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Uniqueness of Borophene and its Exceptional Properties for Advance Application-A Review

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Abstract: *Borophene, a two-dimensional (2D) allotrope of boron, has garnered significant attention due to its unique structural, electronic, and mechanical properties, which make it a promising material for applications in electronics, energy storage, and catalysis. This review provides a comprehensive overview of the current state of borophene synthesis, focusing on various methods such as chemical vapor deposition (CVD), molecular beam epitaxy (MBE), and liquid-phase exfoliation. Despite its potential, borophene faces significant challenges related to instability, which limits its practical applications. The review highlights the primary causes of this instability, including surface oxidation, phase transitions, and the inherent reactivity of boron. We also explore various strategies to mitigate these issues, such as surface passivation, alloying with other elements, and the optimization of growth conditions. Additionally, the effects of substrate choice and the interaction between borophene and underlying materials are examined, revealing their critical role in stabilizing the 2D structure. Finally, the growth mechanisms of borophene are discussed, providing insights into the formation of its unique structures and the underlying principles that govern its growth on different substrates. This review aims to serve as a valuable resource for researchers seeking to advance the development and application of borophene in various technological fields.*

Keywords: Borophene, epitaxy, exfoliation, superconductivity, electrochemical

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INTRODUCTION

Boron is a non-metallic element known for its versatility and ability to form a variety of compounds with different bond arrangements. Borophene is a 2D material made entirely of boron atoms stacked into a complex structure. Unlike graphene, due to its electron-poor nature, borophene is formed from a single p-shell electron ($2S^2 2P^1$), which reveals its unique properties (Wang *et al.*, 2019). It has anisotropic mechanical properties such as capacity to expand under tension, an intriguing property that cannot be underestimated.

Furthermore, borophene has unique electronic mobility, making its application for high-speed, low-power electronics viable (Bhavyashree *et al.*, 2022). The various borophene structures are controlled by different binding mechanisms and surface protrusions (Hess, 2021), is attributed to its diverse properties. The structure of borophene is characterized by its flexibility and the ability to form various lattice configurations, which influence its physical and chemical properties. Borophene exhibits a range of electronic properties, including metallic and semiconducting properties. Its electronic band structure can vary depending on the specific borophene phase and external conditions such as voltage or doping. The stability of borophene is a result of bonding theory, which provides important information about the stability pattern of borophene. The introduction of the three-center two-electron bond theory (3c-2e) reveals the uniqueness of the bonding strategy of boron atoms, which is consistent with the octet rule, and thus shedding more light on boron chemistry (Aziz *et al.*, 2021). The theory emphasized on a novel type of resonance in borophene that arises from the delocalization of electrons within the 2D plane (Wang *et al.*, 2019). The discovery of this resonance has complemented the well-known out-of-plane π resonance, which increases the stability of the triangular boron lattice. Variations in borophene phases provide tunable electronic properties suitable for a variety of electronic devices. The unique structure of borophene has resulted in unique mechanical and thermal properties that make it suitable for flexible materials and efficient heat dissipation in electronics (Moguikoc *et al.*, 2018).

Hence, this paper focuses on extensive review of the synthesis techniques, causes of instability of borophene and the possible ways of mitigating it and hence making it readily available for engineering application.Borophene holds great promise for engineering applications, but challenges in its synthesis and instability hinder its practical use. Current methods like CVD, MBE, and wet chemistry lack a comparative review on key factors such as yield, scalability, and reproducibility. Additionally, borophene's reactivity with oxygen and moisture limits its stability. Although strategies like substrate engineering and encapsulation exist, a comprehensive evaluation is missing. This review aims to consolidate knowledge on synthesis, identify instability causes, explore mitigation strategies, and highlight engineering relevance, thereby guiding future research and enabling the material's transition from lab-scale innovation to real-world application.

2. Structural Properties of Borophene

Borophene is a 2-D allotrope of boron with unique and tunable structural characteristics. Unlike graphene, which has a fixed honeycomb lattice, borophene exhibits a wide variety of polymorphs due to the electron-deficient nature of boron and its ability to form multicenter bonds. Highlighted below are the major structural properties of borophene:

2.1 Atomic Structure and Crystallographic Configurations

The stability of borophene is a result of bonding theory, which provides important information about the stability pattern of borophene. The introduction of the three-center two-electron bond theory (3c-2e) reveals the uniqueness of the bonding style of boron atoms, which is consistent with the octet rule, and thus avoids shedding more light on boron chemistry (Qiul *et al.*, 2023). The theory emphasized a novel type of resonance in borophene that arises from the delocalization of electrons within the 2D plane (Wang *et al.*, 2019). The discovery of this resonance has complemented the well-known out-of-plane π resonance, which increases the stability of the triangular boron lattice.

Bonding theory has highlighted the influence of hole ratio and substrate doping on hole concentration in boron and has a parallel with atomicity in carbon materials. Variations in borophene phases provide tunable electronic properties making it applicable for a variety of electronic devices. The exceptional structure of borophene has resulted in unique mechanical and thermal properties that make it suitable for flexible materials and efficient heat dissipation in electronics (Moguikoc *et al*., 2018). Specific boron structures such as β_{12} and χ_3 are promising for application in transistors and logic gates (Xie *et al*., 2020 and Campbel *et al*., 2018).

2.2 Thermal Properties of Borophene

The thermal conductivity of borophene has been extensively studied (Sun *et al*., 2017; Wang *et al*., 2017; Tan *et at*., 2017; Mortazav *et al*., 2018; Hassan *et al*., 2021). Isotropic α-sheet borophene has a thermal conductivity of 1.43 nWK-1 $nm^{-2.}$ The thermal transport of borophene is due to the high phonon frequency and distinguishes it from other nano-elemental 2D group (Tan *et al*., 2017 and Mishra *et al*., 2018). It has been studied that the thermal conductivity of borophene is anisotropic. For instance, the thermal conductivities of β 12 are approximately 3.30 and 10.97 nWK-1nm^{-2} along the armchair and zigzag directions, respectively. Yakobson *et al.* (2018) studied the superconductivity property of borophene with the aid of first-principles calculation (Amiri *et al*., 2018) and their results show that all types of stable borophene exhibit superconductivity.

2.3 Mechanical Properties of Borophene

Boron is known to be deficient in electrons, which causes it to form a large number of multicenter bonds, giving rise to its unique properties. Mortazav et al. first proposed that vacancy defects of borophene have a significant influence on its mechanical properties (Lee *et al*., 2012). The young modulus of borophene of the synthesized β_{12} and χ_3 sheets was about 179.0 and 198.5 N/m along the chair direction, respectively. Furthermore, defect-free 2-pmm has a higher elastic modulus of 398 N/m than that reported for β_{12} and $\chi_{3.}$ The Poisson ratio is negative in contrast to previous reports on other 2D materials (Zavabeti *et al*., 2020). Both theoretically and experimentally, most 2D boron layers are metallic. Penev et al. have predicted using the local density approximation (LDA) that the metallic states of β_{12} and χ_3 layers originate from the 2Px and 2Py states, which consequently gives the band that is close to the Fermi level of the boron layers with these values of n = 10 ˜15% (Liu *et al*., 2022).

2.4 Electronic Properties of Borophene

Boron is a two-dimensional material with a complex atomic arrangement and a symmetrical lattice, displaying an exceptional variety of electronic behaviors (Ashraf and Abghoui, 2023). Its electronic bonding structure can either be metallic or semiconducting, each offering distinct applications in electronics. The metallic phase of borophene demonstrates high electrical conductivity due to partially filled states, making it ideal for interconnections and electrical contacts. In its semi-metallic phase, borophene features electron and hole pockets near the Fermi level, enabling its use in spintronic devices (Ranjan *et al*., 2019). The semiconducting phase has a significant energy band gap between the valence and conduction bands, which can be tuned by altering the atomic structure or through doping

2.5 Superconductivity of Borophene

The discovery of superconductivity in borophene has garnered significant attention within the scientific community. The successful synthesis of borophene on the Ag (111) surface, revealing the β_{12} and χ_3 structures, marked a major scientific breakthrough. The application of first-principles calculations to nano-superconducting devices has sparked considerable research interest, aiming to explore the electron-phonon coupling in β_{12} and χ_3 borophenes (Gao *et al*., 2017).

Both structures demonstrate metallic properties, with electron-phonon coupling surpassing that of MgB_2, a well-known superconductor. The calculated superconducting transition temperatures for β_{12} and χ_3 borophenes are 18.7 K and 24.7 K, respectively, exceeding theoretical predictions for graphene (Gao *et al.*, 2017 and Huang *et al.*, 2012), thus marking a significant advancement in the study of 2D superconductivity.

The presence of an anisotropic Dirac cone in borophene's band structure indicates its potential to form Cooper pairs, a key feature for superconductivity (Gao *et al.*, 2017 and Gupta *et al.*, 2018). Recently, the synthesis of the β_{12} polymorph on the Ag (111) substrate revealed Dirac fermions, offering further insight into the electronic behavior of borophene (Gupta *et al.*, 2018). Researchers are investigating practical applications of borophene superconductivity through methods such as heterostructure engineering and controlled doping (Balandin, 2011). Studies on bilayer borophenes (BL), stabilized by specific strategies, have uncovered intrinsic superconducting properties, with transition temperatures (Tc) of 11.9 K and 4.9 K for BL-B8 and BL-B30, respectively. The out-of-plane vibrations of boron atoms in the low-frequency region play a significant role in enhancing their superconductivity (Yan *et al*, 2021).

3. Synthesis Techniques of Borophene

The synthesis of borophene is an area of immense research focus due to its potential applications arising from its exceptional electronic mobility and metallic properties (Fisher *et al.*, 2015 and Folarunso *et al.*, 2021). Scientists are actively developing various synthesis techniques. Borophene synthesis techniques can be divided into two main categories: top-down and bottom-up techniques, each with unique advantages and limitations (Gupta *et al.*, 2024 and Lei *et al.*, 2022). Top-down approaches start with boron in large quantities and break it down into nanoscale borophene layers. In bottom-up methods, however, borophene structures are built atom by atom. The optimal approach is largely determined by the specific requirements of the application. Factors such as the desired properties of borophene, production scale, and cost limitations all influence the selection of the synthesis technique (Gupta *et al.*, 2024). Fig 1 illustrates the synthesis techniques of borophene.

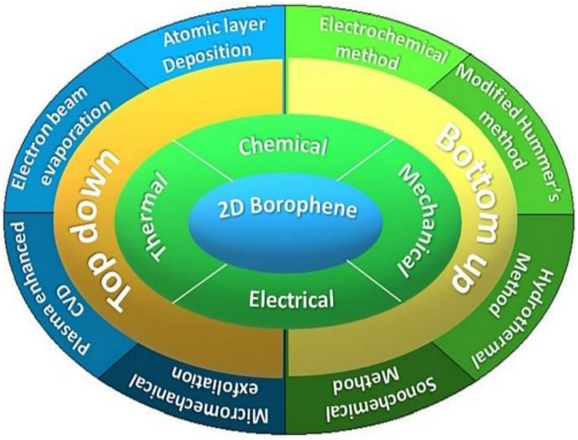

Fig.1 Borophene Synthesis Techniques (Gupta *et al.*, 2024)

3.1 Top-down Approaches

Top-down approaches to borophene synthesis involve starting with a bulk boron material and breaking it down into nanoscale sheets (Gupta *et al.*, 2024). The techniques commonly used in top-down approaches include: mechanical exfoliation, chemical exfoliation, Sonochemical exfoliation, and modified Hummer's Method.

3.1.1 Exfoliation Technique

Exfoliation techniques for synthesizing borophene involve breaking down bulk boron materials into thin, nanoscale sheets. These methods are used for producing high-quality borophene with well-defined properties. Examples of exfoliation technique used for the synthesis of borophene are highlighted below:

3.1.2 Micromechanical Technique

The micromechanical technique involves mechanical cleavage of the bulk precursor to obtain atomically thin layers. Micromechanical exfoliation has been used to study the electronic behavior of borophene as well as the formation of borophene-based heterolayers with materials such as black phosphorus (BP) and molybdenum disulfide (MoS2), which exhibit unique excitonic properties. Layered volume crystals are removed using adhesive tape and then deposited on a target substrate. Borophene synthesized using this technique has high quality, large lateral size, and few defects. The disadvantage is that the yield is low and mass production is not possible.

3.1.3 Ball Milling Induced Technique

Ball milling is a mechanical exfoliation technique that is often used to produce less layered borophene flakes. The technique involves subjecting the large boron precursors to a ball mill and using the resulting mechanical energy to induce exfoliation. The milling parameters such as rotation speed, milling and precursor mass loading directly affect the resulting flake thickness and distribution, therefore these factors require careful attention. In addition, the crystalline phase of the exfoliated borophene is affected by mechanical energy and heat generated during ball milling.

3.1.4 Electrochemical Exfoliation (EE)

Thin-film borophene flakes have shown promise for preparation by electrochemical exfoliation (Sielick *et al.*, 2018). By incorporating boron in large quantities into a conductive metal mesh, the method enables electrochemical exfoliation in a range of electrolytes. The type of electrolyte used largely determines the thickness and crystal structure of the exfoliated borophene. Its scalable manufacturing approach was revealed by studying the borophene-EE mechanism (Sielick *et al.*, 2018). Mohammed and others. reveal a new method to synthesize borophene using EE processes derived from graphene synthesis.

3.1.5 Liquid Phase Technique (LPE)

Liquid phase exfoliation is a simple method for producing two-dimensional materials such as borophene. It exfoliates the boron compounds dissolved in a liquid by using solvent and ultrasonic forces to remove thin layers, creating borophene layers. To create a suspension, a solvent or surfactant is combined with boron bulk material. Using shear forces or ultrasound, the layers are separated into a two-dimensional shape. The type of solvents, centrifugation speed, and sonication parameters are the main determinants of the thickness and yield of the exfoliated borophene layer (Zielinkiewicz et al., 2024). Mass production is supported by LPE, which is solution processable. Disadvantages include the low yield of monolayers, the inability to regulate the number of layers, and the relatively small lateral size. Li and colleagues (Li *et al.*, 2018) Ultrasound-assisted LPE utilized isopropyl alcohol (IPA) and dimethylformamide (DMF) as solvents to synthesize borophene layers at room temperature. The average solvent thickness was 1–8 nm with 4 layers for DMF and 4–7 nm with 11 layers for IPA.

Guo *et al.* (2018) created 2D borophene nanosheets (less than 2 nm) using a sonication-assisted LPE and showed promise as anodes for lithium-ion batteries in 500 cycles at 167 mAh g−1 with an ultrahigh capacity of 782.9 mAh g−1.

3.2. Bottom-Up Approaches

Bottom-up approaches to borophene synthesis involve assembling nanoscale structures from individual atoms or molecules (Gupta *et al.*, 2024; Kaneti *et al.*, 2022). The commonly used bottom-up approaches include: chemical vapour deposition (CVD), physical vapour deposition (PVD), Molecular Beam Epitaxy (MBE), Atomic Layer Deposition (ALD).

3.2.1 Vapour Deposition Techniques

Vapour deposition techniques are widely used for synthesizing 2-D materials like borophene. These methods involve depositing material from a vapour phase onto a substrate to form thin films or layers. Examples of vapour deposition exfoliation technique used for the synthesis of borophene are highlighted below:

3.2.2 Molecular Beam Epitaxy (MBE)

MBE is a method for creating thin films that involves letting material evaporate in a high-vacuum setting and then letting it condense on a substrate. MBE takes place in an extremely high vacuum. It is regarded as the most accurate synthesis technique for borophene. From a high-temperature source, boron atoms are evaporated and then carefully deposited onto a substrate (Feng *et al.*, 2021). A chamber with a high vacuum is used to hold the substrate. An evaporator source heats boron to create a molecular beam of atoms. When approaching the substrate, the boron atoms condense and form a borophene layer. Careful regulation of growth parameters such as chamber pressure, substrate temperature and jet flow lead to the desired material properties. This method produces highly pure borophene with a distinct structure, which also allows precise control over film composition and thickness. Mannix et al pioneered the MBE growth of 2D boron on Ag (111), by vaporizing and depositing pure boron at high temperatures (450– 700 °C) and deposition rates of 0.01–0.1 monolayer (ML) per minute. They identified 2 distinct phases of borophene, referred to as the β_{12} ($\eta = 1/6$) and χ_3 ($\eta = 1/5$) phases, whose formation depended on the deposition rate and the annealing temperature. Furthermore, Ag (111) was reported to have a new metallic phase with hexagonal symmetry called α-sheet, which increases the structural diversity of borophene.

3.2.3 Segregation Enhanced Epitaxy

Segregation-enhanced epitaxy has been shown to be an alternative to MBE for the synthesis of borophene and has been used to prepare Ir (111) (Omambac *et al.*, 2021). In this method, borazine ($B_3N_3H_6$) was applied to the Ir (111) surface at high temperatures (1100 °C), causing borazine to thermally decompose, nitrogen to desorb, and boron to diffuse into the substrate. After cooling, the boron separates beneath the surface and returns to the surface to form the borophene domains.

3.2.4 Van der waal Epitaxy

To overcome the limitations of metal substrates and enable the synthesis of borophene on nonmetallic substrates, van der Waals epitaxy was employed to synthesize borophene on nonmetallic substrates and overcome the limitations of metallic substrates. Wu *et al.* (2021) carried out the growth of borophene films on a mica substrate using hydrogen as a carrier gas and $NaBH_4$ as a boron source.

The as-synthesized borophene featured the α'' boron sheet lattice structure and exhibited exceptional properties as a photodetector with a photosensitivity of 1.04 A W−1 and a specific detectivity of 1.27 × 1011 Jones at a reverse bias voltage of 4 V below a 625 nm illumination (Wu *et al.*, 2021).

3.2.5 Plasma-Assisted Ion Implantation

In order to do this, layered bulk compounds are intercalated with L or Na ions and then sonicated in solution. You can process it in a solution. It has a monolayer borophene yield and supports mass production. It may have defects and undergo phase transformation, but its lateral size is small. Tsai and colleagues used the plasma-assisted ion implantation technique. The synthesis of β-borophene on an insulating structure was accomplished using a multilayer plasma-assisted ion implantation technique (Tsai *et al.*, 2016). Reminiscent of the synthesis of multilayer graphene, the technique combines a plasma-assisted process with boron ion implantation. The surface area of a p+-Si substrate that has been implanted with boron is exposed to nitrogen ions produced by radiofrequency plasma, which are then annealed at 800 C. The formation of the borophene layers resulted from this process, which made it easier for the boron atoms to be ejected from the substrate's surface.

3.2.6 Chemical Vapour Deposition (CVD)

Chemical vapor deposition (CVD) is a promising technique for producing borophene. CVD is one of the most widely used methods for synthesizing borophene. This technique uses a precursor gas that decomposes on a heated substrate under high temperature and vacuum to form a thin film of borophene. This is the chemical reaction of gaseous boron-containing precursors on a substrate to form a borophene layer. A suitable substrate, such as silver (Ag) or copper (Cu), is cleaned and placed in a CVD chamber. Boron-containing gases such as diborane (B_2H_6), boron trichloride (BCl_3) or borane (BH_3) are introduced into the chamber. To create borophene, the substrate is heated to a certain temperature, which allows the gaseous precursors to split and deposit boron atoms on the substrate. The growth rate, thickness and quality of the borophene layer are all carefully regulated by factors such as temperature, pressure and gas flow rates. The advantages of the technique lie in the ability to produce high-quality large-area borophene and the ability to fine-tune layer thickness and structural properties. However, the method is often more expensive and labor-intensive. Xu et al successfully combined 2D boron layers using Chemical Vapor Deposition (CVD) by heating diborane (B_2H_6) on a silicon wafer to 950 °C and a pressure of 8 Pa. The resulting single-crystalline borophene layers were of high quality, ranging in width from tens of nanometers to 3 µm, length from 3 to 20 µm, and thickness around 10 nm, suggesting the formation of multi-atomic layers of the α-boron phase. This study paved the way for further exploration of CVD as a method for creating borophene. Guo et al. developed a method for growing tetragonal borophene single-crystal layers on copper foils through low-pressure CVD (LPCVD), employing a vapor-solid reaction. The electrical conductivity of these borophene layers varied from 4 to 5 × 10^{-4} S cm^{-1}, with a band gap of about 2.1 eV, suggesting they have semiconducting properties. The borophene layers showed promising emission properties, with a peak current close to 1 µA, and they remained stable in normal conditions, preserving their electrical conductivity and emission properties over several days in the air.

Tai et al have used CVD to synthesize borophene nanosheet for catalytic application. They prepared borophene nanosheets on carbon cloth through the CVD strategy utilizing sodium borohydride as the boron source and hydrogen gas as the carrier. The crystal structure of the borophene nanosheets gotten is in understanding with the hypothetical α'- borophene nanosheet. These borophene nanosheets, shown great electrocatalytic movement for the hydrogen advancement response (HER), with a Tafel slope of 69 mV dec−1 and great cycling steadiness in a 0.5 M H_2SO_4 arrangement, which was ascribed to their copious surface-active destinations and the related low charge exchange resistance.

4. Substrate Effects and Growth Mechanisms of Borophene

The substrate plays an important role in determining the growth, structural integrity, and electronic properties of borophene. Understanding these interactions is vital for tailoring borophene for various applications in nanoelectronics, sensors, and other advanced materials technologies. Further studies are needed to explore the full potential of borophene as influenced by different substrate materials and growth techniques.

4.1 Substrate Types

4.1.1 Metallic Substrates

Metals like silver (Ag) or gold (Au) can facilitate the growth of borophene by providing a good lattice match and allowing for high mobility of boron atoms. This can lead to the formation of well-ordered structures. When borophene was first synthesized on Ag(111), it was only a few dozens of nanometers in size, which made of nanometers in size, which made of nanometers in size, which made of nanometers in size, which made of nanometers in size, which made of nanometers in size, which made of nanometers in size, which made of nanometers in size, which made it difficult to fabricate devices and limited the ability to examine its mechanical and electrical characteristics. In order to overcome this difficulty, Wu et al (Cuxart *et al.,* 2021) synthesized borophene on a Cu(111) substrate under UHV in 2019, producing massive single-crystal domains up to 100 μm2. With a hexagonal vacancy concentration of η=1/5, the borophene structure on Cu(111) was represented as a new triangular network. Borophene was also grown aluminum substrate. A planar hexagonal honeycomb structure of borophene on Al(111) was discovered by Li et al (Cuxart *et al.,* 2021) . A 2D boron allotrope, namely χ6 type borophene, was synthesized on an Ir(111) substrate according to Vinogradov et al (Cuxart *et al.,* 2021). Fig. 2 shows the major breakthrough in borophene nanostructure from both theoretical and experimental point of view.

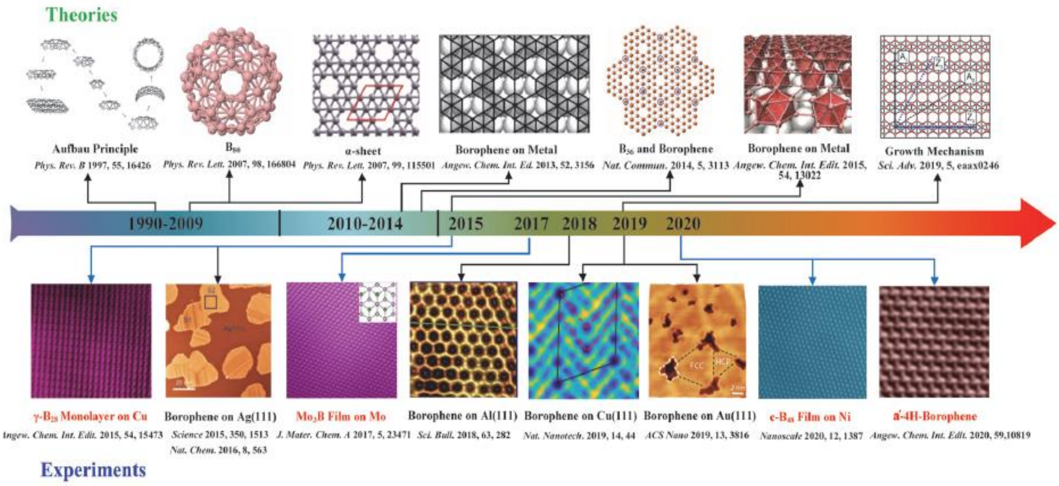

Fig. 2 Major breakthrough in borophene nanostructure from both theoretical and experimental point of view (Cuxart *et al.,* 2021)

4.1.2 Insulating Substrates

Materials such as hexagonal boron nitride (h-BN) or graphene can also be used. These substrates can help stabilize certain borophene phases and can influence the electronic properties through charge transfer or hybridization.

4.2 Growth Methods of Borophene

4.2.1 Molecular Beam Epitaxy (MBE)

This technique allows for precise control over the growth conditions and can yield high-quality borophene on various substrates.

4.2.2 Chemical Vapor Deposition (CVD)

CVD can also be employed, with the choice of precursor gases affecting the final structure and quality of the borophene.

4.3 Structural Properties of Borophene

The symmetry and orientation of borophene can be influenced by the underlying substrate. For example, a closely matched lattice can help promote a specific phase of borophene, while a mismatch can introduce defects or lead to the formation of different structural phases. The substrate can also induce strain in the borophene layer, which can further affect its stability and electronic properties.

4.4 Electronic Properties

The interaction between borophene and the substrate can lead to changes in band structure. For instance, the presence of a metallic substrate can alter the electronic density of states, potentially affecting conductivity and other electronic properties. Borophene's unique electronic features, such as its potential for superconductivity, can be modulated by the choice of substrate, allowing for tunable properties that can be beneficial for applications in electronics.

4.5 Surface Interactions

The chemical interaction between borophene and the substrate can lead to surface reconstruction or doping effects, which can significantly impact the physical properties of borophene. The degree of interaction can vary widely depending on the substrate material, potentially leading to enhanced stability or altered reactivity.

4.6 Epitaxial Growth and Interface Interactions

In order to optimize the synthesis of high quality borophene and enable its use in a variety of advanced applications, it is crucial to understand the intricate process of epitaxial growth of borophene, which is influenced by substrate choice, growth techniques, and interface interactions. Further research in this area focuses on developing new substrates and improving growth methods to improve borophene's performance and integration in computer devices.

4.6.1 Substrate Selection

The choice of substrate plays a crucial role in determining the growth orientation and quality of borophene. Common substrates include metals (like copper and nickel) and insulators (like silicon dioxide), each offering different lattice mismatches and chemical interactions.

4.7 Interface Interactions

4.7.1 Chemical Bonding

The interaction between borophene and the substrate can involve van der Waals forces or stronger covalent bonding, depending on the substrate material. These interactions significantly affect the nucleation process and growth rate.

4.7.2 Lattice Mismatch

Lattice mismatch between borophene and the substrate can lead to strain in the borophene layers, affecting their stability and electronic properties. A small mismatch can promote coherent growth, while larger mismatches may lead to defects.

4.7.3 Surface Energy

The surface energy of the substrate influences the morphology and growth mechanism. Low surface energy substrates can facilitate smoother layer growth, while high-energy surfaces might encourage rougher, island-like growth.

4.7.4 Defects and Impurities

Interface defects can arise from misalignment, which may affect electronic properties and stability. Controlling the cleanliness and uniformity of the substrate is crucial to minimize these defects.

4.8 Growth Conditions of Borophene

4.8.1 Temperature and Pressure

Optimal growth temperature and pressure conditions are essential for achieving high-quality borophene. Higher temperatures can enhance atom mobility, promoting better layer formation, but excessive temperatures might lead to degradation or unwanted phase transformations.

4.8.2 Doping

Incorporating dopants during the growth process can alter the electronic and structural properties of borophene. The effects of doping depend on how it interacts at the interface and within the layers.

4.8.3 Electronic Properties

The interface interactions and growth conditions can significantly influence the electronic properties of borophene, including conductivity and band structure, which are critical for applications in electronics.

4.8.4 Stability Issues and Strategies for Enhancing Stability

Borophene, a two-dimensional (2D) material composed of boron atoms, has gained significant attention due to its unique structural and electronic properties, including high conductivity, flexibility, and potential for applications in areas such as catalysis, energy storage, and sensors. However, borophene is inherently unstable, particularly under ambient conditions, and faces several challenges that hinder its practical use. These stability issues are crucial to address for borophene to become a viable material for real-world applications.

4.9 Stability Issues of Borophene

4.9.1 Thermodynamic Instability

Borophene, particularly in its freestanding form, is thermodynamically unstable at room temperature. Unlike graphene, which is stable due to its highly symmetrical sp^2 bonding, borophene's unique bonding configurations (such as sp^2/sp^3 hybridization) result in a tendency to undergo structural transformations that reduce its stability.The hexagonal borophene structure, in particular, may undergo phase transitions, such as converting to a more stable boron allotrope, like boron nanotubes or other boron-based compounds, under certain conditions such as exposure to heat or high pressure).

4.9.2 Air and Moisture Sensitivity

Borophene is highly sensitive to oxygen and moisture, which can lead to oxidation and degradation of its properties. The high reactivity of borophene's surface, due to the presence of boron’s electron deficiency, makes it prone to reactions with atmospheric molecules. This sensitivity leads to the degradation of its mechanical, electrical, and chemical properties, particularly when exposed to humid or oxidative environments.

4.9.3 Mechanical Instability

The mechanical properties of borophene can also be compromised when exposed to certain external factors such as strain, temperature fluctuations, or mechanical stress. The relatively weak van der Waals interactions between layers in multilayer borophene could make the material prone to delamination or fracture under mechanical stress.

4.9.4 Electron Deficiency and Charge Redistribution

Borophene exhibits electron-deficient regions, which contribute to its high reactivity. This feature, while making borophene useful for catalytic applications, also makes it vulnerable to instability in electronic and structural properties. The charge redistribution can result in the formation of defects or irregularities in the structure.

4.9.5 Strategies for Enhancing Stability of Borophene

To overcome these stability challenges and enhance the practical viability of borophene, several strategies can be explored.

4.9.6 Chemical Doping and Alloying

Doping with other elements such as nitrogen, carbon, or metals can be an effective way to stabilize borophene by modifying its electronic structure and reducing its reactivity. For example, doping borophene with carbon or nitrogen atoms can fill electron-deficient regions, reducing its tendency to react with environmental molecules. Alloying with other elements such as aluminum or gallium can enhance stability by modifying the bonding and mechanical properties of borophene, preventing undesirable transformations.

4.9.7 Passivation with Protective Coatings

Surface passivation with inert materials like graphene, h-BN (hexagonal boron nitride), or other 2D materials can help protect borophene from oxidation and environmental degradation. Polymer coatings or the use of molecules that form a protective layer can also serve as an effective barrier, shielding borophene from air and moisture while maintaining its intrinsic properties.

4.9.8 Strain Engineering

Applying external strain can help to stabilize the borophene structure. Strain can be used to tune the electronic properties and reduce the tendency for phase transitions that lead to instability. Controlled strain engineering has been shown to stabilize borophene in some cases by promoting favourable bonding configurations. Layered borophene materials, where strain can be distributed across layers, might also offer improved mechanical stability compared to freestanding monolayers.

4.9.9 Encapsulation Techniques

Encapsulation in protective materials like carbon nanotubes or other 2D materials can shield borophene from direct exposure to the environment. This approach has been successfully used in other 2D materials like graphene to enhance their stability under ambient conditions. Encapsulation not only prevents oxidation but can also improve the material's mechanical robustness by providing additional structural support.

4.9.10 Temperature and Environmental Control

Borophene's stability can be enhanced by controlling the synthesis temperature and environmental conditions. For example, synthesizing borophene at low temperatures or in vacuum conditions can help to preserve its structural integrity and prevent unwanted phase transitions. Low-temperature storage or synthesis under inert gas atmospheres such as argon or nitrogen can further minimize the exposure to reactive species such as oxygen and moisture, extending the material's lifetime and usability.

4.9.11 Hybridization with Other 2D Materials

Hybridizing borophene with other stable 2D materials, such as graphene or boron nitride (BN), can provide a synergistic effect that enhances its overall stability. The combined material could inherit the strength, stability, and environmental resistance of the other 2D material while maintaining the unique properties of borophene.

This approach could lead to the development of composites or heterostructures with improved mechanical, electronic, and chemical stability, making borophene more versatile for different applications.

4.9.12 Defect Engineering

Controlled introduction of defects into borophene can stabilize the material by altering the distribution of strain and charge, preventing the formation of larger-scale defects that could lead to instability. By carefully tuning the defect density, it may be possible to improve the material's resilience without sacrificing its desirable properties. Defect passivation using various chemical treatments can also reduce the reactivity of borophene's surface, thus improving its long-term stability.

5. Potential Applications of Borophene

The extraordinary attributes of borophene have made it a unique material with great potential applications such as in sensor, nano-electronics and optoelectronic devices and in energy storage technologies. Theory has reaved boron to be one of the most lighted 2D metal materials and hence viewed as an ideal material for energy storage (Jiang *et al*., 2016 and Chen *et al*., 2017). It has been studied that the interaction of H_2 with borophene is similar to that of graphene but the capacity of H_2 storage for borophene is larger than that of graphene. Studies show that the alkali metals such as Li, Na and K atom existing on the 2D boron sheet increase the binding energy and storage capacity for H_2. Studies have shown that the target gas on borophene surface is stronger than other 2D materials like graphene, MoS_2 and phosphorene (Leenaert *et al*., 2008; Kou *et al*., 2014 and Kuo *et al*., 2014). Hence borophene was predicted to be a potential candidate for nanoscale gas sensor. Borophene has demonstrated a similar behaviour that of semiconductor. The results obtained from experiment show that the device has ultralow switching voltage of less than 0.4V, suggesting its potential use in future electronic devices with a low energy consumption. Few layered B sheets prepared by ultrasound-assisted liquid phase exfoliation have been used as superconductor electrodes materials. The fabricated device exhibits an excellent electrochemical performance (Li *et al*., 2018). Boron element has also been used as a basic building block unit element for a new 2D compound material. Additionally, the high electroactive surface area, high electron mobility and anisotropic nature enhanced analytical properties in biosensing applications. This property has also enabled borophene to be applicable in the fabrication of biosensor used for detecting various diseases. Kailasa et al. used water-dispersed borophene quantum dots for the fabrication of a biosensor platform for sensing of dehydroepiandrosterone. The synthesized borophene quantum dots with a particle size of 1.61 _ 0.28 nm exhibit blue fluorescence under a 365 nm excitation wavelength and exhibit a quantum yield of 24.12%. This fluorescence property helps in the development of fluorescence biosensors. In the sensing results, it has been observed that the dehydroepiandrosterone selectively binds with borophene quantum dots and enhances the fluorescence of the borophene quantum dots. Fig 4 gives the several applications of borophene.

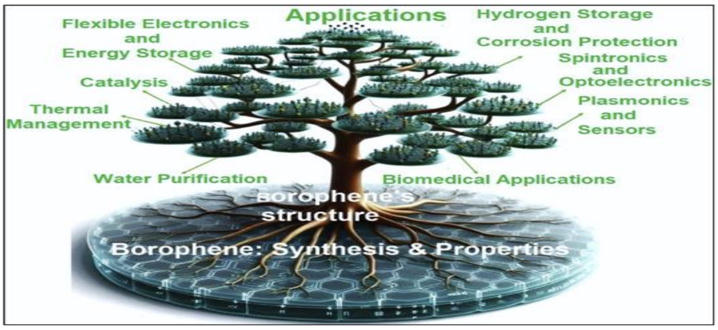

Fig 4. Application of borophene (Cuxart *et al*., 2021)

6. Summary of the Findings

Borophene synthesis can be achieved via top-down and bottom-up approaches. Top-down methods involve breaking down bulk boron into nanosheets using mechanical, chemical, and electrochemical exfoliation. Techniques like micromechanical cleavage and ball milling yield high-quality sheets but suffer from low scalability. Electrochemical exfoliation (EE) and liquid phase exfoliation (LPE) offer better scalability, with sonication and solvent selection significantly affecting thickness and yield. LPE, although promising for mass production, has limitations in layer control and monolayer yield. Bottom-up methods, including Molecular Beam Epitaxy (MBE), Chemical Vapor Deposition (CVD), and Van der Waals epitaxy, build borophene atom by atom. MBE offers precise control and high-quality borophene, while CVD is favourable for large-area production using gaseous boron precursors on substrates like Ag or Cu. Novel methods such as segregation-enhanced epitaxy and plasma-assisted ion implantation enable synthesis on alternative substrates. Substrate type and interaction play vital roles in borophene's structure, growth orientation, and electronic behaviour. Metal substrates aid structural order, while insulating substrates stabilize specific phases. Borophene's stability remains a critical issue. It is thermodynamically unstable, highly reactive to air and moisture, and sensitive to mechanical stress. Stability-enhancing strategies include chemical doping, surface passivation, encapsulation, strain engineering, and hybridization with other 2D materials. These methods aim to preserve borophene’s unique properties for practical applications. Borophene exhibits great potential in various fields, including energy storage, sensors, optoelectronics, and biomedicine. It shows promise as a gas sensor, hydrogen storage material, electrode in energy devices, and biosensor due to its high surface area, electronic conductivity, and unique fluorescence properties. Despite challenges, continued development in synthesis and stabilization techniques will pave the way for borophene’s integration into real-world technologies.

CONTRIBUTION TO KNOWLEDGE

This review consolidates current research on borophene, addressing problems in synthesis, stability, and application. It critically compares top-down and bottom-up synthesis techniques, evaluating their scalability and efficiency. The review also explores the fundamental causes of borophene’s instability and compiles strategies for enhancing its structural and environmental resilience, including doping, encapsulation, and strain engineering. Additionally, it emphasizes the influence of substrates and growth conditions on borophene’s properties. By linking material science to real-world applications in electronics, energy, and biosensing, the review offers a comprehensive roadmap for future research and supports borophene’s transition into practical engineering use.

CONCLUSION

Borophene synthesis techniques and the effect of substrate on growth mechanisms has been studied. The versatility and ability of boron to form various compound has unfolded its unique properties. The stability of boron is borophene is attributed to the nature of bonding of its atom which is in agreement with octet rule. The thermal stability of borophene is attribute to high phonon frequency which distinguishes it from other 2D group element. The electron deficiency of boron causes it to form a large number of multi-centre bonds that gives rise to its unique mechanical properties. Substrate effects play a critical role in the growth and stability of borophene, influencing its structural and electronic properties. The choice of substrate, such as silver, gold, or silicon, affects the lattice mismatch, interfacial interactions, and the degree of strain, which in turn dictate the morphology and quality of the borophene. Growth mechanisms involve complex processes like layer-by-layer deposition, nucleation, and the stabilization of boron’s unique bonding structures. Factors such as temperature, pressure, and substrate preparation also influence the formation of borophene’s 2D structure. Optimizing these conditions is key to controlling borophene’s properties and scalability for practical applications.

CONFLICT OF INTEREST

The authors declare no conflict of interest for this research work.

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REFERENCES

Amiri A, M. Naraghi, G. Ahmadi, M. Soleymaniha, M. Shanbedi (2018). A review on liquid-phase exfoliation for scalable production of pure graphene, wrinkled, crumpled and functionalized graphene and challenges, *FlatChem 8*, 40–71, https://doi.org/10.1016/j.flatc.2018.03.004.

Ashraf N, Y. Abghoui (2023). Borophene potential for developing next-generation battery applications: a comprehensive review, *Energy & Fuels*. https://doi.org/10.1021/acs.energyfuels.3c02319.

Aziz B, A.S. Asha, M.A. Ali, (2021). Evaluation of mechanical properties of borophene Nanotube by molecular dynamics simulation, https://doi.org/10.1063/5.0037898.

Balandin A.A (2011). Thermal properties of graphene and nanostructured carbon materials. *Nat Mater*, 10, 569–581, https://doi.org/10.1038/nmat3064.

Bhavyashree M, S.R. Rondiya, K. Hareesh (2022). Exploring the emerging applications of the advanced 2-dimensional material borophene with its unique properties. *RSC Adv.*, 12, 12166–12192, https://doi.org/10.1039/D2RA00677D.

Cuxart M. G, K. Seufert, V. Chesnyak, W. A. Waqas, A. Robert, M.-L. Bocquet, G. S. Duesberg, H. Sachdev, W. Auwarter (2021). *Sci. Adv.*, *7*, eabk1490.

Campbel G. Pl, A.J. Mannix, J.D. Emery, T.-L. Lee, N.P. Guisinger, M.C. Hersam, Wang Z. Q, T.Y. Lü, H.Q. Wang, Y.P. Feng, J.C. Zheng (2017). Band structure engineering of borophane by first principles calculations. *RSC Adv.*, 7, https://doi.org/10.1039/c7ra05704k.

Chen X, L. Wang, W. Zhang, J. Zhang, Y. Yuan (2017). *Int. J. Hydrogen Energ.*, *42*, 20036-20045. Feng B, L. Chen, K. Wu, Synthesis of borophene, in: 2D Boron: Boraphene, Borophene, Boronene, Springer International Publishing, Cham, 2021, pp. 51–72. https://doi.org/10.1007/978-3-030-49999-0_3.

Fisher B.L., U. Santiago, J.R. Guest, M.J. Yacaman, A. Ponce, A.R. Oganov, M.C. Hersam, N.P. (2015). Guisinger, Synthesis of borophenes: anisotropic, two-dimensional boron polymorphs. *Science*, 350, 1513–1516 https://doi.org/10.1126/science.aad1080 (1979).

Folorunso O., Y. Hamam, R. Sadiku, S.S. Ray, G.J. Adekoya (2021). Synthesis methods of borophene, graphene-loaded polypyrrole nanocomposites and their benefits for energy storage applications: a brief overview. *FlatChem*, 26, 100211. https://doi.org/10.1016/j.flatc.2020.100211.

Gupta G.H, S. Kadakia, D. Agiwal, T. Keshari, S. Kumar (2024). Borophene nanomaterials: synthesis and applications in biosensors. *Mater Adv.*, . https://doi.org/10.1039/D3MA00829K.

Gao M, Q.Z. Li, X.W. Yan, J. Wang (2017). Prediction of phonon-mediated superconductivity in borophene. *Phys Rev B.*, 95, https://doi.org/10.1103/PhysRevB.95.024505.

Gupta S., A. Kutana, B.I. Yakobson (2018). Dirac cones and nodal line in borophene. *Journal of Physical Chemistry Letters*, 9. https://doi.org/10.1021/acs.jpclett.8b00640.

Hasan M.A.M, Y. Wang, C.R. Bowen, Y. Yang (2021). 2D nanomaterials for effective energy Scavenging, Nanomicro. *Lett.,* 13, 82. https://doi.org/10.1007/s40820-021-00603-9.
Hess P, Bonding, structure, and mechanical stability of 2D materials: the predictive power of the periodic table. *Nanoscale Horiz*, 6, 856–892, https://doi.org/10.1039/D1NH00113B.

Huang Y., J. Liang, Y. Chen (2012). An overview of the applications of graphene-based materials in supercapacitors. *Small*, 8, 1805–1834, https://doi.org/10.1002/smll.201102635.

Jiang H. R, Z. Lu, M. C. Wu, F. Ciucci, T. S. Zhao (2016). *Nano Energy*, *23*, 97-104.

Kaneti Y.V, D.P. Benu, X. Xu, B. Yuliarto, Y. Yamauchi, D. Golberg, Borophene: two-dimensional boron monolayer: synthesis, properties, and potential applications. *Chem Rev.*, 122, 1000–1051. https://doi.org/10.1021/acs.chemrev.1c00233.

Kou L, T. Frauenheim, C. Chen, *J.* (2014). *Phys. Chem. Lett. 5*, 2675-2681.

Leenaerts O, B. Partoens, F. M. Peeters (2008). *Phys. Rev. B.*, *77*, 125416.

Lee K.H., H.J. Shin, J. Lee, I.Y. Lee, G.H. Kim, J.Y. Choi, S.W. Kim, Large-scale synthesis of high-quality hexagonal boron nitride nanosheets for large-area graphene electronics. *Nano Lett*,12. https://doi.org/10.1021/nl203635v.

Lei Y, T. Zhang, Y.-C. Lin, T. Granzier-Nakajima, G. Bepete, D.A. Kowalczyk, Z. Lin, D. Zhou, T.F. Schranghamer, A. Dodda, A. Sebastian, Y. Chen, Y. Liu, G. Pourtois, T.J. Kempa, B. Schuler, M.T. Edmonds, S.Y. Quek, U. Wurstbauer, S.M. Wu, N.R. Glavin, S. Das, S.P. Dash, J.M. Redwing, J.A. Robinson, M. Terrones (2022). Graphene and beyond: recent advances in two-dimensional materials synthesis, properties, and devices, ACS Nanoscience Au 2, 450–485, https://doi.org/

Liu J, Y. Ma, J. Yang, L. Sun, D. Guo, P. Xiao (2022). Recent advance of metal borohydrides for hydrogen storage, Front Chem 10. https://doi.org/10.3389/fchem.2022.945208.

Li H, L. Jing, W. Liu, J. Lin, R. Y. Tay, S. H. Tsang, E. H. T. Teo (2018). *ACS Nano*, *12*, 1262-1272.

Li H, L. Jing, W. Liu, J. Lin, R. Y. Tay, S. H. Tsang, E. H. T. Teo (2018). *ACS Nano*, *12*, 1262. 10.1021/acsnanoscienceau.2c00017.

Mannix A. J, Z. Zhang, N. P. Guisinger, B. I. Yakobson, M. C. Hersam (2018). *Nat. Nanotechnol.*, *13*, 444.

Mishra R.V.R. R, K.N. C.J, T.S. (2018). Nanostructured epoxy/block copolymer blends: characterization of micro- and nanostructure by atomic force microscopy, scanning electron microscopy, and transmission electron microscopy, in: N.K.S.T.A.P. Aparna Thankappan (Ed.), Polymeric and Nanostructured Materials, first ed., Apple Academic Press, New York, pp. 71–126.

Mogulkoc A, Y. Mogulkoc, D. Kecik, E. Durgun (2018). The effect of strain and functionalization on the optical properties of borophene, Physical Chemistry Chemical Physics 20, 21043–21050, https://doi.org/10.1039/C8CP03594F.

Mortazavi B, M. Makaremi, M. Shahrokhi, M. Raeisi, C.V. Singh, T. Rabczuk, L.F.C. Pereira (2018). Borophene hydride: a stiff 2D material with high thermal conductivity and attractive optical and electronic properties, Nanoscale, 10, 3759–3768, https://doi.org/10.1039/C7NR08725J.

Omambac K. M, M. Petrovi´c, P. Bampoulis, C. Brand, M. A. Kriegel, P. Dreher, D. Janoschka, U. Hagemann, N. Hartmann, P. Valerius, T. Michely, F. J. (2021). Horn-von Hoegen, *ACS Nano*, *15*, 7421.

Qiu L, X. Zhang, X. Kong, I. Mitchell, T. Yan, S.Y. Kim, B.I. Yakobson, F. Ding (2023). Theory of sigma bond resonance in flat boron materials, Nat Commun 14, 1804, https://doi.org/10.1038/s41467-023-37442-8.

Ranjan P, T.K. Sahu, R. Bhushan, S.S.R.K.C. Yamijala, D.J. Late, P. Kumar, A.Vinu (2019). Freestanding borophene and its hybrids, Advanced Materials 31. https://doi.org/10.1002/adma.201900353.

Sielicki K, K. Ma´slana, X. Chen, E. Mijowska (2022). *Sci. Rep.*, *12*, 15683.

Sun X, X. Liu, J. Yin, J. Yu, Y. Li, Y. Hang, X. Zhou, M. Yu, J. Li, G. Tai, W. Guo (2017). Two-dimensional boron crystals: structural stability, tunable properties, fabrications and applications. Adv Funct Mater 27, https://doi.org/10.1002/adfm.201603300.

Tai G, M. Xu, C. Hou, R. Liu, X. Liang, Z. Wu (2021). *ACS Appl. Mater. Interfaces*, *13*, 60987.

Tsai H. S., C.-H. Hsiao, Y.-P. Lin, C.-W. Chen, H. Ouyang, J.-H. Liang (2016). *Small*, *12*, 5251.

Wang Z. Q, T.-Y. Lü, H.-Q. Wang, Y.P. Feng, J.-C. Zheng (2019). Review of borophene and its potential applications, https://doi.org/10.1007/s11467-019-0884-5,2019.

Wu Z, G. Tai, R. Liu, C. Hou, W. Shao, X. Liang, Z. Wu (2021). *ACS Appl. Mater. Interfaces*, *13*, 31808.

Xie Z, X. Meng, X. Li, W. Liang, W. Huang, K. Chen, J. Chen, C. Xing, M. Qiu, B. Zhang, G. Nie, N. Xie, X. Yan, H. Zhang (2020). Two-dimensional borophene: properties,fabrication, and promising applications, research, https://doi.org/10.34133/2020/2624617, 2020.

Xu J, Y. Chang, L. Gan, Y. Ma, T. Zhai (2015). *Adv. Sci.*, *2*, 1500023.

Yan L., R. Ku, J. Zou, L. Zhou, J. Zhao, X. Jiang, B.T. Wang (2021). Prediction of superconductivity in bilayer borophenes, RSC Adv 11, https://doi.org/10.1039/d1ra08014h.

Zavabeti A., A. Jannat, L. Zhong, A.A. Haidry, Z. Yao, J.Z. Ou (2020). Two-dimensional materials in large-areas: synthesis, properties and applications, Nanomicro Lett 12. https://doi.org/10.1007/s40820-020-0402-x.

Zielinkiewicz K, E. Mijowska (2024). *Sustain. Mater. Technol. 39*, e00860.