth parameters, allowing fine control over functional properties. This tunability makes MAC a versatile material with potential applications spanning electronic devices, biosensors, flexible electronics, and energy storage systems.

This review provides an overview of the current state of MAC research, encompassing its structural characteristics, synthesis strategies, properties, and emerging applications. We examine the fundamental differences between MAC and conventional carbon materials, analyze MAC's unique structure-property relationships, and highlight recent breakthroughs in MAC research. Furthermore, we discuss future research directions and technological prospects. By synthesizing current knowledge and identifying key challenges, this review aims to establish a foundational understanding of MAC and stimulate further exploration of this intriguing carbon allotrope.

2. Fundamental Properties and Structural Characteristics of MAC

2.1. Discovery and Structural Insights of MAC

MAC is a two-dimensional material composed of a single layer of carbon atoms arranged in a disordered configuration, exhibiting no long-range order—a striking contrast to the crystalline lattice of graphene [4] (Figure 2). The emergence of MAC stems from growing interest in amorphous 2D materials [8–11]. Materials scientists have sought to synthesize and characterize non-crystalline 2D systems, and the discovery of MAC has provided a crucial platform for such investigations [12–14].

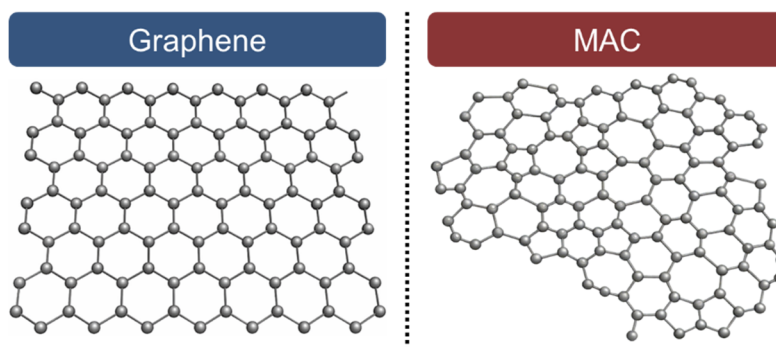


Figure 2. Structural comparison between graphene and MAC.

In materials science and condensed matter physics, understanding the relationship between atomic structure and macroscopic properties in amorphous materials has long been a fundamental challenge. Traditional 3D amorphous materials pose difficulties due to the complexity of precisely determining atomic positions. However,

2D systems offer a unique perspective by directly visualizing all atoms, thereby facilitating structural analysis [4]. Direct imaging of MAC has confirmed its atomic configurations, supporting modern grain-based theories over random network models, thereby providing key insights into the nature of glassy solids [5].

MAC research has evolved through improvements in both synthesis and characterization approaches. The large-scale synthesis of MAC was initially achieved through laser-assisted deposition [4]. Subsequently, CVD methods were successfully adapted for large-area MAC fabrication, advancing research progress in this field [5,15,16]. Advances in characterization techniques, particularly high-resolution electron microscopy, have further deepened our understanding of the microstructure of MAC, laying the foundation for elucidating its unique properties.

In addition to bottom-up synthesis, an alternative route to produce MAC-like materials proceeds via amorphization of crystalline graphene. In situ ion irradiation combined with electron diffraction and atomic-resolution STEM has enabled direct observation of the gradual loss of long-range order in suspended graphene sheets under irradiation, ultimately leading to a fully amorphous state [17]. This approach provided one of the earliest direct experimental demonstrations of the crystalline-to-amorphous transition in a two-dimensional carbon system, offering valuable insights into the structural evolution of disordered carbon monolayers. Such irradiation-induced amorphization studies complement bottom-up synthesis strategies and have contributed to the fundamental understanding of MAC formation mechanisms.

2.2. Structural Characteristics and Order Parameters of MAC

The structural features of MAC are crucial for understanding its unique properties. Unlike graphene's hexagonal lattice, MAC possesses an amorphous structure lacking long-range order (Figure 3). However, MAC is not completely random, exhibiting distinct medium-range order (MRO) characteristics [10,11]. In the study of amorphous materials, order beyond the nearest-neighbor coordination shell is typically categorized into short-range order (SRO) and MRO. While SRO refers to atomic arrangements at the interatomic distance scale, MRO extends to 0.5–2 nm and represents the structural organization beyond the first coordination shell [18]. In covalent amorphous solids, MRO has been shown to play a decisive role in determining macroscopic properties, as SRO alone is insufficient to explain behaviors such as glass stability against crystallization [19]. High-resolution electron microscopy observations reveal the presence of highly distorted nanocrystalline domains embedded within a continuous random network [4,20]. The existence and density of these domains serve as critical parameters for characterizing the disorder degree of MAC.

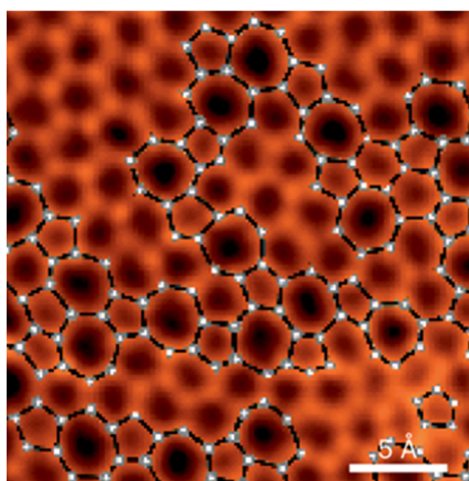


Figure 3. The atomic-resolution STEM-ADF image of MAC. Copyright 2025, Springer Nature [21].

The disorder level in MAC can be quantified by two order parameters: the presence of MRO and the temperature-dependent density of nanocrystalline domains. These parameters collectively form a conductivity map that directly correlates microscopic structure with electrical properties [5]. This discovery provides fundamental insights into the structure-property relationship of amorphous materials and establishes a theoretical framework for tuning the characteristics of MAC.

The structural characteristics of MAC also invite comparison with other amorphous two-dimensional systems. Kinetic Monte Carlo simulations have enabled a systematic comparison between elemental MAC and binary monolayer amorphous boron nitride (a-BN). The results reveal that the favored structure of elemental MAC is a crystallite-containing Zachariasen continuous random network, consistent with experimental observations of

nanocrystalline domains embedded in a disordered matrix. In striking contrast, the most likely structure of binary a-BN is a compositionally disordered “pseudo-CRN” comprising a mixture of B-N bonds and non-canonical B-B and N-N bonds, along with honeycomb-like “pseudocrystallites” made of non-canonical hexagons [22]. This comparative study highlights a fundamental distinction between elemental and binary amorphous monolayers: the disorder in MAC is primarily topological in nature, whereas disorder in binary systems involves both topological and compositional degrees of freedom. These insights suggest that composition can serve as a new lever to control the disorder type in amorphous two-dimensional materials.

Furthermore, MAC exhibits disordered hyperuniformity, a recently discovered state of amorphous systems characterized by strongly suppressed density fluctuations at large scales, resembling crystalline materials. Studies demonstrate a strong correlation between MAC’s thermal conductivity and hyperuniformity index (H). As H increases from 0.0004 to 0.024, the room-temperature thermal conductivity decreases from $26.3 \text{ W m}^{-1} \text{ K}^{-1}$ to $5.3 \text{ W m}^{-1} \text{ K}^{-1}$ [23]. This finding not only reveals the exceptional properties of MAC but also offers new strategies for designing amorphous materials with tailored thermal performance.

2.3. Comparative Properties of MAC and Crystalline Carbon Materials

MAC exhibits fundamentally different characteristics from graphene and other carbon allotropes due to its unique disordered structure. Unlike graphene’s perfect hexagonal lattice with long-range order, MAC’s amorphous configuration results in distinct mechanical, electronic, and thermal properties that offer new application possibilities.

In mechanical terms, graphene exhibits high strength but approaches the theoretical limit of brittleness for solids, whereas MAC displays substantially improved toughness, with measured values exceeding graphene’s by a factor of 8 [7]. This enhanced fracture resistance makes MAC particularly suitable for flexible electronics and biomedical applications where mechanical durability is crucial.

Electronically, the contrast is equally striking: graphene behaves as a semimetal with zero bandgap, whereas MAC exhibits tunable conductivity spanning from semiconducting to metallic behavior. Precise control of growth conditions allows tuning of the sheet resistance of MAC over nine orders of magnitude, enabling versatile device engineering applications [5].

MAC exhibits frequency-dependent dielectric properties, with values measuring 2.25 at 10 kHz and 0.75 at 1 MHz, along with thermal stability maintained up to 340°C [16]. These properties make it suitable for high-frequency and high-temperature applications.

This unique combination of graphene-like thinness with amorphous carbon’s structural variability positions MAC as a novel material platform. A systematic understanding of the structure-property relationships of MAC enables the development of new generations of electronic, mechanical, and thermal devices that complement rather than replace existing carbon materials.

3. Synthesis Methods of MAC

3.1. Chemical Vapor Deposition

CVD has emerged as one of the most prevalent techniques for synthesizing MAC. This method enables the growth of MAC films through the deposition of carbon-containing precursors onto substrates, offering controllability and scalability. In typical CVD processes (Figure 4a), the carbon-containing precursors are typically generated through either sublimation of graphite rods via Joule heating [16] or pyrolysis of organic compounds [5,6,15]. Researchers have successfully produced large-area, uniform MAC films on copper foils using this approach. In addition to the CVD synthesis on metal substrates, the direct growth of MAC on insulating substrates has been realized in recent advances, with Te-assisted growth achieved on silicon wafers [24] and direct growth also feasible on mica substrates [25].

Several derivative techniques based on CVD have also been developed for MAC synthesis. Laser-assisted deposition utilizes laser activation and localized heating to enable precursor deposition, forming MAC in a single step [4]. The principal advantage of this approach lies in the precise control over laser pulse energy and frequency, enabling fine-tuning of MAC’s structural characteristics. As shown in Figure 4b, plasma-enhanced chemical vapor deposition (PECVD) provides another viable route, in which carbon precursor gases undergo plasma-induced decomposition to form reactive carbon species that deposit as MAC films [21]. Modulation of plasma parameters, including power, frequency, and gas flow rates, allows tailored material characteristics.

A distinctive advantage of CVD lies in its ability to precisely tune MAC’s disorder degree and conductivity by adjusting growth temperature. Notably, the pyrolysis threshold temperature serves as a critical parameter for controlling MRO and variable-range hopping conductivity in MAC. A mere 25°C temperature increase can eliminate MRO and transform MAC into an electrical insulator, accompanied by a dramatic sheet resistance

increase of up to 10^9 [5]. This sensitivity to growth parameters establishes CVD as a tool for investigating the structure-property relationships of MAC.

Beyond empirical optimization, recent simulation and experimental studies have begun to unravel the atomic-scale growth dynamics of MAC. The formation of a disordered carbon monolayer from gaseous precursors proceeds via a three-stage process: chaining/branching, where carbon monomers and small radicals oligomerize into short chains; networking, during which these chains interconnect through random collisions to form a continuous random network rich in pentagons, heptagons, and other non-hexagonal rings; and annealing, where the network undergoes local structural relaxation to reach its final disordered state [26]. Unlike the layer-by-layer epitaxy of graphene, MAC growth is inherently stochastic, and the density of topological defects—and thus the final degree of disorder—is exquisitely sensitive to the substrate temperature and precursor flux. Understanding these growth kinetics provides a rational basis for designing synthesis protocols that target specific disorder levels and, consequently, tailored functional properties.

3.2. Solution-Phase Synthesis

Complementary to CVD approaches, solution-phase methods have emerged as an alternative for synthesizing MAC. These solution-based techniques offer distinct advantages including operational simplicity, cost-effectiveness, and environmental friendliness.

As shown in Figure 4c, a representative solution-phase strategy involves the polymerization of pyrrole within the confined interlayer spaces of removable layered double hydroxide templates, yielding freestanding nitrogen-doped MAC (NMAC) containing mixed pentagonal, hexagonal, and heptagonal rings [27]. The spatial constraints effectively suppress C-C bond rotation and chain entanglement during polymerization, resulting in atomically thin continuous amorphous layers with in-plane π -conjugated electronic structures. This confined radical polymerization approach using solid templates and ion-exchange strategies demonstrates potential as a versatile synthetic route for obtaining two-dimensional covalent networks, as evidenced by successful extensions to polythiophene and polycarbazole monolayers.

Another solution-based route is the Langmuir-Blodgett (LB) method (Figure 4d), which enables the fabrication of amorphous carbon monolayers from self-assembled molecular precursors at the air-water interface [28]. In this approach, amphiphilic carbon-rich molecules are spread as a solution onto a water subphase. The amphiphilic design prevents molecular aggregation and allows the formation of a stable monolayer upon compression to an appropriate surface pressure. The as-formed molecular monolayer is then transferred onto a solid substrate and subjected to rapid high-temperature pyrolysis under an inert atmosphere, which converts the organic layer into an amorphous carbon monolayer. The resulting MAC films can reach centimeter-scale dimensions, limited primarily by the size of the LB trough and the annealing setup.

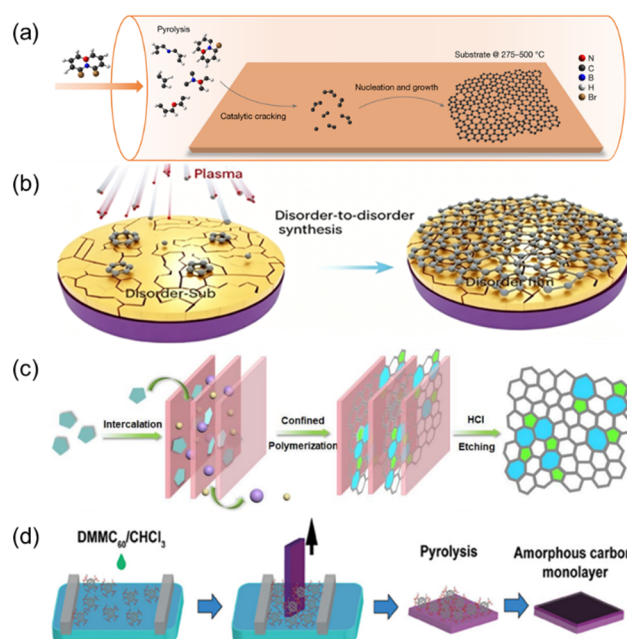


Figure 4. Different synthesis methods of MAC. **(a)** CVD. Copyright 2023, Springer Nature [5]. **(b)** PECVD. Copyright 2025, Springer Nature [21]. **(c)** Template method. Copyright 2024, Springer Nature [27]. **(d)** LB method [28].

4. Properties of MAC

4.1. Mechanical Properties

MAC demonstrates enhanced toughness with experimental measurements showing up to 8 times greater fracture resistance than crystalline graphene [7]. This exceptional mechanical behavior stems from the distinctive structural architecture of MAC, which combines amorphous and nanocrystalline domains in a single atomic layer. Unlike the uniform hexagonal lattice of graphene that leads to intrinsic brittleness, the disordered structure of MAC with embedded distorted nanocrystalline regions effectively inhibits crack propagation through multiple energy dissipation mechanisms.

The enhanced fracture toughness of MAC can be attributed to three synergistic energy-dissipation mechanisms that operate at the atomic scale. First, crack blunting: when a crack tip encounters a nanocrystalline domain, the local stress field induces plastic deformation that rounds the tip, reducing the stress concentration. Second, crack deflection: the tortuous path imposed by the amorphous network forces the crack to deviate from its original propagation direction, increasing the total fracture surface area and consuming more energy. Third, crack bridging: ligament-like amorphous regions spanning the crack wake exert a closing traction that counteracts further opening. These mechanisms are enabled by the intimate mixture of amorphous and nanocrystalline phases within the same atomic monolayer. A quantitative order parameter—the areal fraction of crystallites (F_x)—has been shown to correlate directly with the fracture resistance: moderate F_x values (around 0.3–0.5) maximize toughening, whereas too few crystallites eliminate bridging sites and too many crystallites make the material prone to brittle cleavage [29]. This structure-property relation provides a clear guideline for designing MAC with optimal mechanical performance for flexible electronics and protective coatings.

In addition to fracture toughness, the fundamental elastic and strength properties of MAC have been experimentally characterized using nanoindentation techniques [4]. In a typical setup, a freestanding MAC membrane is suspended over micro-scale circular holes on a substrate, and a sharp tip is used to apply a localized load at the center of the suspended membrane. By recording the resulting force–displacement curve and fitting it to classical elastic models for thin films, the two-dimensional Young's modulus (E_{2D}) can be extracted. Using this approach, a 2D Young's modulus of 115 ± 21 N/m and have been reported for freestanding MAC (Figure 5a).

The combination of measurable strength, improved toughness, and thermal stability suggests potential for MAC in mechanical applications where conventional carbon materials show limitations, including flexible electronics and biomedical devices. Current investigations focus on understanding how the disordered atomic structure in MAC influences its mechanical behavior, which could inform the development of carbon-based materials with customized properties.

4.2. Electronic Properties

The electronic properties of MAC represent a critical determinant for its potential applications in electronic devices. Unlike graphene's zero-gap semiconducting behavior, MAC exhibits tunable electronic characteristics ranging from semiconducting to metallic states, providing exceptional versatility for device applications.

MAC exhibits temperature-dependent electrical conductivity modulated by structural order. Below a critical growth temperature, MRO structures enable variable-range hopping conduction, while a 25 °C increase transitions the material to an insulating state with sheet resistance reaching $10^9 \Omega/\text{sq}$ [5] (Figure 5b). As mentioned above, high-resolution microscopy reveals conductivity correlates with nanocrystalline domain distribution, and theoretical models describe this relationship through two key parameters: MRO presence and temperature-dependent domain density.

To understand how the disordered structure gives rise to such dramatically tunable conductivity, one must consider the interplay between morphology and charge transport. Theoretical analysis based on percolation theory shows that MAC can be viewed as a two-phase composite: conductive nanocrystalline domains embedded in a more resistive amorphous matrix [30]. When the areal fraction of crystalline domains exceeds a critical percolation threshold, a connected conducting pathway emerges, enabling variable-range hopping conduction. Below that threshold, the material becomes an insulator. The growth-temperature-controlled elimination of medium-range order effectively reduces the size and density of the conductive domains, pushing the system across the percolation transition. Furthermore, the electronic states near the Fermi level are spatially localized at defect sites, while states deeper in the band edges are more extended across the nanocrystalline regions. This energy-dependent localization offers a pathway for gate-tunable transport—a feature that distinguishes MAC from crystalline 2D materials and opens possibilities for reconfigurable electronic devices. These findings establish MAC as a model system for studying amorphous material properties.

The tunable electronic properties of MAC enable potential applications in electronic devices, optoelectronics, and sensing technologies. Further research on the relationship between disordered structure and electronic behavior in MAC could support the development of materials with customized functionalities for specific applications.

4.3. Thermal Properties

The thermal characteristics of MAC represent critical parameters determining its suitability for thermal management and high-temperature applications. MAC exhibits distinctive thermal behavior that arises from its amorphous structure and tunable disorder characteristics.

MAC exhibits thermal stability up to 340 °C [16], with thermal conductivity tunable through H modulation. Increased H values correlate with reduced room-temperature conductivity, enabling customized thermal management [23]. The thermal transport in MAC depends on structural disorder, where hyperuniform configurations enhance conductivity through long-range correlations, while disordered regions limit heat transfer. These findings provide guidelines for designing MAC materials with controlled thermal properties.

The tunable thermal conductivity and high thermal stability of MAC suggest potential for thermal management applications in electronics and energy systems where heat flow control is needed. Further study of thermal transport mechanisms in this material could lead to optimized versions for specific performance needs.

4.4. Membrane Properties of MAC

As an atomically thin, freestanding material, MAC also exhibits properties relevant to membrane-based applications. Unlike conventional polymer or graphene oxide membranes, which are typically thicker or contain irregular pores, MAC offers a well-defined monolayer structure with tunable nanoporosity and surface chemistry.

A representative application of MAC as a functional membrane is its use as an ultrathin protective overcoat for hard disk drives (HDDs) [31]. The continuous reduction of magnetic recording media spacing to achieve higher areal density demands overcoats thinner than the current 2 nm carbon-based films. Direct growth of MAC on heterogeneous HDD surfaces at ~300 °C has been shown to yield a uniform 0.8 nm thick film across 2.5-inch disks. As shown in Figure 5c, despite its atomic thickness, this MAC overcoat provides wear and corrosion protection comparable to industry-standard carbon overcoats of 2–3 nm thickness, making it a promising candidate for breaking the 2 nm barrier in HDD technology. Beyond mechanical and chemical protection, the MAC overcoat also exhibits high thermal stability under repeated localized thermal cycling, a critical requirement for next-generation heat-assisted magnetic recording systems.

Another notable membrane property is tunable ion transport. By controlling the growth temperature of MAC, the density and size of intrinsic nanopores can be modulated. Experimental measurements show that the transmembrane ionic conductivity of MAC membranes can be tuned over 2 orders of magnitude (Figure 5d) [6], enabling selective transport of monovalent and multivalent ions. This tunability is directly linked to the degree of disorder in MAC, distinguishing it from crystalline membranes such as pristine graphene, which is impermeable to ions unless artificially perforated.

The tunable ion transport in MAC originates from two coupled effects: size exclusion and surface-charge-mediated selectivity. As the growth temperature decreases, the as-formed MAC films contain a higher density of intrinsic nanopores with diameters ranging from sub-nanometers to ~2 nm. These pores act as molecular sieves: smaller ions can pass through narrower pores, whereas larger ions are blocked. In parallel, the non-hexagonal rings and dangling bonds at the pore edges create localized charge distributions that interact electrostatically with ions of different valences. This dual mechanism allows the transmembrane conductance to be tuned over two orders of magnitude simply by varying the growth temperature. Moreover, the intrinsically low dielectric constant of MAC reduces the dielectric penalty for ion dehydration, thereby lowering the energy barrier for ion entry into nanopores [16]. Collectively, these features position MAC as a highly promising platform for ion-selective membranes, where both pore architecture and surface chemistry can be engineered through disorder control.

These membrane-specific properties—ultrathin protective coating capability and tunable ion selectivity—highlight the potential of MAC in applications ranging from data storage to nanofiltration. Further exploration of MAC membranes for gas separation, water permeation, and pressure-driven filtration would help to fully assess their technological promise.

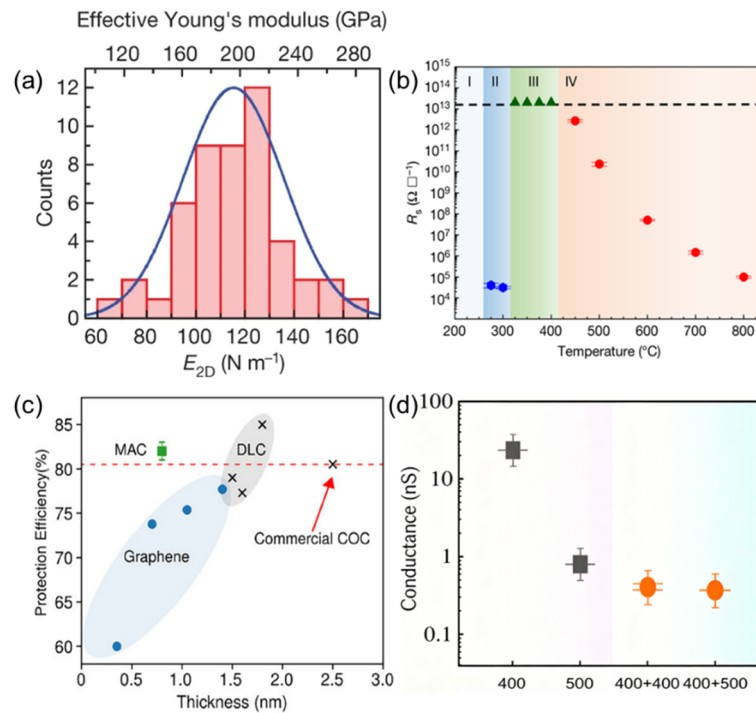


Figure 5. Properties of MAC. (a) Histogram of the E_{2D} of MAC. Copyright 2020, Springer Nature [4]. (b) Conductivity diagram for MAC as a function of growth temperature. Copyright 2023, Springer Nature [5]. (c) The corrosion protection efficiency of MAC compared to other materials [31]. (d) The transmembrane conductance of MAC [6]. The horizontal axis indicates the MAC growth temperature ($^{\circ}C$), and “+” denotes vertically stacked bilayer MAC.

5. Applications of MAC

5.1. Electronic Device Applications

The properties of MAC make it suitable for developing future electronic devices (Figure 6). Its dielectric constant, conductivity tunability, thermal stability, and mechanical flexibility support various applications in electronics.

In high-frequency electronic applications, the ultralow dielectric constant of MAC provides significant advantages. Measurements reveal dielectric constants of 2.25 at 10 kHz and 0.75 at 1 MHz [16], substantially lower than conventional SiO_2 . This property minimizes signal delay and crosstalk in high-speed devices while its high breakdown strength suggests potential for high-voltage applications.

The tunable conductivity of MAC supports multiple electronic component designs. Growth temperature modulation enables precise control over electrical behavior, with sheet resistance spanning nine orders of magnitude from variable-range hopping conduction to insulating states [5]. This tunability facilitates applications in reconfigurable electronics, including adjustable resistors, sensors, and memristive devices where dynamic property modification through disorder engineering is required.

The combination of thermal and mechanical properties makes MAC advantageous for demanding electronic applications. The thermal stability of MAC makes it suitable for high-temperature electronics such as thermal sensors and thermoelectric devices [16]. Its mechanical resilience, exhibiting eightfold greater toughness than graphene, enables robust performance in flexible electronics including wearable devices and electronic skins that undergo bending and stretching deformations [7].

NMAC demonstrates additional electronic functionality, exhibiting p-type semiconducting behavior that provides insights into dopant-induced electronic localization in 2D amorphous systems [27]. This characteristic enables transistor and photodetector applications while serving as a platform for studying doping effects in disordered materials.

To provide a quantitative comparison, key device-relevant properties of MAC are summarized alongside those of graphene and MoS_2 in Table 1. Graphene exhibits high mobility but has no bandgap, resulting in an on/off ratio near unity. MoS_2 offers a large on/off ratio but with moderate mobility. In contrast, the key advantage of MAC lies in its tunable electrical properties. The values listed in the table are those experimentally reported so far.

MAC exhibits multiple functional properties that could be applied in various electronic systems, including high-frequency, reconfigurable, high-temperature, and flexible devices. Ongoing research on structure-property correlations could enhance device performance.

Table 1. Comparison of key device-relevant properties among MAC, graphene, and MoS₂.

Property	MAC	Graphene	MoS ₂
Bandgap (eV)	2.1 [4]	0 (semimetal)	~1–2 (monolayer)
On/off ratio	~2 (for NMAC) [27]	~1	10 ⁶ –10 ⁸
Carrier mobility (cm ² V ^{−1} s ^{−1})	0.1 [5]	~10 ⁴ –10 ⁵	~10–200
Key advantage	Tunable conductivity	High mobility	Large on/off ratio

5.2. Nanofiltration and Separation Technologies

The nanostructural characteristics and tunable properties of MAC offer unique advantages for advanced nanofiltration and separation technologies (Figure 5), presenting new opportunities for membrane development.

For nanofiltration applications, cryogenic-temperature grown MAC has been shown to contain tunable nanopores with size and density controllable through growth temperature modulation [6]. This finding establishes the foundation for MAC-based nanofiltration membranes capable of size-selective filtration of nanoscale particles including viruses, proteins, and nanoparticles.

In ion-selective separation systems, the nanoporous architecture and surface characteristics of MAC enable selective ion transport. Experimental studies demonstrate that MAC membranes with varying disorder degrees exhibit tunable transmembrane ionic conductivity spanning over two orders of magnitude [6]. This property facilitates efficient separation of monovalent and multivalent ions, while MAC's low dielectric constant contributes to energy-efficient operation through reduced ion transport resistance.

For molecular separation applications, the combination of nanoporosity and tailorable surface chemistry in MAC could enable selective permeation based on molecular size and polarity. Precise control over pore dimensions and surface functionalization would allow potential applications ranging from water/organic solvent separation to fractionation of organic molecules. Additionally, the inherent flexibility and lightweight nature of MAC further suggest its potential for use in portable separation devices, though such applications have not been reported to date.

Collectively, MAC demonstrates significant potential for developing separation technologies. Continued investigation of the fundamental transport mechanisms and property-structure relationships in MAC will enable the rational design of high-efficiency, selective, and energy-effective filtration systems for environmental, biomedical, and industrial applications.

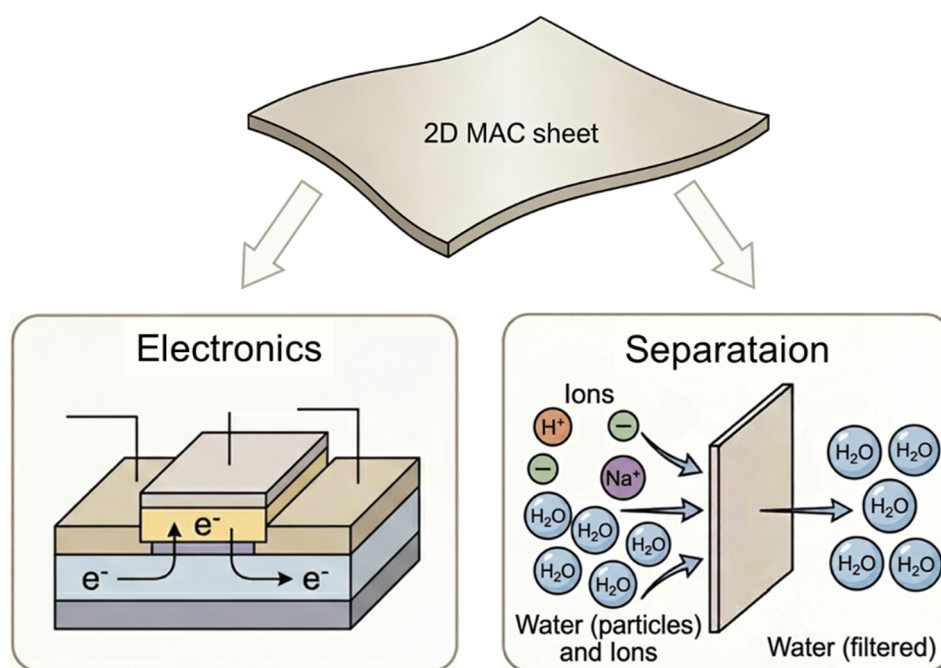


Figure 6. Applications of MAC.

6. Future Research Directions for MAC

6.1. Fundamental Understanding of Structure-Property Relationships

The structure-property relationship of MAC represents a critical research frontier for both fundamental understanding and performance optimization. While significant progress has been made in MAC research, deeper insights into these correlations remain essential for advancing the field.

A primary research direction involves establishing quantitative relationships between disorder parameters and material properties. Current studies have demonstrated strong correlations between MAC's disorder degree and its electrical, mechanical, and thermal characteristics. However, the precise mathematical formulations and underlying physical mechanisms require further elucidation. For instance, while MAC's conductivity has been described using two order parameters (presence of medium-range order and temperature-dependent nanocrystalline domain density), a unified theoretical framework for predicting property variations remains to be developed.

Defect engineering in MAC warrants particular attention, as controlled defect introduction could enable precise property tuning. Preliminary studies suggest that lattice disorder-induced ripples in MAC can mitigate stress concentration near crack tips, enhancing defect tolerance [7]. Detailed understanding of defect-property relationships could facilitate the design of MAC with tailored functionalities.

Addressing these research challenges will enable optimization of synthesis protocols, precise property control, and expanded application possibilities for MAC. Future investigations should focus on integrating experimental characterization, theoretical modeling, and computational approaches to establish comprehensive structure-property relationships in this unique 2D amorphous system.

6.2. Controlled Synthesis and Structural Design of MAC

The development of precise synthesis and structural design methodologies for MAC represents a fundamental requirement for realizing its full application potential. While various synthesis approaches have been established, achieving atomic-level control over MAC's structure and properties remains a research challenge.

A critical research direction involves advancing synthesis techniques for precise structural control. Current CVD methods enable coarse tuning of MAC's disorder degree and conductivity through temperature modulation, but lack the precision required for controlling atomic arrangement, defect distribution, and nanocrystalline domain size at the nanoscale. Developing synthesis protocols with enhanced spatial and energetic control represents an essential step toward property-engineered MAC.

The exploration of patterned growth and integration techniques constitutes another important research frontier. Practical device applications typically require spatially controlled deposition of MAC with specific geometries and seamless integration with other materials. While existing methods focus primarily on large-area uniform films, systematic investigation of spatially selective growth processes and heterointegration approaches remains largely unexplored.

Advanced structural design methodologies for amorphous systems present unique challenges compared to crystalline materials. Conventional symmetry-based design principles may not apply, necessitating the development of novel theoretical frameworks specifically for amorphous materials. Promising approaches include machine learning-based prediction of macroscopic properties from structural descriptors, which could inform rational design strategies for tailored MAC architectures.

Addressing these synthesis and design challenges will enable precise property control and facilitate the development of MAC-based devices with optimized performance. Future research should focus on combining advanced synthesis techniques with computational design tools to establish comprehensive structure-property relationships in this amorphous 2D material system.

6.3. Functionalization and Composite Materials of MAC

The functionalization and composite engineering of MAC represent research directions for expanding its application scope. Strategic modification and hybridization approaches can impart novel functionalities or enhance specific properties of MAC to meet diverse application requirements.

Advanced functionalization methodologies for MAC require focused development. Current techniques relying on doping and surface modification suffer from limitations including low efficiency and poor uniformity. Innovative approaches such as plasma treatment, ion implantation, and chemical grafting could enable precise introduction of functional groups or nanostructures, allowing tailored property modulation at the atomic scale.

The multifunctional roles of MAC in composite systems warrant systematic investigation. MAC can serve variously as a matrix, reinforcement, or functional phase in composites, enabling applications ranging from flexible conductive layers in electronics to sensing interfaces in biosensors and active filtration membranes. Understanding the fundamental mechanisms governing MAC's performance in these diverse configurations is essential for developing next-generation functional materials.

Theoretical modeling and design frameworks specific to MAC functionalization and composites require dedicated development. Unlike crystalline materials, MAC's amorphous nature may lead to distinct modification behaviors, necessitating specialized computational approaches. Molecular dynamics simulations and finite element analysis could provide predictive insights into property evolution during functionalization and composite formation, guiding experimental optimization.

These research advances in functionalization and composite engineering will significantly broaden MAC's application potential while enhancing its performance characteristics. Future work should integrate experimental synthesis with computational design to establish comprehensive structure-property relationships in modified MAC systems.

7. Conclusions

MAC has emerged as a novel two-dimensional carbon allotrope attracting significant scientific interest in recent years. This comprehensive review has systematically examined the current state of MAC research, encompassing its fundamental characteristics, synthesis methodologies, physicochemical properties, potential applications, and future research directions.

MAC exhibits distinct structural and property differences compared to graphene. Its amorphous architecture incorporates MRO and nanocrystalline domains, with tunable disorder achieved through growth parameter modulation. This unique configuration endows MAC with exceptional mechanical properties, including toughness 8 times greater than graphene. Furthermore, MAC demonstrates tunable electrical conductivity, low dielectric constant, and remarkable thermal stability, making it promising for diverse applications in electronic devices, energy storage, flexible electronics, and biomedical systems.

Regarding synthesis approaches, CVD currently represents the most widely employed technique, enabling control over MAC's disorder and conductivity through temperature variation. Solution-phase methods offer an alternative route, facilitating doping and functionalization through confined polymerization within layered double hydroxide templates. Additional techniques, including laser-assisted deposition and plasma-enhanced CVD, provide complementary fabrication options.

MAC exhibits a unique combination of mechanical, electronic, thermal, and chemical properties. Its mechanical performance surpasses graphene in toughness while maintaining comparable strength. The electronic properties span from variable-range hopping conduction to insulating states, and thermal stability persists up to at least 340 °C. These characteristics are precisely tunable through disorder engineering, rendering MAC a highly customizable material for specialized applications.

Potential applications leverage MAC's distinctive properties: its low dielectric constant benefits high-frequency electronics; high surface area and conductivity suggest promise for energy storage electrodes; exceptional toughness enables flexible electronics; and nanoporous variants show potential for advanced separation technologies.

Despite significant progress, challenges and opportunities remain in establishing fundamental structure-property relationships, developing precise synthesis and design methodologies, exploring functionalization and composite systems, and enabling scalable production and integration.

In summary, MAC represents a versatile carbon material with broad research and application potential. Continued multidisciplinary efforts and technological innovation are expected to realize MAC's practical implementation across diverse fields, offering new opportunities for materials science and related disciplines.

Author Contributions

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used ChatGPT to polish the text and figures in the paper. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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