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Borophene: A 2D wonder shaping the future of nanotechnology and materials science

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ABSTRACT

Two-dimensional (2D) materials have attracted considerable research interest due to their precisely defined properties and versatile applications. In this realm, borophene - a single atomic sheet of boron atoms arranged in a honeycomb lattice - has emerged as a promising candidate. While borophenes were theoretically predicted to have unique structural, optical, and electronic properties, the experimental synthesis of crystalline borophene sheets was first demonstrated on metal substrates in 2015, marking a crucial milestone. Since then, research efforts have focused on controlling the synthesis of semiconducting borophene polymorphs and exploring their novel physical characteristics. This review aims to explore the potential of 2D materials, specifically borophene, in various technological fields such as batteries, supercapacitors, fuel cells, and more. The analysis emphasises meticulous scrutiny of synthesis techniques due to their fundamental importance in realising borophene's properties. Specifically, the high carrier mobilities, tuneable bandgaps, and exceptional thermal conductivity of borophene are highlighted. By providing a comprehensive outlook on the significance of borophene in advancing materials science and technologies, this review contributes to shaping the landscape of 2D material research.

1. Introduction

Two-dimensional (2D) nanomaterials, with their extraordinary properties, spark innovations across diverse research fields, including sectors such as energy storage, electronics, and catalysis [1,2]. Borophene, a single-atom layer of boron arranged in a graphene-like structure, stands out as a particularly promising member of this 2D material family [3]. While first theorised in the 1990s, the experimental synthesis of borophene presented significant hurdles due to the complex nature of boron's chemical bonding and its resulting polymorphism [4,5]. The complexity hindered the early creation of atomically thin borophene. A significant breakthrough occurred in 2015 when researchers successfully synthesised various borophene polymorphs [6,7]. This was accomplished using physical vapor deposition, where boron was deposited from high-purity solid sources onto a silver single-crystal surface under ultra-high vacuum conditions. This advancement marked a pivotal turning point in borophene research. The term "borophene" was introduced in a 2014 [8] to describe this unique material. Its distinctive structure, featuring intricate triangular and hexagonal motifs, arises from the complex in-plane bonding characteristic of electron-deficient boron [9]. Computational studies suggest the possibility of stable extended boron sheets with partially filled hexagonal holes. This concept was further solidified by the experimental discovery of the highly stable, quasi-planar boron cluster B36, which features a central hexagonal hole. This breakthrough provided the first concrete evidence for the feasibility of single-atom-thick boron sheets with hexagonal vacancies. Borophene's atomic structure offers exceptional mechanical flexibility and, in specific configurations, strength that surpasses even graphene [8]. Moreover, theoretical studies predict metallic electronic properties, making borophene the lightest element to form a stable 2D metal. These unique properties make borophene a promising material for energy storage applications. Researchers are actively exploring its use in various areas,

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including thin-film electronics, optoelectronics, capacitors, and biosensors [10]. Borophene's exceptional theoretical capacity, conductivity, and ion transport make it a promising high-capacity anode for Li, Na, and Mg batteries [4]. Borophene's bandgap can be modulated through applied shear strain, reaching up to 0.538 eV [11]. This tunability is crucial for customising electronic properties and for potential use in devices with specific bandgap requirements. Borophene polymorphs demonstrate excellent thermal conductivity, with values such as 335 W/mK and 293 W/mK in borophene hydride [12]. This property is beneficial for efficient thermal management in various applications. Introducing vacancies or defects into borophene's structure allows for customising its properties. Researchers have explored the impact of strain, hydrogen defects, and boron-hydrogen dimers on band structure tuning [11]. Borophene can be utilised in gas sensors, energy conversion devices, and hydrogen storage [13,14]. Borophene's high thermal conductivity holds promise for enhancing the efficiency of energy storage devices [15]. Research shows borophene's promise as a battery anode with strong electrochemical performance for Li-ion and Na-ion storage [16–18]. Theoretical evaluations suggest that borophene could serve as high-capacity anodes for metal-ion batteries due to its favourable electrical conductivity, mechanical durability, surface area, and ion transport [19]. Calculations show that borophene polymorphs such as β_{12} and χ_3 exhibit capacities up to 1984 mAh/g for Li-ion storage, surpassing conventional graphite anodes and other 2D materials [20]. Studies also predict fast Na-ion diffusion in puckered borophene with a low 30 meV barrier, enabling high theoretical capacities around 1240 mAh/g as sodium-ion anodes [21]. Borophene and boron-rich compounds also hold promise for hydrogen storage, which is crucial for sustainable transportation [20,22,23]. The high surface area and conductivity of borophene make it attractive for hydrogen storage, especially when doped with metal atoms to enhance H_2 binding [24]. Divacancy-containing borophene can achieve an impressive 9.2% H2 weight fraction due to increased interactions between H_2 and borophene [25]. Light borohydrides, such as Mg $(BH_4)_2$, containing 14.9 wt% H_2, have been extensively researched as hydrogen storage materials. Investigations reveal intermediate species formed during dehydrogenation [26]. Boron and nitrogen-containing compounds also enable high hydrogen densities. The combination of versatile borophene sheets and tailored boron-rich hydrides shows promise in addressing hydrogen storage requirements for sustainable transportation [27]. Additionally, borophene-based sensors effectively detect gases such as NO_2 [28]. NO_2 is one of the major components of air pollution. It causes respiratory problems, especially in individuals with asthma or other lung conditions. Investigations of a chemiresistive borophene sensor demonstrate high sensitivity to NO_2, fast response and recovery times, excellent selectivity, and stability. The device exhibits a low 200 ppb detection limit, a wide 200 ppb-100 ppm range, and response and recovery times of 30 s and 200 s at room temperature, outperforming other reported 2D material sensors. First-principles calculations reveal that the NO_2 sensing mechanism in borophene involves charge transfer. Experiments confirm the distinctive selectivity of borophene for NO_2 over other common gases [29]. Theoretical insights into the sensing mechanisms and experimental gas testing results validate the efficacy of borophene-based sensors for NO_2 detection and monitoring [10]. Recent synthesis of macroscale borophene sheets enables their integration into various applications in energy technology and biomedicine [9,29]. In energy technology, borophene shows promise for energy storage devices due to its outstanding properties [9]. Additionally, its exceptional optical, electrical, mechanical, thermal, and magnetic properties position borophene as a potentially revolutionary material for biomedical applications [30]. This includes biomedical sensors, diagnostic tools, high-performance healthcare devices, and energy storage. Borophene could drive advancements in smart healthcare devices assisted by AI, IoT, and IoMT [9]. Fig. 1 illustrates the diverse range of applications for borophene, a two-dimensional material composed of boron atoms. Borophene's unique properties make it suitable for various fields, including flexible electronics, energy storage, catalysis, sensors, spintronics, thermal management, water purification, and optoelectronics. This review aims to provide a comprehensive understanding of 2D nanomaterials, focusing on borophene's versatility due to its adjustable electronic, thermal, and optical properties. This analysis of borophene provides insights for developing advanced materials solutions to address global energy and technology challenges.

2. Background on 2D materials

Nanomaterials, due to their nanoscale dimensions, have a profound

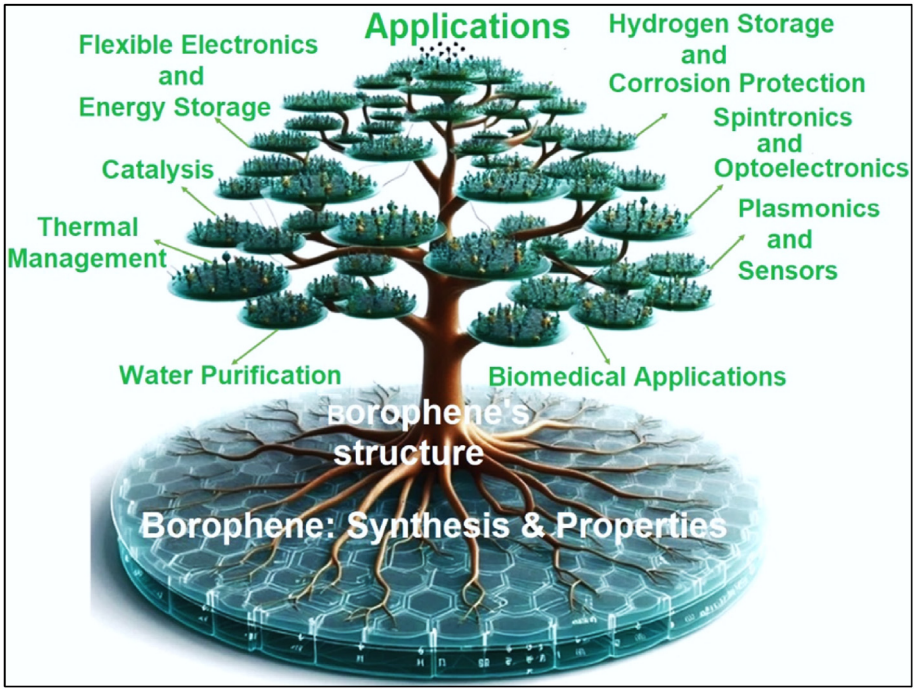


Fig. 1. From roots to diverse applications of borophene research.

impact on materials science. They are classified into zero-dimensional (0D), one-dimensional (1D), two-dimensional (2D), and bulk materials (Fig. 2a). Zero-dimensional (0D) nanomaterials, such as nanoparticles, lack extended nanoscale dimensions and exhibit spherical or cubic shapes. One-dimensional (1D) nanomaterials, such as nanowires and nanotubes, have elongated structures with high aspect ratios [31,32]. Two-dimensional (2D) nanomaterials possess sheet-like structures. Graphene [33], renowned for its exceptional electrical conductivity and mechanical strength, sparked a surge of interest in 2D materials [34]. Other significant 2D materials include transition metal dichalcogenides (TMDs), hexagonal boron nitride (h-BN), phosphorene, and Xenes, each tailored for specific applications [35,36]. Borophene, with its hexagonal lattice structure, exhibits intriguing mechanical and electrical properties, attracting considerable scientific attention [37]. Understanding nanomaterial classifications enables targeted development for diverse materials science applications. The unique properties of 2D materials such as borophene and graphene are transforming various sectors, including energy, electronics, sensing, and biomedicine [38]. This diverse array of 2D materials, including graphene, h-BN, TMDs, phosphorene, Xenes, borophene, and MXenes, offers exceptional promise for electronics, optoelectronics, and magneto-electronics applications (Fig. 2b and c) [39, 40]. Their high carrier mobility, tuneable bandgaps, exceptional thermal conductivity, and potential for magnetic control position them at the forefront of technological innovation. Researchers worldwide are developing novel synthesis methods to unlock the full potential of 2D materials [41,42]. Xenes, including borophene, offer unique properties ideal for electronic applications, such as high conductivity and tunable bandgaps [43,44]. Their atomic thinness enables applications in catalysis, sensing, and energy conversion. Precise control over electrical properties can be achieved by adjusting the layer count or introducing dopants. Borophene's superconductivity, elasticity, and thermal conductivity make it promising for advanced energy storage and catalysis [4]. Fig. 2d presents a comprehensive overview of the fabrication methods and research progress for various 2D materials, such as graphene derivatives, TMDs, boron nitride nanosheets, black phosphorus nanosheets, metal nanosheets, g-C3N4 nanosheets, layered double hydroxides, and clay nanosheets [45–48].

The fabrication of 2D materials involves diverse top-down and bottom-up techniques, each with advantages and limitations. Top-down methods, such as mechanical cleavage and liquid exfoliation, rely on breaking weak van der Waals forces within layered materials to obtain thin sheets. Mechanical cleavage, the original method used to isolate

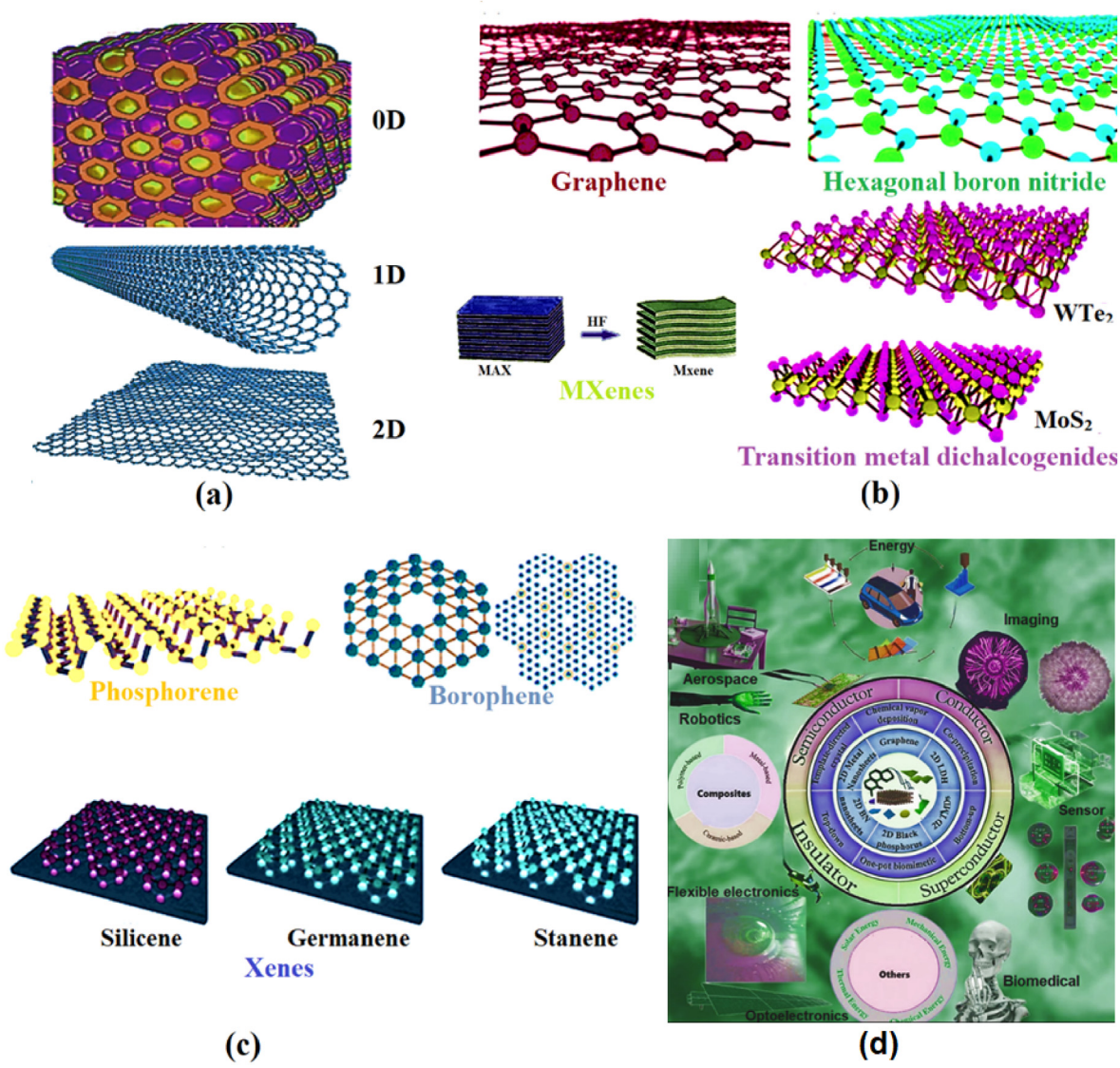


Fig. 2. (a) Classification of nanomaterials based on their nanoscopic dimensions, **(a)** Zero-Dimensional (0D) materials are represented by nanoparticles, One-Dimensional (1D) materials by carbon nanotubes, Two-Dimensional (2D) materials, A Diverse Ensemble of 2D Materials: **(b)** Graphene, Hexagonal boron nitride, transition metal dichalcogenides, **(c)** Phosphorene, Borophene (type of xenes), xenes, and **(d)** 2D Nanomaterials: From Fabrication, properties to applications.

graphene, offers high-quality 2D materials but has limited scalability [49]. Liquid exfoliation, while more scalable, often results in variations in flake size and thickness [50]. Bottom-up approaches, such as chemical vapor deposition (CVD) and wet-chemical synthesis, involve constructing 2D materials from atomic or molecular precursors. CVD enables the growth of large-area, uniform 2D materials but often requires high temperatures, specialised substrates, and controlled environments [51]. Wet-chemical methods, such as hydrothermal/solvothermal synthesis and soft colloidal synthesis, provide versatility, scalability, and control over morphology by adjusting conditions like temperature, precursors, and solvents [52,53]. Table 1 summarises various synthesis methods, providing descriptions, advantages, disadvantages, and recent advancements. 2D materials hold immense promise, but production costs, scalability, and environmental concerns must be addressed for widespread adoption.

The field of 2D materials research and applications is rapidly advancing, with significant progress in synthesis and applications across diverse scientific domains. Graphene, renowned for its exceptional electronic and optical properties, has revolutionised electronics and optoelectronics. It drives innovation in faster, more energy-efficient devices, advanced photodetectors, and LEDs [63–66]. Graphene also has significant applications in energy storage solutions, enhancing the performance of supercapacitors and batteries [67]. Its use in gas and biosensors enables precise detection for environmental monitoring, medical diagnostics, and industrial applications [68,69]. Moreover, graphene's potential for mechanical reinforcement holds promise for lighter and stronger materials in various sectors [70]. Borophene, with its high thermal conductivity, metallic behaviour, and superior electron mobility, is a rising star in energy harvesting, storage, and sensing [71,72]. Its effectiveness in thermal management, ion battery enhancement, and hydrogen storage solutions has far-reaching implications for clean energy technologies [4,71]. Borophene's role in gas and electrochemical sensors contributes to advances in environmental monitoring and medical diagnostics [73]. Additionally, its biocompatibility and unique properties pave the way for innovations in drug delivery and biomaterials [74]. The remarkable physical, electronic, optical, and chemical properties resulting from the reduced dimensionality of 2D nanomaterials have broad implications for biomedicine. Their large surface area and atomic thickness facilitate effective interactions with therapeutic molecules, enhancing drug delivery systems and nucleic acid carriers [75,76]. These ultra-thin, strong structures offer flexibility and resilience for applications in stem cell differentiation, tissue engineering, neural monitoring, and controlled drug release [77–79]. 2D materials exhibit a spectrum of electronic behaviours (semiconducting, insulating, etc.), enabling customised biomedical applications. For example, semiconducting 2D materials are utilised in photodynamic therapy (PDT) and photoacoustic imaging (PAI), demonstrating selective targeting of bacteria and cancer cells [79]. Their tuneable conductivity, achieved through structural modifications, doping, and thickness control, facilitates their use in biosensors, drug delivery systems, and sequence-specific transistors [80]. The optical properties of 2D materials, which are linked to their band structure, are utilised in bioimaging and biosensing across a wide optical range [81]. Particularly in near-infrared (NIR) applications, semiconducting 2D materials exhibit strong photothermal effects, rendering them suitable for various phototherapies (PTT, PDT), and chemotherapy [81,82]. Controlled introduction of defects further enhances their utility in optoelectronics. Finally, the surface chemistry of 2D materials is crucial in biomedicine. Functionalisation strategies enhance biocompatibility and enable targeted interactions, facilitating drug delivery, targeted molecule release, and controlled release mechanisms [83–85]. Table 2 provides a comprehensive overview of the exceptional properties of 2D materials.

3. Borophene

Borophene, a recently discovered two-dimensional material with a hexagonal boron lattice, has captured significant scientific interest. Unlike graphene, borophene's electron-deficient nature, stemming from a single p-shell electron ($2s^2 2p^1$), leads to unique properties [4]. Its anisotropic mechanical behaviour, including the ability to expand under tensile stress, is particularly intriguing. Moreover, borophene exhibits exceptional electronic mobility, making it a promising candidate for high-speed, low-power electronics [100]. The diverse structures of borophene, driven by distinct bonding mechanisms and sheet protrusions [101], contribute to its multifaceted characteristics. Its anisotropic thermal conductivity and distinct electronic structure hold promise for thermal management and nanoelectronics applications. Different phases, such as β_{12} and X_3, offer customised properties for sensing and electronics [102]. However, addressing borophene's environmental stability, particularly its susceptibility to defects and functionalisation, is a crucial area for further research [103]. Ensuring scalable and cost-effective synthesis methods is essential for widespread practical application. Recent breakthroughs have introduced two new metallic 2D boron sheets with properties comparable to graphene [104]. The successful growth of borophene on a silver substrate (Ag (111)) demonstrates enhanced stability, resistance to oxidation, and weak binding with the substrate [104]. Molecular beam epitaxy has produced two distinct borophene polymorphs with triangular lattices and varying hexagonal hole arrangements. Studying temperature-induced phase transitions in these structures reveals the formation of monolayer borophene islands with unique features, providing valuable insights for potential nanoelectronic applications [105]. The stability of borophene islands on a silver substrate, even under elevated oxygen exposure, is remarkable. Their weak edge-based substrate interaction suggests borophene's suitability for isolation, like graphene, enabling manipulation and integration into electronic and nanomaterial systems. Theoretical studies predict

Table 1
Methods for 2D Material synthesis.

Method	Brief Description	Advantages	Disadvantages	State of the Art Knowledge	Ref.
Mechanical Exfoliation	Use of adhesive Scotch tape to peel layered bulk crystals, followed by deposition on a target substrate	High quality, large lateral size, few defects	Low yield, non-massive production	Automation and controlled layer thickness advancements	[52, 54]
Liquid Exfoliation	Direct sonication of layered bulk crystals in solvents or with surfactants/ polymers	Solution processibility, massive production	Low yield of single layers, uncontrollable layer number, relatively small lateral size	Improved solvents and surfactants	[55, 56]
Ion-Intercalation and Exfoliation	Intercalation of layered bulk compounds with Li or Na ions followed by sonication in solution	Solution processibility, massive production, high yield of monolayers	Relatively small lateral size with possible defects and phase transformation, sensitivity to water and oxygen	Enhanced intercalation strategies	[57, 58]
Chemical Vapor Deposition	Precursors react and/or decompose on the substrate surface at high temperature and high vacuum	High quality, large lateral size, controllable thickness, few defects	High temperature, high vacuum, complex experiments, high cost	Advances in precursors and growth techniques	[59, 60]
Wet-Chemical Synthesis	Direct synthesis in solution phase with surfactants or polymers	Solution processibility, high yield, massive production	Surfactants required, difficulty in obtaining uniform single-layer nanosheets	Tailored surfactants and improved synthesis conditions	[61, 62]

Table 2
Properties of 2D materials, including Physical, Chemical Electronic, Properties.

Property	Description	Applications	Ref.
High Surface Area	Due to atomic thickness and large lateral dimension, 2D nanomaterials offer exceptionally high specific surface area per volume.	Biomedical applications (drug delivery, nucleic acid carriers), catalytic reactions, removing pollutants from water and air	[86, 87]
Flexibility and Strength	In-plane covalent bonding results in high strength; flexibility can be tuned by altering bonding and thickness.	Lightweight composite materials for aircraft and spacecraft, wearable technology, smart clothing	[88]
Surface Functionalisation	Surface modifications enhance biocompatibility, protect, encapsulate, and target linker functionalisation.	Removing pollutants and contaminants, improving electrode performance in batteries and supercapacitors	[89, 90]
Rapid Response to Stimuli	2D nanomaterials can rapidly respond to external stimuli like pH changes, enabling controlled molecule release.	Sensors for detecting environmental changes, precise release of drugs or chemicals in response to specific stimuli	[91]
Tuneable Surface Chemistry	Versatile tuning of surface chemistry provides selectivity and analysis for various biomedical applications.	Chemical and biological sensors, nanoscale electronic devices with specific properties	[92]
Air and Water Stability	Surface functionalisation enhances stability; used as protective coatings to improve corrosion resistance.	Protective coatings, water treatment processes to remove contaminants	[93]
Diverse Electronic Types	2D nanomaterials exhibit a range of electronic properties from semimetals to insulators to semiconductors.	Electronic devices (transistors, sensors, memory devices), solar cell applications	[94]
Tuneable Conductivity	Conductivity can be tuned by altering structure, doping, and thickness.	Conductive coatings for aircraft, prevention of lightning strikes and electromagnetic interference	[94]
Defect-Induced Effects	Defects can change conductivity and electron movement.	Gas sensors, photocatalytic reactions for environmental remediation	[95]
Interaction with Light	Optical properties depend on the electronic band structure.	Optoelectronic devices (photodetectors, LEDs, lasers), optical communication systems for data transmission and signal processing	[96]
Photothermal Effects	Semiconducting 2D nanomaterials exhibit high photothermal effects under NIR irradiation.	Photothermal therapy (PTT) for cancer treatment, pH/photosensitive drug delivery systems	[97]
Emission Properties	Some 2D nanomaterials can emit light upon excitation.	Displays, lighting applications, imaging techniques for fluorescence imaging and labelling	[98]
Plasmonic Resonance	Some 2D nanomaterials exhibit localised surface plasmon resonance.	Plasmonic sensors for detecting changes in refractive index, high-resolution imaging techniques based on plasmon resonance	[99]

potential superconductivity in borophene sheets at approximately 10 K, further highlighting its promise for boron-based electronics when combined with its stability and weak substrate binding [106]. Borophene's exceptional metallic behaviour, drastically different from bulk boron, underscores its significance for further research. Moreover, its synthesis via non-toxic electron-beam evaporation demonstrates a pathway for producing borophene with metallic behaviour, suitable for exploration in electronics and photovoltaics [90]. Fig. 3 presents large-scale scanning tunnelling microscopy (STM) images providing an overview of monolayer borophene islands on an Ag (111) substrate [90,106]. High-resolution scanning tunnelling microscopy (STM) further reveals atomic-scale structural details. Theoretical models depict borophene's triangular lattice with periodic boron vacancies, emphasising its unique characteristics on the silver substrate. These images, models, and the description of electron-beam evaporation synthesis provide a comprehensive understanding of borophene's behavior and production [90].

4. Borophene synthesis techniques

Borophene synthesis is a key research focus due to its exceptional electronic mobility and metallic properties, offering possibilities for various applications [90,107]. Borophene's characteristics inspire the development of various production methods. Borophene synthesis methods include top-down and bottom-up approaches, each with distinct advantages and limitations [10,108]. Top-down approaches involve starting with bulk boron and breaking it down into nanoscale borophene sheets. Bottom-up methods, on the other hand, construct borophene structures atom by atom. The optimal approach depends heavily on the specific application requirements. Factors such as desired borophene properties, the scale of production, and cost constraints all play a role in the decision [10]. Molecular Beam Epitaxy (MBE) is performed in ultra-high vacuum. It is considered the most precise method for borophene synthesis. It involves evaporating boron atoms from a high-temperature source, which deposit in a controlled manner onto a

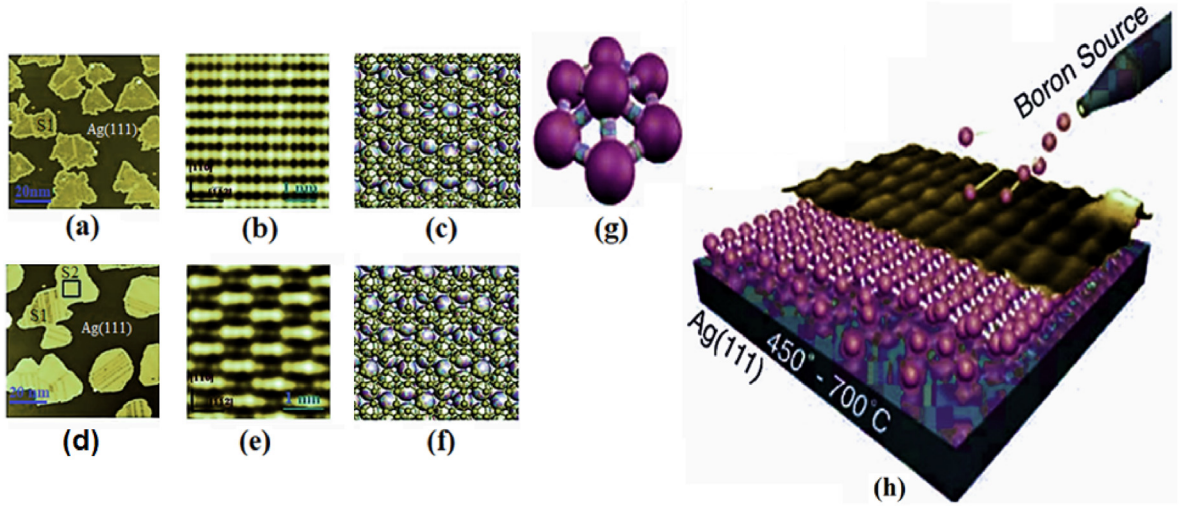


Fig. .3. (a, d) Large-scale scanning tunnelling microscopy (STM) images provide an overview of monolayer borophene islands on the Ag (111) substrate, **(b, e)** High-resolution STM images reveal finer details within these borophene islands, **(c, f)** Atomic structure models depict triangular boron lattices with periodic boron vacancy arrangements of borophene on the silver substrate [106], **(g–h)** Synthesis of borophenes: Anisotropic, two-dimensional boron polymorphs [90].

substrate [5]. While chemical vapor deposition (CVD) can also produce borophene, it often requires higher costs and more time. This technique involves a precursor gas that decomposes on a heated substrate, forming a thin borophene film. Similar to chemical vapor deposition (CVD), physical vapor deposition (PVD) can be used to synthesise borophene, but it is also known to be costly and time-consuming. PVD utilises evaporation or sputtering of boron to deposit a thin film onto a substrate [109]. The optimal synthesis method depends on specific application needs. MBE is often preferred for its ability to produce high-quality borophene, while CVD and PVD may be more suitable for larger-scale production [5,109].

4.1. Top-down approaches

Top-down approaches to borophene synthesis involve starting with a bulk boron material and breaking it down into nanoscale sheets [10]. Fig. 4 illustrates several top-down methods for borophene synthesis. Mechanical exfoliation (Fig. 4a) involves isolating thin borophene layers from bulk crystals, similar to the process used for graphene production. While this results in high-quality material, scalability poses a significant challenge. In chemical exfoliation (Fig. 4b), chemical agents are used for controlled etching to produce borophene. The Modified Hummer's Method (Fig. 4c) is a promising approach with potential for scalability and has already been used in prototype devices. Sonochemical exfoliation (Fig. 4d) utilises ultrasound waves to fragment bulk boron. Researchers are actively optimising this method for large-scale production. While mechanical exfoliation is common for graphene synthesis, it faces challenges when applied to borophene. This difficulty arises from boron's polymorphism and the absence of a layered, graphite-like structure in its bulk forms [16]. A novel solvothermal-assisted liquid-phase exfoliation process has been developed for borophene production. This method involves ball milling for thinning, solvothermal swelling, and probe ultrasonic delamination. The exfoliation effectiveness of bulk boron precursors depends on the surface tension and Hildebrand parameter of

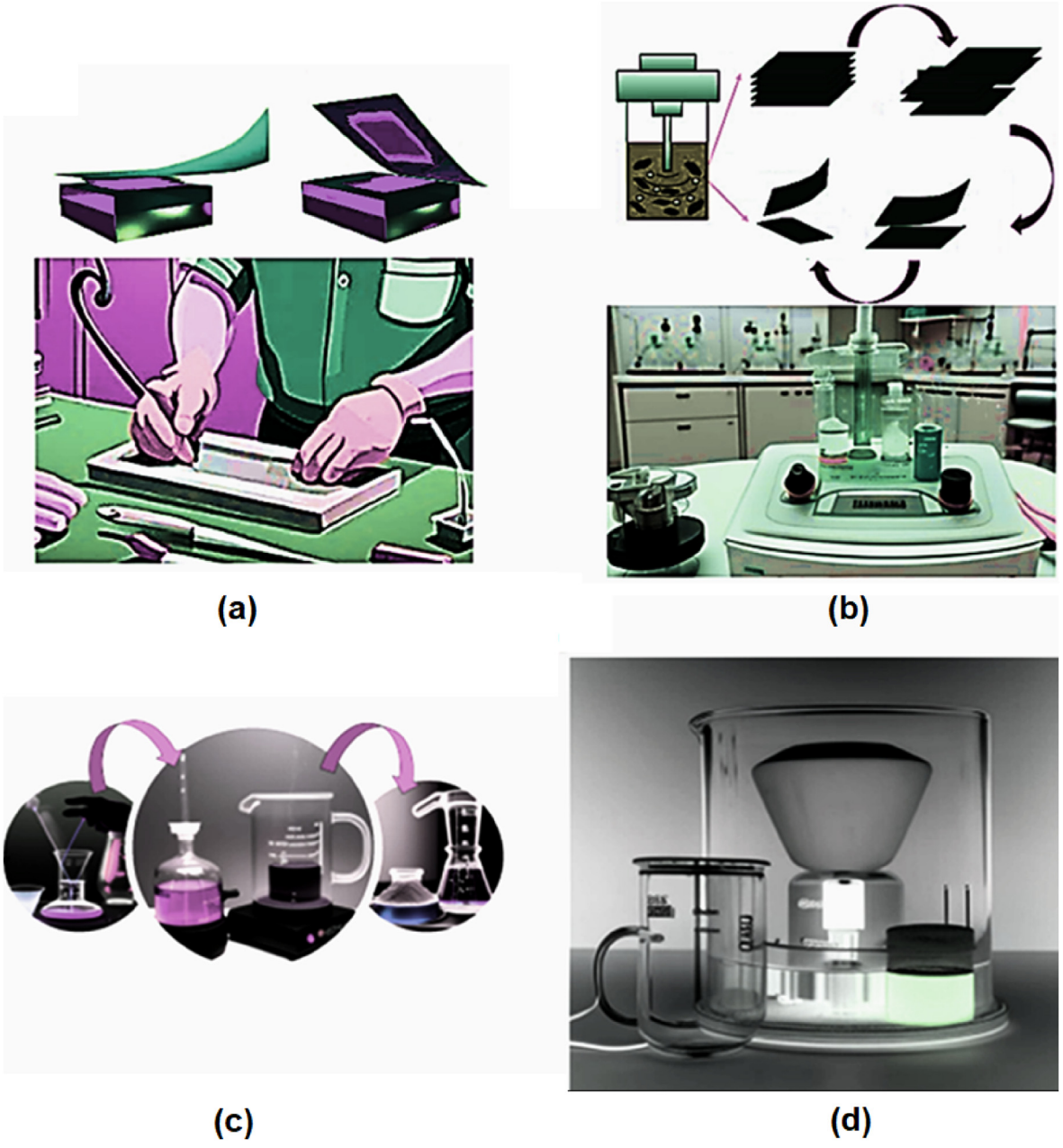


Fig. .4. a) Mechanical Exfoliation, b) Chemical Exfoliation, (c) Modified Hummer's Approach, (d) Sonochemical Exfoliation.

the selected solvents. This technique can yield few-layer borophene with large flake sizes [110].

4.2. Bottom-up approaches

Bottom-up approaches to borophene synthesis involve assembling nanoscale structures from individual atoms or molecules [10,16]. Key methods in this category include chemical vapor deposition (CVD), physical vapor deposition (PVD), and others [4,109]. Fig. 5 illustrates these techniques. Molecular Beam Epitaxy (MBE) offers exceptional control over borophene structure by precisely depositing boron atoms onto a substrate. This precision is crucial for research and device development (Fig. 5a) [111]. Chemical Vapor Deposition (CVD) is a versatile and scalable method. It involves a precursor gas decomposing on a heated substrate to form a borophene film. Researchers are actively optimising chemical vapor deposition (CVD) for improved borophene quality and growth control (Fig. 5b) [112]. Atomic Layer Deposition (ALD) enables the growth of high-quality borophene on various substrates through sequential deposition processes [113,114]. Fig. 5c illustrates the fundamental concept of Atomic Layer Deposition (ALD) for borophene synthesis.

The development of borophene synthesis methods has made remarkable progress, transitioning from theoretical predictions to practical applications. This journey marks a significant advancement in the field of two-dimensional (2D) materials. While manual mechanical exfoliation yielded the first experimental success in 2016, subsequent research has refined techniques such as chemical vapor deposition (CVD), atomic layer deposition (ALD), and sonochemical exfoliation. Borophene's polymorphism allows for adjustable properties. Zhong et al. [115] have discovered two novel and repeatable phases of 2D boron sheets on Ag (111) surfaces. One of these phases resembles the unique phase (β_{12} sheet) in atomic structure but displays unique characteristics in scanning tunnelling microscopy (STM) images due to a distinct rotational alignment with the substrate. The second phase exhibits hexagonal symmetry and is proposed to be the anticipated α-sheet. Scanning tunnelling spectroscopy confirms the metallic nature of both phases of boron sheets. Wang et al. [116] achieved ordered mixed-chain phases on Ag (100), mediated by the substrate. These phases, which are more stable than pure forms, interact weakly with the substrate. They can be effectively separated based on crystal direction, deepening the impact of substrate-tailored synthesis. These advancements aim to enhance scalability and control over the growth process. Two-dimensional boron materials have attracted significant theoretical interest because of their complex structures and distinctive properties. However, synthesising these 2D boron monolayers presents unique challenges. One notable success is the recent synthesis of atomically thin 2D γ-boron films on copper foils using chemical vapor deposition. The synthesised boron film displayed an optical band gap of approximately 2.25 eV, closely aligning with theoretical predictions. This suggests potential applications in electronics and photonics as a direct bandgap semiconductor. The observed 626 nm photoluminescence band further supports borophene's potential in electronics and photonics [117]. Chen et al. [118] synthesised large, single-crystalline bilayer borophene on Cu (111) using molecular beam epitaxy. The bilayer consists of stacked monolayers held together by covalent interlayer boron–boron bonding, exhibiting β_{12}-like structures with zigzag rows. The formation involves significant charge transfer, enabling the growth of the second layer. Bilayer borophene exhibits metallic properties and greater resistance to oxidation compared to monolayers. Despite the successful synthesis of borophene sheets, their metallic nature and structural instability hinder broader applications. Hydrogenated borophene offers a promising alternative, exhibiting superior stability along with favourable electronic and mechanical properties. However, fabricating hydrogenated borophene remains challenging. A recent study successfully developed a method to produce large quantities of hydrogenated borophenes without requiring metal substrates. This synthesis involves a stepwise in-situ thermal decomposition of sodium borohydride using hydrogen as the carrier gas. The resulting hydrogenated borophenes demonstrate superior stability and a structure consistent with the predicted semiconducting α-boron sheet. Furthermore, a borophene-based memory device created using this method exhibited a high ON/OFF current ratio and excellent stability [119]. Borophene's unique physical and chemical properties make it attractive for potential use in energy conversion, storage, sensors, and detectors. However, existing production methods often face obstacles such as structural oxidation, complex transfer processes, and inconsistent quality control. To address these issues, a novel approach was developed for growing borophene directly on insulating quartz using chemical vapor deposition with hydrogen and $NaBH_4$. The resulting "borophene

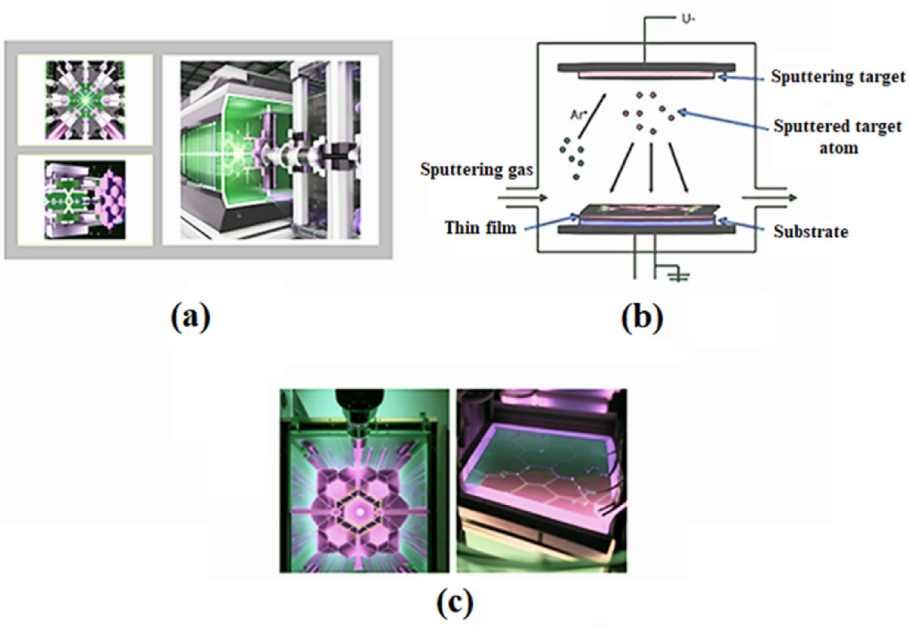


Fig. .5. (a) Molecular beam epitaxy (MBE) setup, **(b)** chemical vapor deposition (CVD) process for borophene synthesis, **(c)** atomic layer deposition (ALD) for borophene synthesis.

glass" aligns closely with the structure of α′-2H-borophene predicted by first-principles calculations. This method has the potential to drive significant advancements in the development of energy devices and sensors [120]. Borophene's discovery has spurred research into its unique structural anisotropy for photoelectronic applications, but challenges remain with its structural instability and reliance on metal substrates. Van der Waals epitaxy (vdWE) shows promise in enabling stable and scalable synthesis of borophene, offering versatility across substrates and high stability for real-world applications. Despite these advantages, the challenge of precisely controlling growth factors remains a focal point of research efforts aimed at harnessing borophene's full potential in various technological domains. A recent study successfully employed vdWE to grow borophene films on a mica substrate. This borophene demonstrated impressive photoresponsivity and detectivity, outperforming reported boron nanosheets and highlighting its potential for optoelectronic devices [121]. Table 3 highlights the borophene's versatility, outlining applications in electronics, optoelectronics, and other industries.

4.3. Borophene's structural and characterisation

Borophene and borospherene, with their unique properties, have emerged as exciting research subjects with applications across diverse fields. As previously mentioned, borophene, a 2D form of boron, was first proposed in the mid-1990s but only achieved successful synthesis in 2015 [8]. Its atomic structure features a combination of triangular and hexagonal motifs, providing exceptional in-plane elasticity and optimal strength. In some configurations, borophene can even surpass graphene in strength and flexibility. Theoretical studies predict that borophene exhibits metallic electronic structures, distinguishing it as the lightest experimentally confirmed 2D metal. Borophene's unique properties make it promising for applications in electronics, energy storage, transportation, catalysis, plasmonics, superconductivity, sensors, and more [126]. In contrast, borospherene (B40) is an electron-deficient cluster molecule composed of 40 boron atoms. It shares similarities with structures like buckminsterfullerene (C60) but exhibits a distinct symmetry. The first experimental evidence for borospherene was presented [127]. While numerous theoretical investigations have explored the structure and properties of borospherene, a reliable method for synthesising and isolating it remains elusive. This limits the current understanding of borospherene compared to other fullerenes. These exciting discoveries in boron-based materials have propelled research toward new possibilities across scientific and technological domains. The unique properties of borophene and borospherene hold promise for breakthroughs in various applications, spanning electronics, energy storage, and beyond [128]. Feng et al. [129] synthesised monolayer boron in the β_{12}-sheet structure on an Ag (111) surface, confirming its metallic properties using angle-resolved photoemission spectroscopy. This discovery opens avenues for new physics and chemistry in materials science. Matsuda et al. [130] examined the β_{12} borophene sheet on Ag (111), revealing its potential for Dirac fermions similar to honeycomb lattices. Tight-binding analysis revealed triangular sublattices that contain Dirac cones, which were confirmed by spectroscopy and calculations. This suggests the use of monolayer boron for innovative, low-dissipation devices. Feng et al. [131] discovered 2D anisotropic Dirac cones in χ_3 borophene, a monolayer of boron sheet, using advanced angle-resolved photoemission spectroscopy. χ_3 borophene, a distinctive phase of boron's two-dimensional allotrope, displays anisotropic Dirac cones at specific points and maintains its unique electronic structure due to weak substrate hybridisation. The Dirac cones are cantered at the X and X' points. Weak borophene-Ag (111) hybridisation ensures the preservation of these Dirac cones. Given the predicted superconducting nature of χ_3 borophene, these findings may catalyse further exploration into the unique physics of borophene, particularly the interplay between Cooper pairs and massless Dirac fermions. Kong et al. [132] discovered one-dimensional nearly free electron (NFE) states in β_{12} borophene on an Ag (111) surface, which arise from line defects characteristic of the χ_3 sheet. The nearly free electron (NFE) states in borophene exhibit electron behaviour similar to that of free electrons, but they are influenced by defects or specific structural features. An in-plane potential well indicates a localized region within the material where electron energy is lower, influencing electron behavior. These states, confined near the borophene plane, exhibit unique in-plane potential well behavior, which suggests applications in transport and field emission nanodevices. Sheng et al. [133] reported on the vibrational spectra and electron-phonon coupling

Table 3
The journey of borophene synthesis.

Year	Materials	Methods	Remarks	Ref.
2015	Borophene	MBE	First successful synthesis of crystalline 2D boron sheets	[122]
2015	Atomically Thin Boron Films on Copper Foils	CVD using boron and boron oxide powders with hydrogen gas	Synthesised γ-boron films on copper foils. Optical band gap measured at 2.25 eV, indicating direct band gap semiconductor. Photoluminescence emission observed at 626 nm.	[117]
2016	Borophene	MBE on Copper Substrate	Demonstrated borophene growth on various substrates	[14]
2017	Borophene	STM	Revealed multiple phases and phase transitions	[14]
2018	Borophene	Modified CVD	Synthesised highly conductive borophene on silver substrates	[6]
2019	Borophene	MBE on Semiconducting Substrate (InAs)	Explored integration with semiconducting materials	[73]
2020	Borophene	CVD on Silver Substrate	Achieved growth of high-quality borophene films	[123]
2020	Semiconducting Hydrogenated Borophene	Thermal decomposition of sodium borohydride under hydrogen	Prepared hydrogenated borophenes in large quantities without metal substrates. Exhibited superior stability and performance in memory device.	[119]
2021	Borophene	Solution-Phase Reaction	Presented scalable synthesis for large-scale production	[124]
2021	Synthesis of borophene on quartz based hydroelectric generator	CVD with hydrogen as carrier gas and NaBH4 as boron source	Grew borophene on insulating quartz via CVD. Fabricated borophene hydroelectric generator with superior voltage and power density.	[120]
2021	Van der Waals Epitaxial Growth of Borophene on a Mica Substrate	Van der Waals epitaxy with hydrogen as carrier gas and NaBH4 as boron source	Synthesised borophene films on mica substrate by van der Waals epitaxy. Exhibited excellent photoresponsivity and specific detectivity.	[121]
2021	Borophane polymorphs via hydrogenation of borophene	Hydrogenation of borophene with atomic hydrogen in ultrahigh vacuum	Synthesised borophane polymorphs with metallic properties. Can be reversibly returned to pristine borophene.	[125]

(EPC) in monolayer boron sheets, using in situ Raman and tip-enhanced Raman spectroscopy (TERS) at low temperatures and ultrahigh vacuum. The gap-mode TERS demonstrates a 3×10^9 selective enhancements on vertical vibrational Raman modes, achieving a spatial resolution of 1 nm. Combined with first-principles calculations, the study determines the vibrational properties and electron-phonon coupling (EPC) in borophene, contributing to the understanding of its mechanical, electronic, and potential superconducting properties. Zhang et al. [134] utilised scanning tunnelling microscopy (STM) and tip-enhanced Raman spectroscopy (TERS) to investigate α-borophene. They found Raman peaks corresponding to phonon modes in an asymmetric buckled α structure. TERS shows enhanced high-frequency Raman peaks, attributed to borophene's unique buckling on Ag (111). This highlights TERS' ability for nanoscale vibrational property analysis. A buckled α structure refers to boron atoms arranged in a non-planar lattice, which affects electronic and vibrational properties. Haifeng et al. [135] synthesised small boron clusters that are crucial for boron chemistry and borophene materials. They formed B5 clusters on monolayer borophene (MLB) on a Cu (111) surface, selectively binding to monolayer borophene sites with a periodic arrangement. This binding prohibits the co-adsorption of nearby B5 clusters. Additionally, close-packed B5 adsorption facilitates bilayer borophene synthesis, displaying a domino effect-like growth mode. This study enriches our understanding of boron-based nanomaterials and highlights the importance of small clusters in borophene growth. The "domino effect" here signifies a cascading process where the close-packed adsorption of B5 clusters triggers the successive and interconnected growth of bilayer borophene, similar to falling dominoes in a row. Elucidating borospherene's structure involved a combination of experimental methods and computational modelling, revealing its unique arrangement of triangles, seven-sided rings, and six-membered rings [128], as illustrated in Fig. 6a. Researchers have further expanded boron nanostructures by creating metallo-borospherene's. These hollow cages, composed of boron and lanthanide elements, defy conventional chemical expectations. Their formation through laser-induced processes offers valuable insights into the properties of bulk boron-lanthanide materials [136], as mentioned in Fig. 6b. To address limitations in traditional borophene synthesis, Boris Yakobson et al. [105] developed an approach using hexagonal boron nitride (hBN) substrates. This technique facilitates material removal and allows for direct assessment of borophene's properties without metallic substrate interference, as shown in Fig. 6c. To overcome the small domains produced by molecular beam epitaxy, Michael Horn-von Hoegen et al. developed segregation-enhanced epitaxy. This method uses borazine gas and an iridium substrate to enable large-area growth of pure, structurally ordered borophene [137], as mentioned in Fig. 6d.

Chemical Vapor Deposition (CVD) is a potent technique for synthesising two-dimensional (2D) borophene monolayers on substrates like iridium (Ir) and copper (Cu) [6,138]. The process begins by obtaining diborane, a key precursor, from commercial borazine using a freeze-thaw purification method. The purified diborane is then introduced onto a preheated substrate under ultrahigh vacuum (UHV) conditions. Using this approach, researchers have successfully produced metallic borophene polymorphs on both Ir (111) and Cu (111) single-crystal substrates. Interestingly, insulating hexagonal boron nitride (hBN) is formed alongside the borophene, creating atomically precise lateral borophene-hBN interfaces. This hBN layer provides immediate protection against oxidation. The ability of chemical vapor deposition (CVD) to synthesise high-quality borophene with large single-crystalline domains opens up exciting opportunities for studying its fundamental properties [6,139]. Cuxart et al. [6] advanced borophene synthesis using Chemical Vapor Deposition (CVD) on iridium (Ir) and copper (Cu) substrates. Metallic borophene polymorphs are introduced and insulating hexagonal boron nitride (hBN) ensures precise lateral borophene-hBN interfaces, protecting against oxidation, as illustrated in Fig. 7.

Synthesising pristine borophene presents challenges due to its robust interatomic bonds, which hinder traditional methods such as chemical

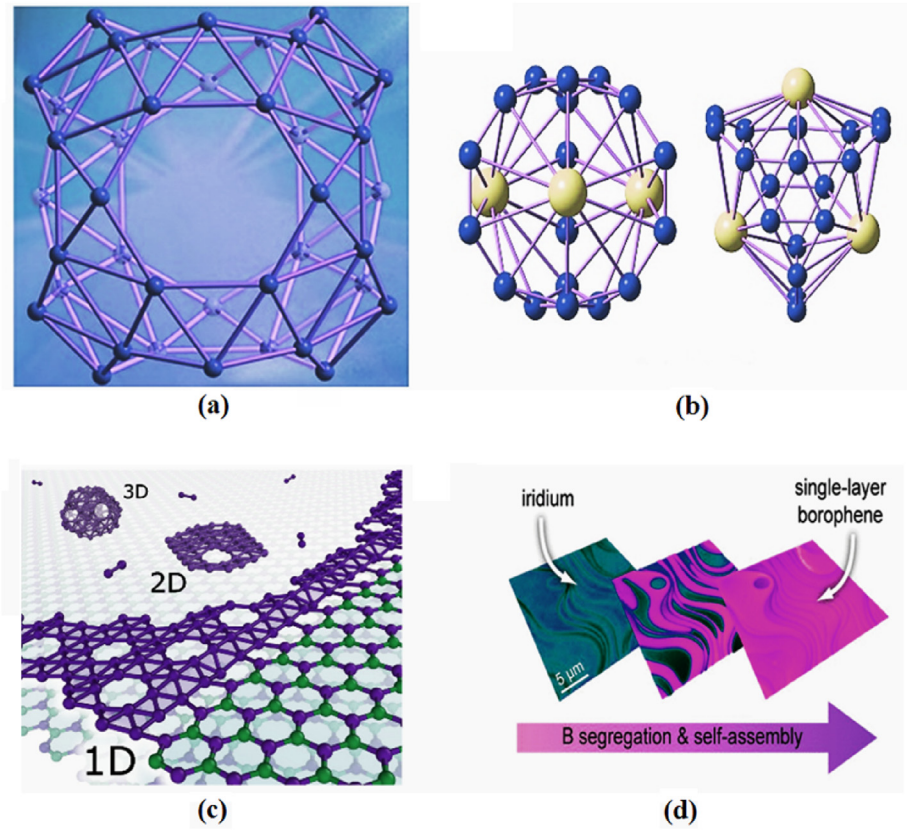


Fig. 6. (a) Clusters of 40 boron atoms form a molecular cage similar to the carbon buckyball. This is the first experimental evidence that such a boron cage structure exists [128], **(b)** The family of boron-based nanostructures has a new member: metallo-borospherene, hollow cages made from 18 boron atoms and three atoms of lanthanide elements [136], **(c)** Borophene Growth on Hexagonal Boron Nitride: Enabling Easy Separation, Reduced Nucleation Dimensionality, and Lowered Barriers for Enhanced Property Evaluation [105], **(d)** Segregation-Enhanced Epitaxy of Borophene on Ir(111) by Thermal Decomposition of Borazine [137].

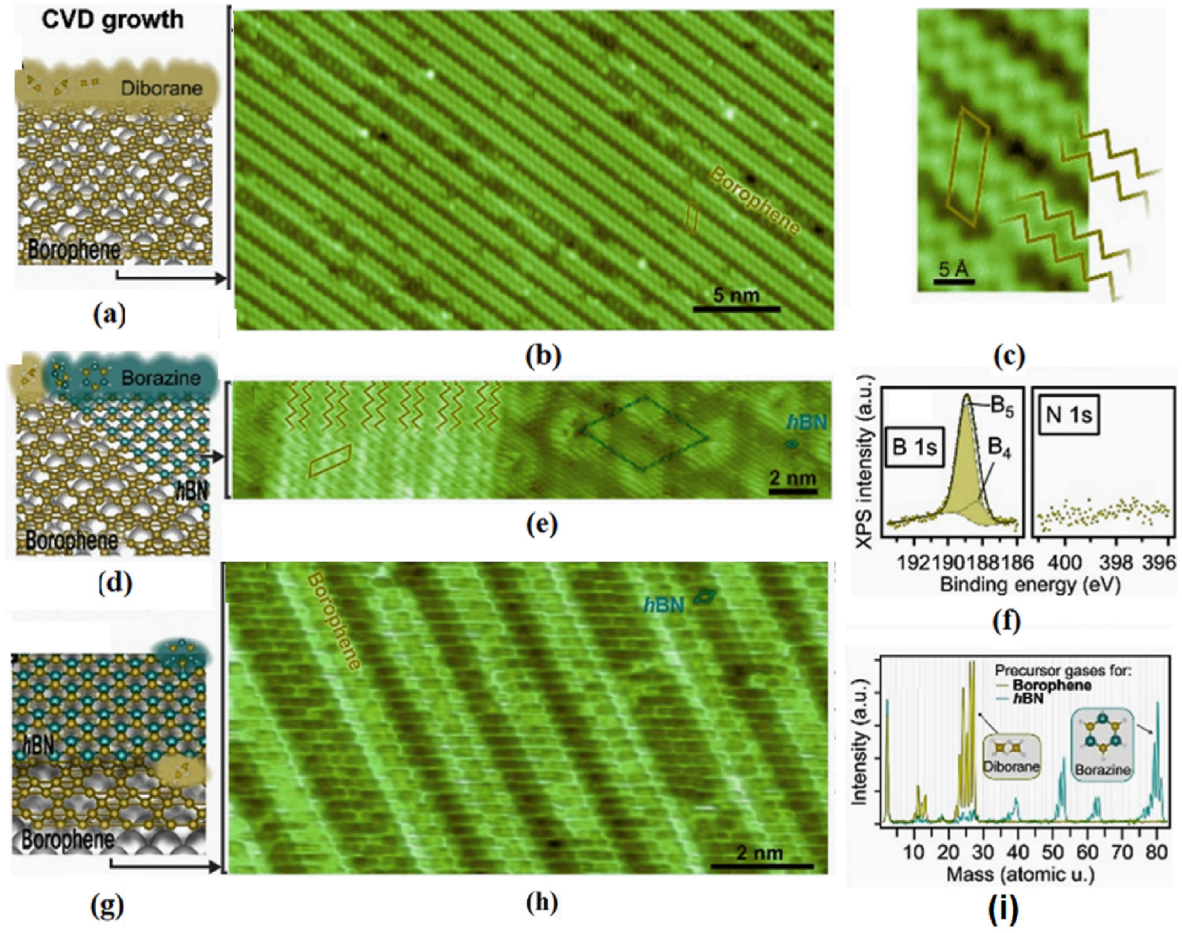


Fig. .7. (a) CVD growth of borophene and borophene-hBN heterostructures on Ir(111) is shown in schematic with diborane dosage, (b) STM image of single-crystalline borophene on Ir(111), and (c) details its structure, (d) Sequential borazine and diborane dosage create borophene-hBN lateral heterostructures, (e) High-res STM image of borophene's wavy appearance and hBN's hexagonal moiré pattern, (f) XPS spectra confirm boron and nitrogen 1s core levels, (g) Vertical heterostructure formation, (h) atomically resolved hBN lattice, (i) Mass spectra of diborane and borazine gases [6].

vapor deposition (CVD) [140,141]. Additionally, borophene's high susceptibility to oxidation complicates its production and handling. To address these issues, researchers have developed borophane, a stable variant formed by bonding borophene with atomic hydrogen under ultrahigh vacuum conditions. Borophane exhibits metallic properties and a modified local work function. Importantly, the process is reversible through thermal hydrogen desorption, restoring pristine borophene [125]. Hydrogenation significantly improves the stability of borophene by modifying its electronic characteristics and reducing its oxidation rate. Borophane, with its reduced work function, remains stable for days in ambient conditions and can be easily converted back to borophene through a simple thermal process [142]. A significant development in two-dimensional (2-D) heterostructures has been achieved by integrating graphene and borophene. This addresses the challenges of precise atomic-scale alignment, as depicted in Fig. 8a. The growth of borophene has advanced with the use of a silver substrate, allowing precise control over temperature and deposition rate. This approach has the potential to produce large-scale conductive wires of atomic width for nanoelectronic devices, as illustrated in Fig. 8b. A solution-based method has been developed to produce atomically flat oxidised borophene sheets from stacked layers of borophene oxide using potassium borohydride salt. The sheets produced exhibit unique conductivity properties, demonstrating semiconductor behaviour in one direction and metal-like behaviour in another. These properties hold promise for practical applications, as demonstrated in Fig. 8c.

Borophene is a single layer of boron atoms that can form various crystalline structures. Its unique atomic arrangement consists of a mix of triangular and hexagonal motifs, a result of the interplay between two-centre and multi-centre in-plane bonding characteristics typical of electron-deficient elements such as boron [4]. This structure contributes to borophene's remarkable in-plane elasticity and ideal strength. In certain configurations, it can even surpass graphene in both strength and flexibility. The specific distribution of vacancies within borophene crystals plays a crucial role in determining their properties. Since its synthesis, researchers have characterised borophene as a good conductor of electricity and heat and have even observed superconductivity. These properties can be adjusted by changing the material's orientation and vacancy patterns [4,145]. Borophene encompasses a diverse family of 2D boron materials with varying isomers. These isomers differ in the concentration and distribution of holes within their triangular lattice [145]. The stability of a specific borophene structure is directly related to the density of its hollow hexagons. Researchers have extensively studied the interplay of these lattice arrangements and their interactions [118]. Strikingly, crystal-like structures with spontaneous alignment form at the boundaries between different borophene phases, setting it apart from other 2D materials. Intermixing and periodic self-assembly of line defects in borophene describe the phenomenon where defects within borophene spontaneously combine and organise themselves in a regular pattern. This behaviour indicates that borophene defects can align and form structured arrangements without external intervention, potentially resulting in unique material characteristics [146], as shown in Fig. 9a–b. A significant achievement is the successful synthesis of graphene-like borophene on an Al (111) surface using molecular beam epitaxy (MBE) under ultra-high vacuum conditions [111], as illustrated in Fig. 9c. This

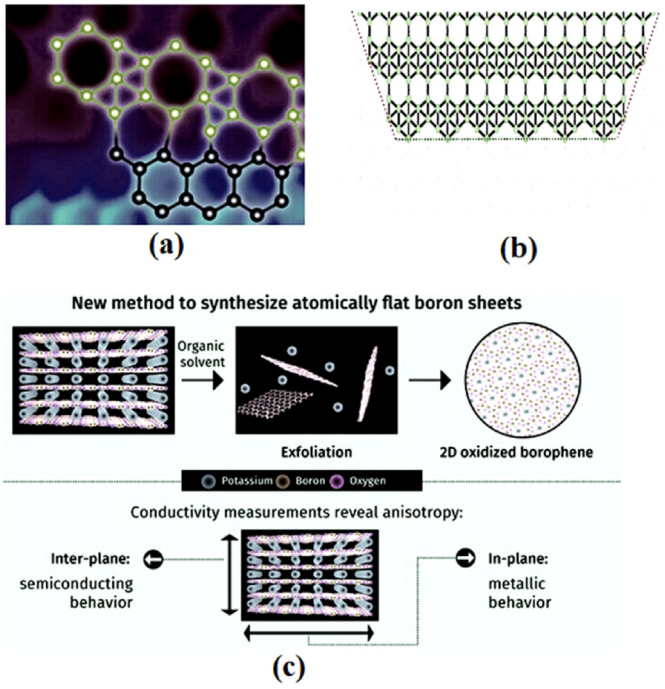


Fig. 8. (a) Atomic-resolution scanning tunnelling microscopy image of a borophene-graphene lateral heterostructure with an overlaid schematic of interfacial boron-carbon bonding [143], (b) Edges connected at the corners of a borophene flake [144], (c)The bottom-up synthesis of crystalline-stacked boron atomic layers from a solution process, conductivity measurements revealed the electronic feature, activation energy of the in-plane conductivity suggested a metal-like behaviour whereas that of the interplane showed a semiconducting nature [111].

opens opportunities to design artificial materials with distinct electronic features, including Dirac states and possible superconductivity, further expanding the possibilities of borophene-based technologies.

To confirm the stability of the large hole formations, additional Kinetic Monte Carlo simulations were performed by Park et al. [145]. Kinetic Monte Carlo simulations model the evolution of a system over time, particularly focusing on processes with known rates. They excel in simulating phenomena where the timescales are too long for direct atomic-level simulations. It is used to study diffusion processes (how atoms move within a material), crystal growth, defect formation, and phase transitions (e.g., solid to liquid) under various conditions. The final configurations resulting from the cooling processes for $\eta = 0.14$ and 0.20 were heated, and the outcomes are illustrated in Fig. 10a and b, respectively. These simulations demonstrate that the double-boron chains effectively protect the holes, maintaining their shape even when the surrounding borophene reaches a liquid state at 1400 K. This stability justifies the term "solid holes" for this borophene phase. Ab initio molecular dynamics simulations further explored the cooling process from 2400 K to 1800 K. These simulations directly calculate the forces acting on atoms based on fundamental quantum mechanical principles. This allows for highly accurate predictions of atomic motions and interactions. It is used to predict detailed atomic-scale behaviour, including chemical reactions, properties of materials under extreme conditions such as high temperature and pressure, as well as structures and dynamics of complex molecules or disordered materials. Eighteen single holes were randomly introduced near the centre of a 10 × 10 unit cell (Fig. 10c). Within 100 fs, these individual holes quickly merged, creating a large central hole (Fig. 10d). After approximately 6 ps, a stable large hole surrounded by a nearly complete double-boron chain was observed (Fig. 10e). The potential energy analysis (Fig. 10f) confirms that this large hole configuration enhances the stability of borophene.

5. Properties of borophene

Geim, Novoselov, and their collaborators' groundbreaking research in 2004 on graphene production sparked a surge of exploration into two-dimensional (2D) materials. These atomically thin materials exhibit exceptional electronic properties [148]. Transition metal dichalcogenides (TMDs) such as MoS_2, WTe_2, and WS_2 have emerged as strong candidates for logic devices because of their flat surfaces and adjustable band gaps. The integration of these materials as channel materials in transistors allows for precise tailoring of electronic properties through layer control. Combining diverse 2D materials into heterostructures propels advancements in materials physics and holds promise for the development of high-performance electronic devices [4,149]. A significant challenge lies in establishing effective contacts with 2D materials, as weak van der Waals interactions often create tunnel barriers that obstruct efficient charge transfer. Recent advances, like forming covalent bonds between graphene and borophene in vertical heterostructures, offer the possibility of improved interfacial properties and enhanced elastic

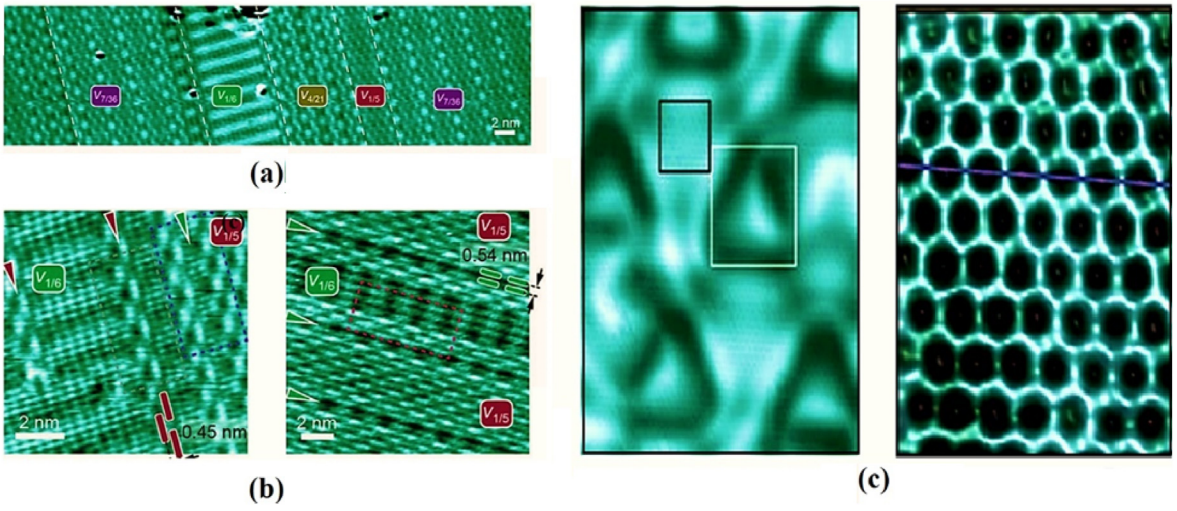


Fig. 9. (a) Atomic-resolution scanning tunnelling microscopy image of a borophene-graphene lateral heterostructure with an overlaid schematic of interfacial boron-carbon bonding [143], (b) Edges connected at the corners of a borophene flake [144], (c) Bottom-up synthesis of crystalline-stacked boron layers from a solution process revealed metal-like in-plane conductivity and semiconducting interplane conductivity [111], high-resolution STM images displayed a borophene monolayer with a honeycomb lattice on Al (1 1 1) [147].

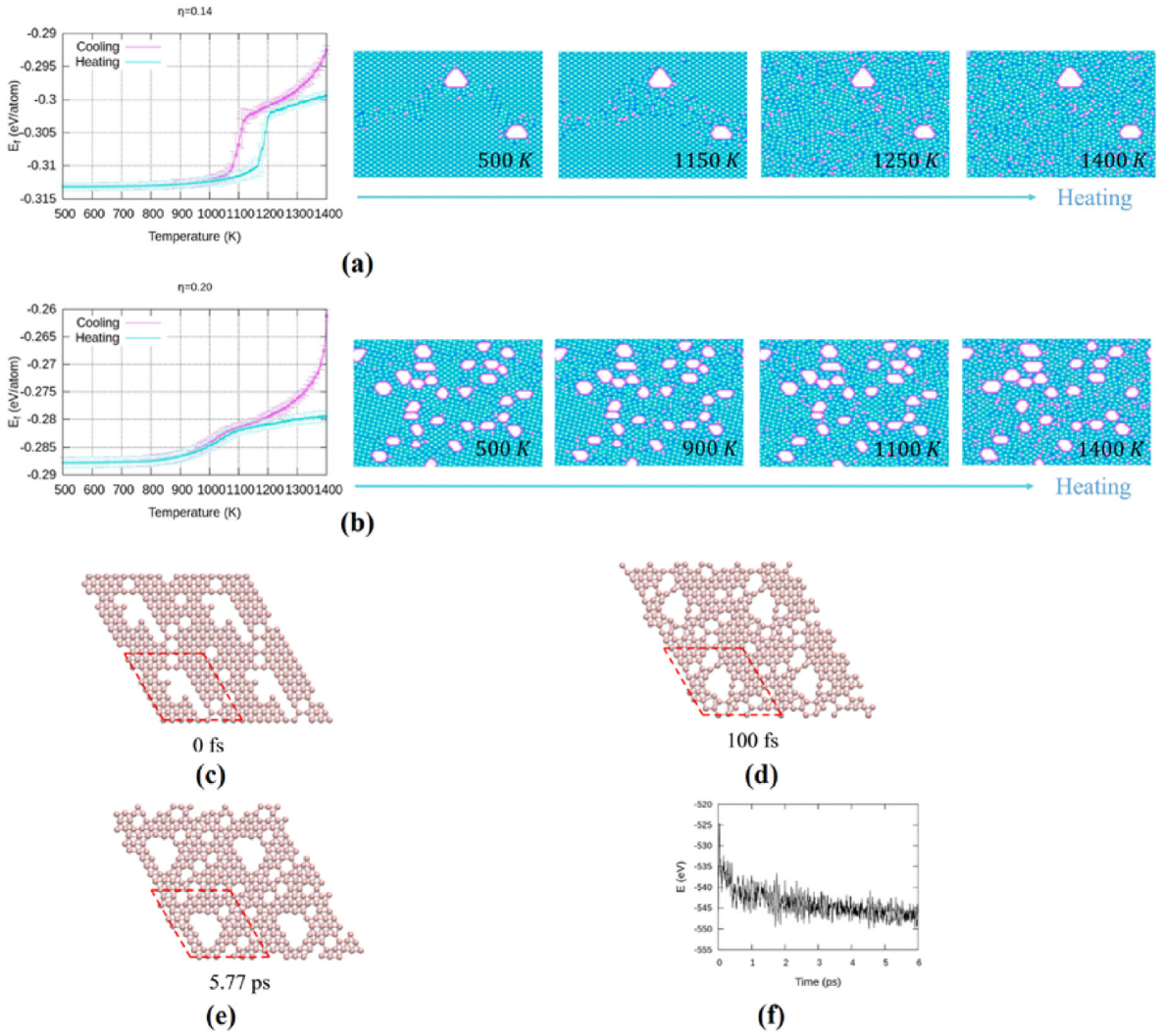


Fig. 10. Energy and configuration changes during heating for (a) $\eta = 0.14$, and (b) $\eta = 0.2$, Ab initio molecular dynamics for a 10×10 borophene supercell during cooling from 2400 K to 1800 K with 0.1 K fs^{-1} cooling rate. (c)–(e) Borophene configurations at specific times: (c) initial, (d) 100 fs, and (e) 5.77 ps and (f) the potential energy during the cooling (the red dashed lines denote the unit cell used in the simulations) [145].

properties [150]. Investigating charge transport in 2D materials requires examining both top and edge contact configurations. The latter demonstrates advantages due to reduced tunnel barriers. While in-plane heterojunctions pave the way for enhanced electronic transport, a persistent obstacle remains in forming low-resistance ohmic contacts between 2D semiconductors and metals. This process is heavily influenced by the metal's work function. Despite these challenges, current investigations are tackling concerns related to stability and the practical applications of devices, thereby propelling sustained advancement in this ever-evolving domain [151]. Inspired by boron's structural resemblance to carbon, research into 2D boron materials is rapidly expanding. Borophene exhibits a range of outstanding properties that make it promising for a variety of applications. Borophene has a unique atomic structure that consists of mixed triangular and hexagonal motifs [4]. This structure is a consequence of the interplay between two-centre and multi-centre in-plane bonding, which is typical for electron-deficient elements like boron [150,152]. Borophene is both strong and flexible. It can be stronger than graphene and more flexible in some configurations. Boron nanotubes are also stiffer than graphene, possessing a higher 2D Young's modulus than any other known carbon and noncarbon nanostructures. The intersection of computational methods and experimental research significantly deepens our understanding of 2D materials, as depicted in Fig. 11 [153].

Borophene is an excellent conductor of both electricity and heat. It is theoretically predicted to have metallic electronic structures, and due to boron being lighter than most elements, borophene is expected to be the lightest experimentally realisable 2D metal [4]. Borophene is expected to have anisotropic properties, meaning its properties vary depending on the direction. In terms of mechanical properties, borophene is theoretically predicted to have an in-plane modulus of up to 210 N/m and a Poisson's ratio of up to 0.171 at v (1/6). Furthermore, the modulus is predicted to be relatively invariant to phase as v varies from 1/5 to 1/9. Due to its outstanding properties, borophene has the potential for a wide range of applications, including thin-layer electronics, optoelectronics, capacitors, and biosensors [10]. Borophene and its hydrogenated counterpart, borophane, are promising two-dimensional materials that exhibit remarkable strength, flexibility, and electronic conductivity. These properties open up potential applications in electronics, batteries, sensors, photovoltaics, and quantum computing. While both are 2D materials, they differ in composition and properties. Borophene, a single layer of boron atoms arranged in a hexagonal lattice, exhibits unique electronic and mechanical properties suitable for diverse applications [154]. Borophane, formed by bonding borophene with atomic hydrogen, inherits some of these properties but displays modified electronic behaviour. Importantly, borophane offers improved stability compared to borophene, which is unstable in ambient conditions [154]. Borophene's

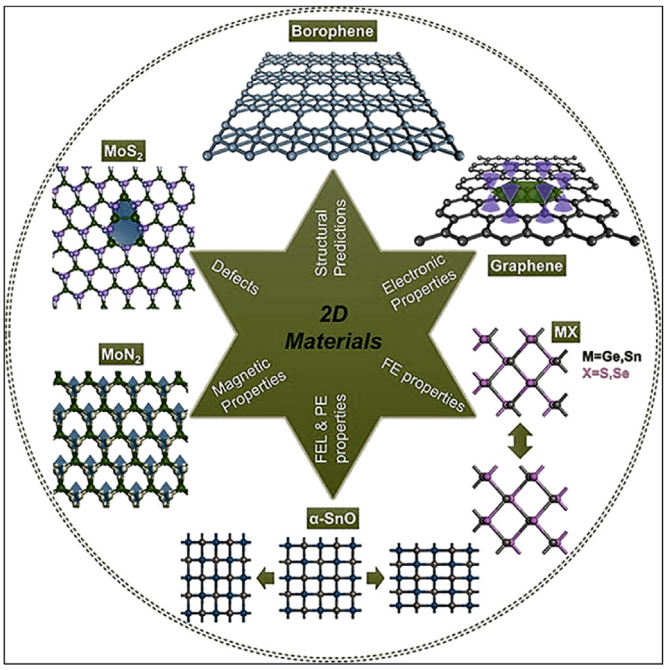


Fig. .11. Structure and Properties of Two-Dimensional Nanostructures" in the context of Design and Property Predictions [153].

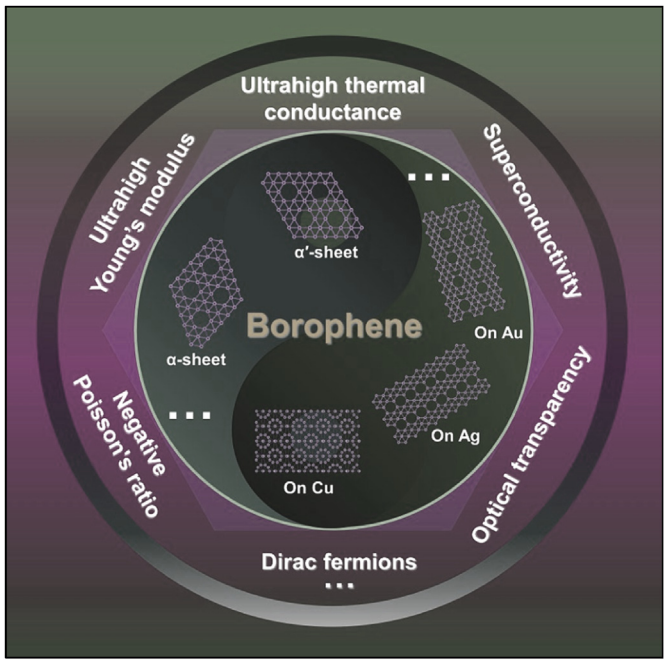


Fig. .12. Various borophene structures and their unique physical properties, including mechanical compliance, anisotropic electronic structure, optical transparency, high thermal conductance, and phonon-mediated superconductivity [158].

versatile properties stem from its unique atomic structure. By carefully controlling growth conditions, researchers can manipulate factors such as atomic configuration, substrate choice, and growth parameters [109]. The ability to form various structural motifs, influenced by the substrate during growth, allows for fine-tuning of its electronic band structures [112]. Additionally, borophene can be doped with other elements or alloyed with different materials to introduce additional functionalities. Doping modifies the electronic band structure and charge carrier properties, while alloying with other 2D materials can create hybrids with synergistic properties [154]. Exploring borophene nanostructures, such as nanoribbons (narrow strips) and nanosheets (larger freestanding single layers), reveals intriguing possibilities. These structures exhibit unique electronic and mechanical properties distinct from bulk borophene, making them suitable for nanoelectronic applications. The high surface-to-volume ratio of nanosheets is particularly attractive for sensing applications and surface-enhanced Raman spectroscopy (SERS) [155]. Integrating borophene with graphene substrates paves the way for advanced electronic devices. The interaction between borophene and graphene significantly influences borophene's electronic properties, leading to changes in its band structure and carrier mobility, and offering novel functionalities. These hybrid structures form a platform for new device architectures, such as tunnelling transistors with enhanced performance. Moreover, the integration of borophene and graphene enhances thermal and electrical conductivity, making it suitable for thermal management and interconnect applications in high-performance electronics [156]. Applying pressure to borophene offers a unique method for tuning its electronic band structure and properties. Under pressure, borophene exhibits changes in its band gap and carrier mobility, highlighting its potential for applications such as sensors and actuators in nanoelectromechanical systems (NEMS) [157]. Fig. 12 illustrates various borophene structures, highlighting properties such as mechanical compliance, highly anisotropic electronic structure, optical transparency, ultrahigh thermal conductance, and phonon-mediated superconductivity.

In a significant breakthrough, three independent research groups almost simultaneously reported the successful synthesis of various 2D boron sheets using chemical vapor deposition (CVD) and molecular beam epitaxy (MBE). Recent advancements in Molecular Beam Epitaxy (MBE) have enabled the creation of diverse borophene structures on various metal substrates [156]. However, challenges persist, including the structural instability and metallic nature of these boron sheets, which limit their potential in nanoelectronic and optical devices. Therefore, realising ultrastable semiconducting borophenes is crucial for expanding applications in advanced nanoelectronics and optoelectronics. To gain a deeper understanding of borophene's distinctive properties, a combination of spectroscopic, microscopic, and thermomechanical characterisation techniques is employed, as summarised in Table 4.

5.1. *Atomic structure of borophene*

Stability in borophene materials is elegantly explained by a recent bonding theory, marking a significant advance in materials science and chemistry. This theory provides a clear understanding of borophene's stability patterns without the need for complex quantum calculations. By introducing the concept of three-centre two-electron (3c-2e) bonds, the theory sheds light on the unique bonding strategy of boron atoms, which respects the octet rule and reshapes our understanding of boron chemistry [163]. Importantly, the theory highlights a novel type of resonance in borophene, which arises from the delocalisation of σ electrons within the 2D plane [4]. This resonance, complementing the well-known out--of-plane π resonance, serves to further stabilise the triangular boron lattice. This insight not only elucidates borophene's structural stability but also facilitates its intuitive design and synthesis. The bonding theory allows for predicting changes in bonding patterns and addresses questions regarding the influence of hole ratios and substrate doping on hole concentration in borophene, drawing parallels with aromaticity in carbon materials [164]. The proposed σ bond resonance theory has far-reaching implications for borophene's applications in electronics, optoelectronics, and quantum devices [163]. Various borophene phases offer tuneable electronic properties suitable for a variety of electronic devices. Borophene's distinctive atomic structure also leads to unique mechanical and thermal properties, making it attractive for flexible materials and efficient heat dissipation in electronics [165]. Specific borophene structures, such as β_{12} and χ_3 borophenes [166,167], are

Table 4
Spectroscopy, Microscopy, and Thermomechanical Characterisation of Borophene under different conditions.

Technique	Key Findings	Ref.
Raman Spectroscopy	Borophene exhibits distinct Raman bands: 1360 cm^{-1} (E_2g mode, in-plane bending), 975 cm^{-1} (A1g mode, out-of-plane bending), and weaker bands (B_1g at 680 cm^{-1}, B_2g at 590 cm^{-1})	[159]
X-ray photoelectron spectroscopy (XPS)	Borophene's unique electronic structure shows semimetallic or semiconducting behaviour with a small band gap (0.1–0.3 eV), promising for electronics, optoelectronics, and catalysis. High electrical conductivity and light absorption are noted.	[90]
Ultraviolet photoelectron spectroscopy (UPS)	Utilising lower-energy ultraviolet light, UPS confirms borophene's semimetallic or semiconducting band structure observed in XPS, providing detailed electronic state information crucial for understanding its properties and applications, particularly for materials with small band gaps.	[106]
STM (Scanning Tunnelling Microscopy)	Visualises borophene's atomic-scale surface morphology, revealing its unique boron atom arrangement.	[106]
AFM (Atomic Force Microscopy)	Provides topographic information and precise measurements of nanoscale features of borophene's surface structure.	[106]
TEM (Transmission Electron Microscopy)	Offers high-resolution structural information about borophene, including lattice spacing and atomic-level defects.	[106]
DSC (Differential Scanning Calorimetry)	Measures borophene's heat capacity and thermal transitions, indicating stability up to 700 °C with phase transition above this temperature. Thermal conductivity decreases at higher temperatures, impacting potential applications in high-temperature electronics and catalysis.	[160]
TGA (Thermogravimetric Analysis)	Reveals a two-step decomposition process: hydrogen evaporation at 300 °C and boron-to-boron oxide conversion at 600 °C, providing insight into borophene's thermal stability crucial for applications in high-temperature environments.	[90]
Mechanical Testing	Confirms excellent mechanical properties: Young's modulus (100–400 GPa), high tensile strength (0.5–1 GPa), and flexural strength (100–300 MPa), making borophene suitable for resilient applications like lightweight composites and impact-resistant devices.	[161, 162]

particularly promising for applications in transistors and logic gates. Fig. 13 illustrates these structures, highlighting the rich diversity of borophene configurations [168].

Understanding the evolution of boron clusters into bilayer borophene provides insights into customising 2D boron materials. The formation of boron clusters opens up possibilities for functional nanomaterials in fields such as catalysis, sensors, and energy storage [169]. The transition from monolayer to bilayer borophene, driven by dense boron cluster adsorption, offers opportunities to customise material properties for specific applications [170]. Table 5 summarises various borophene configurations, highlighting their versatility across technological domains.

5.2. Electronic band structure of borophene

Borophene, a 2D material with complex atomic arrangements and lattice symmetries, exhibits a remarkable range of electronic behaviours [112]. Its electronic band structure can be metallic, semimetallic, or semiconducting, each offering unique potential applications in electronics. The metallic phase of borophene exhibits high electrical conductivity because of partially filled energy states, rendering it suitable for interconnects and electrical contacts. Borophene's semimetallic phase, characterised by electron and hole pockets near the Fermi level, opens up possibilities for novel electronic and spintronic devices [173]. The semiconducting phase exhibits a distinct energy gap between the valence and conduction bands. This gap can be precisely tuned through manipulation of the atomic structure or by introducing dopants, enabling the design of tailored electronic devices such as transistors and diodes [174]. Understanding borophene's electrical behaviour involves classifying it as conductive, semiconductive, or insulating based on its band gap. Its intricate band structure positions it as a versatile material for various electronic applications, ranging from efficient charge conduction in metallic phases to customisable semiconducting properties. Borophene also holds potential in emerging fields such as quantum computing, where precise control over electronic states is essential [175]. Density functional theory (DFT) calculations are essential for understanding borophene's electronic properties, guiding its applications and technological development [176]. Table 6 provides a detailed overview of the electronic band structures of various borophene configurations, including types of band structures, gap ranges, and conductivity. The Tuneable emphasises the capability to adjust band gaps by factors such as strain, size, and doping [175,176].

This investigation examines various borophene allotropes, including the α, χ_3, β_{12}, striped, sliced, 8-*P*mmn, and clustered-P1 (CP1) phases. Key properties analysed include total energy values per atom (in eV), band gap values (in eV), lattice parameters (a, b, c in Å), and crystal angles (α, β, γ in degrees). This analysis offers fundamental insights into borophene's unique characteristics and promising applications. Among these allotropes, CP1 (Clustered-P1) exhibits exceptionally low total energy as calculated by both PBE and HSE exchange-correlation functionals [140]. This low energy suggests thermodynamic stability, positioning CP1 near the global energy minimum. Other stable phases, such as sliced borophene, 8-*P*mmn borophene, and several semiconducting phases, are also included in the comparative analysis. Importantly, CP1 exhibits a significant band gap of 0.543 eV (PBE) and 1.084 eV (HSE), rendering it a promising semiconductor for electronic applications [140, 171]. This characteristic sets CP1 apart from other allotropes that often exhibit metallic or semimetallic behaviour. The lattice parameters and crystal angles provide essential structural details specific to its unique atomic arrangement [196]. The combination of CP1's stability and favourable electronic properties makes it a strong candidate for use in high-performance transistors or other semiconductor-based devices. While CP1 stands out as the most energetically stable and semiconducting allotrope, phases like 8-*P*mmn borophene exhibit intriguing properties that permit further exploration in novel electronic and optoelectronic applications [171,196]. Table 7 summarises the analysis of various borophene allotropes, including their total energies, band gaps, and structural parameters.

5.3. Mechanical flexibility of borophene

Borophene, a two-dimensional material composed of boron atoms in a hexagonal lattice, exhibits exceptional mechanical flexibility due to its unique atomic structure and strong covalent bonds [109]. The single-layer hexagonal lattice allows for significant elastic deformations without structural damage [101]. This flexibility is crucial for applications such as flexible electronics, sensors, and nanoscale mechanical systems, where the material needs to withstand strain and repeated deformations. The remarkable mechanical properties of borophene stem from its two-dimensional structure and the strength of its covalent bonds [200]. The unique atomic arrangement allows borophene to bend and stretch without compromising its structural integrity. The strong covalent bonds between boron atoms provide high tensile strength, enabling it to resist external forces without breaking. This combination of

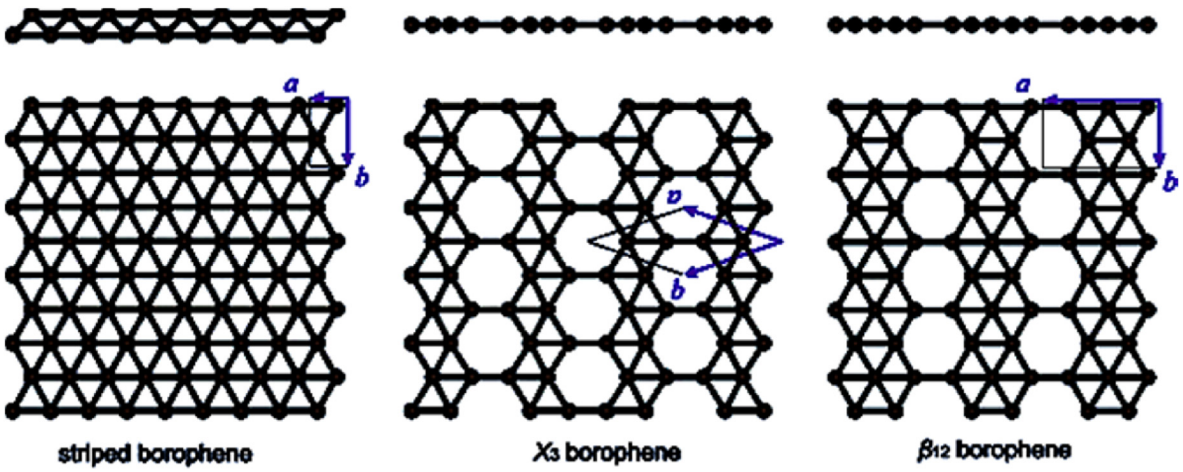


Fig. .13. Crystal structures of experimentally obtained borophenes: Striped borophene (a non-flat borophene form), β_{12} borophene (a.k.a. γ sheet or υ1/6 sheet), χ_3 borophene (a.k.a. υ1/5 sheet) [168].

Table 5
Borophene Configurations, properties, and applications.

Borophene Configuration	Atomic Arrangement	Properties	Applications	Ref.
Parquet Lattice	Complex, non-trivial patterns forming	Interesting electronic behaviour with specific energy gaps and dispersion relations	Tailoring electronic states	[171]
Star-of-David Lattice	Star-like motifs with boron atoms	Unique atomic arrangement leading to intriguing band structures	Novel electronic and optical properties	[166]
Kagome Lattice	Hexagonal lattice with three boron atoms per unit cell	Predicted interesting electronic properties, including Dirac cones	Highly desirable electronic characteristics	[172]
4-Atom Hexagonal Lattice	Four boron atoms arranged hexagonally	Introduction of localised electronic states leading to unique properties	Quantum devices	[4]
5-Atom Pentagon Lattice	Pentagonal pattern with five boron atoms per unit cell	Exhibits intriguing electronic states	Designing borophene functionalities	[6]
Mixed Hexagonal and Honeycomb	Coexistence of hexagonal and honeycomb structures	Borophene's rich electronic structure offer tunable properties	Various electronic and optoelectronic apps	[14]
Armchair Configuration	Boron atoms in linear pattern	Predicted metallic behaviour with unique electronic properties	Electronic devices	[90, 122]
Zigzag Configuration	Boron atoms in staggered, zigzag pattern	Exhibits metallic and semiconducting behaviour	Nanoelectronic applications, e.g., transistors	[152, 169]

flexibility and strength makes borophene suitable for applications requiring endurance against mechanical forces or repeated bending and stretching, such as flexible electronic devices or wearable sensors [201, 202]. Researchers can customise the mechanical properties of borophene by controlling its atomic configuration and lattice symmetry. This allows for the customisation of mechanical strength and flexibility for specific applications. In flexible electronics, borophene's adaptability to various shapes and surfaces enhances design freedom for devices that conform to irregular or curved surfaces [202]. Experimental studies consistently demonstrate borophene's impressive tensile strength and flexibility. The material's Young's modulus, a measure of stiffness, varies depending on its atomic configuration, with the β_{12} phase being particularly notable [203]. Borophene's versatile Young's Modulus, ranging from approximately 100 to 400 GPa, along with its high tensile strength, further solidifies its potential for applications requiring both structural integrity and strength [161]. To better understand borophene's mechanical characteristics, it is helpful to compare it to other nanomaterials. Graphene is lighter than borophene, and it has a modest Young's modulus (~1 GPa) but exceptional strength-to-weight ratio due to its high tensile strength (~130 MPa) [204]. Carbon nanotubes exhibit very high Young's Moduli (1000–2000 GPa) and varying tensile strengths (60–200 MPa), emphasising their suitability for applications requiring outstanding strength and resilience [205,206]. Silicon nanowires demonstrate a balance of stiffness and strength with a Young's Modulus of approximately 100–150 GPa and a tensile strength of around 200 MPa [207].

5.4. Thermal conductivity of borophene

Efficient heat dissipation is essential for optimal performance in electronic devices, and borophene excels in this area due to its remarkable thermal conductivity [208]. Integrated circuits and transistors, which are essential components of electronic devices, produce heat when in operation. To prevent overheating, which can degrade performance and cause damage, effective thermal management is crucial. Borophene's unique atomic structure and strong covalent bonds enable rapid heat transfer, ensuring stable device operation and longevity [208,209]. Borophene's two-dimensional structure is key to efficient heat transfer, minimising overheating issues [209]. This makes it valuable not only for device stability but also as an effective heat spreader in electronic packaging. Borophene finds applications in heat sinks and thermal management systems across various industries. Notably, researchers can customise borophene's thermal properties by modifying its atomic structure and lattice arrangement, providing tailored solutions for various thermal management needs. Within electronic devices, the hexagonal lattice of borophene facilitates the rapid diffusion of heat, maintaining optimal temperatures for consistent and reliable device operation. Its thermal conductivity benefits extend to electronic packaging, making it a valuable material for heat spreaders and thermal management systems. The ability to fine-tune borophene's thermal properties underscores its versatility. As the demand for powerful and compact electronic devices increases, effective thermal management becomes even more critical. Borophene, with its impressive thermal

Table 6
Electronic properties of various borophene Configurations.

Borophene Configuration	Band Structure	Band Gap (eV)	Conductivity Type	Ref.
Free-standing borophene	Semiconducting	0.4–1.2	Semiconducting	[177,178]
Graphene-like borophene	Semiconducting	1.2–2.4	Semiconducting	[16]
Metal-like borophene	Metallic	0	Metallic	[90,179]
Zigzag borophene nanoribbons	Semiconducting	0.8–1.6	Semiconducting	[180,181]
Armchair borophene nanoribbons	Semiconducting	0.4–0.8	Semiconducting	[84,182]
Triangular borophene nanoflakes	Semiconducting	0.6–1.2	Semiconducting	[183,184]
Square borophene nanoflakes	Semiconducting	0.2–0.6	Semiconducting	[169,185]
Hexagonal borophene nanoflakes	Metallic	0	Metallic	[186]
Parquet Lattice	Tuneable	Varies	Varies	[170,187,188]
Star-of-David Lattice	Tuneable	Varies	Varies	[170,187,188]
Kagome Lattice	Semiconducting	Varies	Varies	[170,187,188]
4-Atom Hexagonal Lattice	Tuneable	Varies	Varies	[189–195]
5-Atom Pentagon Lattice	Semiconducting	Varies	Varies	[189–195]
Mixed Hexagonal and Honeycomb	Tuneable	Varies	Varies	[189–195]

properties, offers significant potential in this area [169]. Strategic integration of borophene into electronic devices promises to enhance performance, reliability, and thermal efficiency, driving advancements in the field. Table 8 provides a comprehensive overview of the thermal properties of boron, borophene, and other nanomaterials.

5.5. Optical absorption of borophene

Borophene's remarkable optical properties, particularly its strong light absorption, make it an exciting material for optoelectronics. Its unique atomic structure results in a broad optical absorption spectrum, making it suitable for applications like photodetectors and solar cells [164]. The ability to efficiently absorb light across the visible and ultraviolet regions enhances borophene's potential for use in photodetectors that operate under various wavelengths and lighting conditions [253]. Furthermore, its strong absorption in these regions' positions borophene as a promising material for enhancing the efficiency of solar cells [254]. Borophene's broad optical absorption spectrum also opens up possibilities for light-emitting devices and sensors. The ability to customise its electronic and optical properties provides opportunities for enhanced performance in scientific and technological applications [255,256]. Research demonstrates borophene's impact on optoelectronics, with applications in telecommunications and renewable energy [255,257]. A recent study highlights borophene's versatility as a refractive index sensor in the near-infrared regime [258]. This borophene-based sensor demonstrates exceptional performance, achieving nearly perfect absorption peaks with intensities reaching 99.72%. By optimising geometric parameters, the study achieved wide-angle operation and impressive sensitivity. This sensor has potential applications in label-free biosensing, THz photonics, and biomedical fields. Borophene's high surface-to-volume ratio and surface sensitivity make it particularly well-suited for refractive index sensing applications. THz photonics involves generating, manipulating, detecting, and applying electromagnetic radiation in the terahertz (THz) frequency range, which spans from approximately 0.1 to 10 THz and sits between microwaves and infrared light [258,259]. When compared to materials like graphene, carbon nanotubes, silicon nanowires, various other nanomaterials, and even metals like silver and gold, borophene emerges as a unique player in optoelectronics. Its distinctive optical properties and demonstrated applications position it as a promising material for advancements in light-sensing technologies, renewable energy, and biomedical fields.

5.6. Reactivity of borophene

Borophene's unique atomic structure, characterised by exposed boron atoms, makes it a promising material for catalysis. Its electron-deficient nature enhances its reactivity, facilitating interactions with various molecules [260]. One notable catalytic application of borophene is in hydrogen evolution reactions (HER), which are crucial for clean energy solutions. During Hydrogen Evolution Reaction (HER), borophene's exposed boron atoms serve as active sites for the adsorption and dissociation of water molecules, leading to the generation of hydrogen gas. Borophene's reactivity extends beyond HER, enabling applications in various chemical transformations, including reduction, oxidation, and functionalization reactions [261]. Furthermore, polymorphic 2D boron sheets can offer enhanced catalytic performance due to modifications in their bonding configurations. Electrochemical studies have demonstrated the efficiency of boron nanosheets in converting N_2 to NH_3 [262]. The integration of borophene subunits into the α-phase of molybdenum diboride (α-MoB_2) has been shown to enhance its electrocatalytic properties for hydrogen evolution [263]. This catalyst design principle can be extended to hydrogenated borophene (borophane). While theoretical studies predict the existence of polymorphic borophane phases, further experimental exploration is needed [264]. Recent successful synthesis of hydrogenated borophene (HB) sheets, which release hydrogen as H_2 molecules, is a promising development [265]. In hydrogenated borophene (HB) sheets, hydrogen exists as protons (H^+) rather than hydrides (H^-), suggesting potential applications in energy storage and batteries

Table 7
Comparative analysis of borophene allotropes - total energies, band gaps, and structural parameters [196].

Borophene Polymorph	Etot-PBE (eV/atom)	Etot-HSE (eV/atom)	Eg-PBE (eV)	Eg-HSE (eV)	a (Å)	b (Å)	t (Å)	α (deg)	β (deg)	γ (deg)	Ref.
α Phase	−6.306	−6.943	Metal	Metal	4.47	4.47	0	90	90	81.92	[4]
χ_3 Phase	−6.270	−6.900	Metal	Metal	4.46	4.46	0	90	90	37.92	[4]
β_{12} Phase	−6.259	−6.905	Metal	Metal	5.07	2.93	0	90	90	90	[4]
Striped Phase	−6.212	−6.849	Metal	Metal	1.61	2.87	0.9	90	90	90	[4]
Sliced Borophene	−6.365	−7.043	Metal	Metal	3.18	2.84	3.06	90	90	116.57	[171,196]
8-*P*mmn Borophene	−6.352	−7.027	Semimetal	Semimetal	3.26	4.52	2.19	90	90	90	[197]
Clustered-P_1 (CP1)	−6.300	−6.973	0.543	1.084	3.17	4.49	2.52	90	90	93.94	[196]
B_8-1	−6.207	−6.857	0.210	0.591	–	–	–	–	–	–	[198]
B_{12}-1	−6.208	−6.860	0.560	0.880	–	–	–	–	–	–	[199]
B_{12}-2	−6.186	−6.832	0.539	0.776	–	–	–	–	–	–	[4]

Table 8
Thermal Properties of boron and borophene and other Nanomaterials.

Nanomaterial	Thermal Conductivity (W/m·K)	Melting Point (°C)	Specific Heat Capacity (J/g·K)	Coefficient of Thermal Expansion (CTE) (10^{-6}/K)	Ref.
Boron	~27.4	2079	1.09	6.0	[210,211]
Borophene	14.34–150	~2123	–	–	[208,212,213]
Graphene	~3000–5000	~3800–4300	0.71	~8–10	[214,215]
Carbon Nanotubes	~3000–6000	~3500–4000	~0.7–1.5	~1–10	[216,217]
Silicon Nanowires	~100–200	~1400–1500	~0.7–0.8	~2–4	[218,219]
Silver Nanowires	~400–420	~960	~0.24–0.23	~19–20	[220,221]
Gold Nanowires	~315–320	~1064	~0.13–0.14	~14–19	[222,223]
ZnO Nanowires	~100–150	~1975	~0.27–0.45	~4–6	[224,225]
Carbon Nanofibers	~50–150	~2000–2700	~0.6–1.0	–	[226,227]
Copper Nanowires	~300–400	~1084	~0.39–0.38	~16–18	[228,229]
Nickel Nanowires	~90–100	~1453	~0.44–0.45	~13–14	[230,231]
Titanium Dioxide	~5–10	~1843	~0.7–0.8	~7–9	[230,232,233]
Zinc Oxide	~20–50	~1975	~0.44–0.45	~4–8	[234–236]
MoS_2 (Molybdenum Disulfide)	~10–30	~1185	~0.7	~12–20	[237–239]
WS_2 (Tungsten Disulfide)	~10–40	~1250	~0.7	~8–15	[240–242]
BN (Boron Nitride)	~20–300	~3000	~0.7	~1–2	[240,243,244]
Mxene Ti_3C_2	~30–200	~1600	~0.7	−1 to 20	[245–247]
Hexagonal Boron Nitride (h-BN)	~20–30	~3000	~0.7	–	[248,249]
Phosphorene	~100–300	~350	N/A	−10 to 10	[250–252]

[266]. Fig. 14 demonstrates the catalytic capabilities of HB sheets in ethanol conversion. The stability of the products highlights the reliability of HB sheets for this process. The specific H: B stoichiometry (around 1:2.5 ± 0.5) further underscores the unique catalytic properties of HB sheets [267].

First-principles electronic structure calculations play a vital role in understanding and predicting the catalytic capabilities of borophene [268]. These calculations provide insights into electronic properties, which guide the design of novel catalytic systems. By analysing factors such as ion adsorption behaviour, diffusion pathways, theoretical capacities, and average voltages, researchers have revealed borophene's high specific capacity for lithium ions [269]. Density functional theory studies suggest hydrogenated borophene monolayers are promising candidates for flexible anodes in potassium-ion batteries [270]. Borophene's versatility extends to environmental applications, where it demonstrates efficient piezocatalytic decomposition of organic pollutants in water. Under ultrasonic vibrations, borophene sheets effectively degrade rose Bengal dye molecules. The piezoelectric effect enhances charge transfer during chemical redox reactions, leading to impressive piezocatalytic efficiency [271]. The exceptional catalytic properties of borophene stem from its unique atomic structure. Its applications span a wide range, from hydrogen evolution to environmental remediation. Table 9 outlines reactivity trends in various nanomaterials, highlighting the diverse characteristics and potential applications of these materials.

5.7. *Anisotropic buckling of borophene*

Borophene, a significant two-dimensional material, displays anisotropic buckling, setting it apart from conventional materials [287]. This involves non-uniform bending or warping of its atomic layers, leading to distinct undulations in the third dimension. Unlike isotropic bending, where materials deform uniformly in all directions, borophene's anisotropic buckling occurs directionally, contributing to its exceptional mechanical and electronic characteristics [200]. The specific directionality of anisotropic buckling gives rise to discernible patterns of undulations with varying magnitudes and orientations across the material [288]. This behaviour is intricately linked to bonding interactions among boron atoms and the underlying hexagonal lattice structure of borophene [4].

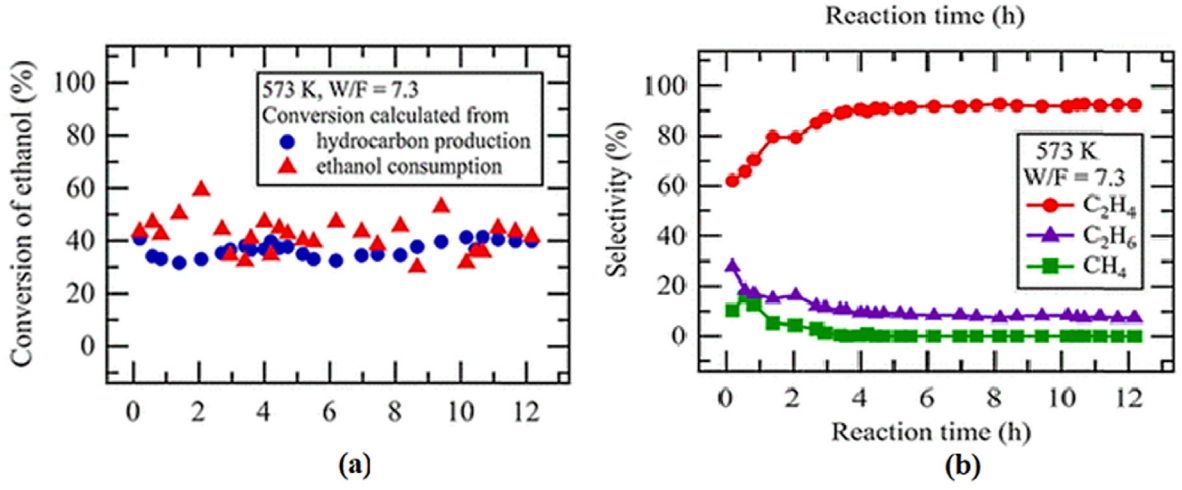


Fig. .14. (a) Conversion of ethanol on hydrogenated borophene (HB) sheets as a function of reaction time at 573 K and W/F = 7.3 g min/mmol, estimated from hydrocarbon production (blue circles) and ethanol consumption (red triangles). (b) Selectivity vs reaction time [267].

Table 9
Reactivity trends in nanomaterials: From Borophene's 2D sensitivity to MXene's versatile stability.

Nanomaterial	Reactivity Trend	Ref.
Borophene	Borophene's 2D atomic structure features exposed boron atoms, rendering it highly reactive. Surface functionalisation allows tailored properties, offering control for materials design and catalytic applications.	[164]
Graphene	Graphene's pristine 2D carbon lattice provides chemical inertness, modifiable through surface functionalisation. This versatility preserves structural properties while enabling adjustment of reactivity, suitable for diverse applications in electronics and nanocomposites.	[272]
Carbon Nanotubes	Carbon nanotubes, inherently inert, undergo reactivity changes via surface functionalisation, adapting properties for applications like sensors and drug delivery. Tuneable reactivity, coupled with unique structure, positions them as promising nanomaterials across various domains.	[273]
Silicon Nanowires	Silicon nanowires exhibit reactivity at defect sites and surface terminations, crucial for applications like sensors and catalysis. Controlling this reactivity is vital for maximising their potential in nanotechnology and electronics.	[274]
Silver Nanowires	Silver nanowires display chemical reactivity, useful for forming oxides and surface modifications, advantageous in applications such as conductive coatings. Controlled harnessing of this reactivity enhances their value in diverse technological fields.	[275]
Gold Nanowires	Gold nanowires' exceptional stability and inertness make them valuable for applications requiring a chemically inert conductor, ensuring reliable performance in biomedical devices and electronic components.	[270]
ZnO Nanowires	ZnO nanowires react with specific acids and bases, particularly at defect sites, offering opportunities for applications like sensors and catalysts where controlled interactions are essential.	[276]
Copper Nanowires	Copper nanowires show reactivity towards certain acids and halogens, susceptible to oxidation in air and moisture, impacting their stability and performance across applications.	[277]
Nickel Nanowires	Nickel nanowires exhibit reactivity when exposed to acids and ligands, influencing their behaviour and applications.	[278]
Molybdenum Wires	Molybdenum wires remain stable under standard conditions but form oxides at high temperatures, offering distinct behaviour across environmental conditions.	[279]
Titanium Wires	Titanium wires react with specific acids and halogens, forming a stable oxide layer, illustrating unique chemical properties.	[280]
Silicon Carbide	Silicon Carbide is generally inert but becomes reactive with strong oxidising agents at elevated temperatures, illustrating distinct behaviour under extreme conditions.	[281]
Aluminium Nitride	Aluminium Nitride exhibits stability under normal conditions but reacts with strong acids and alkalis, highlighting its reactivity in certain environments.	[282]
MoS_2	MoS_2's reactivity primarily occurs at edge sites, valuable for catalysis, sensing, and electronics.	[283]
WS_2	WS_2 exhibits reactivity at edge sites, significant for catalysis and sensing applications.	[284]
BN (Boron Nitride)	BN is highly stable and chemically inert, resistant to most reactions, enhancing its utility across various industrial and scientific domains.	[285]
Mxene	Mxene materials demonstrate commendable stability and versatile functionalisation, valuable for diverse applications in material science and engineering.	[286]

The arrangement of boron atoms within the lattice dictates the directional warping, making anisotropic buckling crucial in shaping borophene's properties. The mechanical implications of anisotropic buckling in borophene are significant. Non-uniform bending enhances the flexibility and resilience of materials, enabling them to withstand stress while maintaining adaptability [200]. This positions borophene as promising for applications that require adaptive materials. Anisotropic buckling also influences the electronic properties of borophene. Warping of atomic layers introduces curvature-induced strain, which impacts the electronic band structure [289]. This modification can lead to intriguing electronic phenomena, such as pseudomagnetic fields, adding complexity to borophene's behaviour. Moreover, anisotropic buckling may affect borophene's interaction with other materials in heterostructures. Out-of-plane undulations impact interfacial properties, emphasising the importance of understanding and controlling these interactions [7]. In the broader context of nanomaterials, buckling behaviour is influenced by factors such as dimensions, crystal structure, and mechanical loading conditions. Table 10 provides an overview of anisotropic and isotropic buckling behaviours in various nanomaterials, offering insights into their responses to external stimuli [171]. It is crucial to note that buckling characteristics may vary based on specific configurations and experimental conditions.

Table 10
The anisotropic and isotropic buckling behaviour trends of the nanomaterials.

Nanomaterial	Anisotropic Buckling Behaviour	Isotropic Buckling Behaviour	Ref.
Borophene	May exhibit anisotropic buckling depending on its atomic configuration and loading.	Buckling behaviour may vary depending on the shape and boundary conditions of the sheet.	[155]
Graphene	In specific configurations or under certain loading conditions.	Typically exhibits isotropic buckling due to its homogeneous and symmetric structure.	[290]
Carbon Nanotubes	May exhibit anisotropic buckling depending on their chirality and loading direction.	Under certain conditions, can also show isotropic buckling behaviour.	[291]
Silicon Nanowires	Anisotropic buckling can occur due to their elongated shape and loading direction.	Isotropic buckling may also be observed under specific conditions, such as uniform loads.	[292]
Silver Nanowires	Anisotropic buckling may occur depending on their aspect ratio and loading direction.	Isotropic buckling may also be observed, particularly for shorter nanowires with less anisotropy.	[293]
Gold Nanowires	Similar to silver nanowires, anisotropic buckling may occur depending on aspect ratio and loading direction.	Isotropic buckling behaviour may also be observed under specific conditions.	[294]
ZnO Nanowires	Anisotropic buckling can occur due to their elongated shape and loading direction.	Isotropic buckling behaviour may also be observed under specific conditions.	[295]

5.8. Superconductivity of borophene

Borophene's predicted superconductivity has garnered significant attention in materials science, holding promise for transformative applications. The successful synthesis of borophene on the Ag (111) surface, revealing β_{12} and χ_3 structures, represents a groundbreaking achievement. Extensive research has been conducted on these borophene polymorphs to understand their electronic properties and superconducting capabilities. Researchers are particularly interested in nano-superconducting devices, using first-principles calculations to elucidate electron-phonon coupling within β_{12} and χ_3 borophenes [296]. Both structures exhibit metallic properties, with electron-phonon coupling surpassing that of MgB_2, a well-known superconductor. Calculated superconducting transition temperatures for β_{12} and χ_3 borophenes, 18.7 K and 24.7 K respectively, exceed theoretical predictions for graphene [296,297], marking a significant advancement in the understanding of two-dimensional superconductivity. Analyzing borophene's electronic band structure is essential for understanding its superconducting

capabilities. The presence of an anisotropic Dirac cone within its band structure suggests borophene's capability for Cooper pair formation, which is fundamental to superconductivity [296,298]. Recent progress in synthesising the β_{12} polymorph on the Ag (111) substrate has revealed Dirac fermions, enhancing our understanding of borophene's electronic behaviour. This study goes beyond experimental observations by employing calculations to elucidate the origin of Dirac fermions in both freestanding and Ag (111)-supported β_{12} borophene [298]. Borophene's electron-deficient nature, stemming from exposed boron atoms, enhances electron-phonon interactions crucial for superconductivity [299]. The study also explores compressed D3S and H3S superconductors, shedding light on the relationship between electron-phonon interactions and superconductivity. Results highlight the vibrational energy range critical for Cooper pair formation and its correlation with critical temperature [299,300]. Theoretical calculations suggest borophene's potential for a high critical temperature (Tc), but practical realisation remains challenging, necessitating precise control over synthesis conditions [301]. Investigating the impact of strain on structural stability, electron-phonon coupling, and superconductivity in various borophene structures provides valuable insights [300]. Environmental factors, such as temperature and pressure, complicate borophene's superconducting behaviour, underscoring the need for precise experimental control. Challenges and opportunities for harnessing borophene's superconducting capabilities are discussed, with an emphasis on enhancing critical temperature, comprehending defects, and establishing large-scale synthesis methods [169]. Researchers are exploring practical applications of superconductivity in borophene through approaches such as heterostructure engineering and controlled doping [214]. The study of bilayer (BL) borophenes, stabilised by specific strategies, reveals intrinsic superconducting characteristics with transition temperatures (Tc) of 11.9 K and 4.9 K for BL-B8 and BL-B30, respectively. The low-frequency range involving out-of-plane vibrations of boron atoms significantly contributes to facilitating their superconductivity [198].

6. Potential applications of borophene

The exploration of two-dimensional (2D) materials has revealed substances with remarkable properties and vast potential applications [302]. Among these, transition metal dichalcogenides (TMDs) stand out, offering a distinct alternative to graphene. MoS_2, a notable transition metal dichalcogenide (TMD), demonstrates exceptional friction resistance for use in lubrication and energy-efficient field-effect transistors. Furthermore, doping can tune the bandgaps of transition metal dichalcogenides (TMDs), including MoS_2, making them valuable for various electronic applications. MoS_2 also demonstrates cost-effectiveness and stability as an electrocatalyst for hydrogen evolution reactions, which is a crucial process for clean energy production and storage [303]. Research on TMDs emphasises the development of heterostructures and alloys to customise optical and physical properties, with the goal of applications in electrocatalysis, optoelectronics, energy storage, and biomedicine [304,305]. The transition from transition metal dichalcogenides (TMDs) to borophene, a 2D planar material analogous to graphene, marks a significant shift in materials research. The successful synthesis of borophene, particularly on silver substrates, has expanded our understanding of this material, which is predicted to exhibit metallic behaviour. Studies on borophene's atomic structure on Ag (111) surfaces reveal energetically favourable arrangements and slight surface buckling, contributing to its metallic conductivity [306]. Investigating growth processes, including the selection of substrates, precursors, and reaction conditions, remains a focal point of research [307]. Additionally, energy stability studies provide insights into factors that influence borophene growth, helping to optimise synthesis and produce high-quality material [14]. Researchers are actively exploring borophene's potential for various technological applications, including electronics, energy storage, and optoelectronics. Borophene's tuneable electronic band structure makes it a promising candidate for advanced electronic devices [308]. Formed through techniques such as chemical vapor deposition and molecular beam epitaxy, borophene's hexagonal lattice structure imparts exceptional strength, flexibility, and high electronic conductivity. The identification of different borophene phases based on atomic arrangements highlights the importance of understanding its properties for diverse applications. This material holds promise in electronics, sensing, and catalysis, potentially leading to high-performance electronic devices and advanced sensor technologies. Borophene's metallic nature opens up possibilities for its use in electronic devices. Borophene's remarkable conductivity positions it as a contender for enhancing electronic device performance [109]. Borophene's properties make it a strong candidate for use in various energy storage technologies, such as alkali metal ion batteries and Li–S batteries. Its atomic structure indicates suitability for hydrogen storage. Borophene's unique characteristics enable the development of high-performance supercapacitors. Borophene offers promise for creating highly sensitive sensors. It can also act as a catalyst for various reactions, including hydrogen evolution, oxygen reduction, oxygen evolution, and CO_2 electroreduction [4,109]. Borophene's distinctive properties may find applications in the fields of plasmonics and superconductivity [126]. Fig. 15 illustrates the synthesis, properties, and potential applications of borophene.

Stacking borophene with MoS_2 to form heterojunctions enables the creation of tuneable Schottky contacts and extends light responsiveness. This versatility highlights the ability to design optoelectronic devices with customizable optical properties, offering opportunities for innovation across various industries [309,310]. Borophene shows significant promise as a material for gas sensing applications. It demonstrates high sensitivity, rapid response times, exceptional selectivity, flexibility, and long-term stability [311]. Researchers are actively exploring borophene-based gas sensors capable of detecting nitrogen dioxide (NO_2), with implications for environmental monitoring and air quality assessment. Borophene's highly anisotropic nature in gas sensing suggests the potential for precise and reliable detection of specific gas molecules [312]. Additionally, borophene's structural features allow for tailoring sensors to meet specific requirements, offering the possibility of customised sensing devices [313]. Borophene's potential extends to information storage technologies. Its unique properties make it suitable for developing high-density data storage systems [314]. Furthermore,

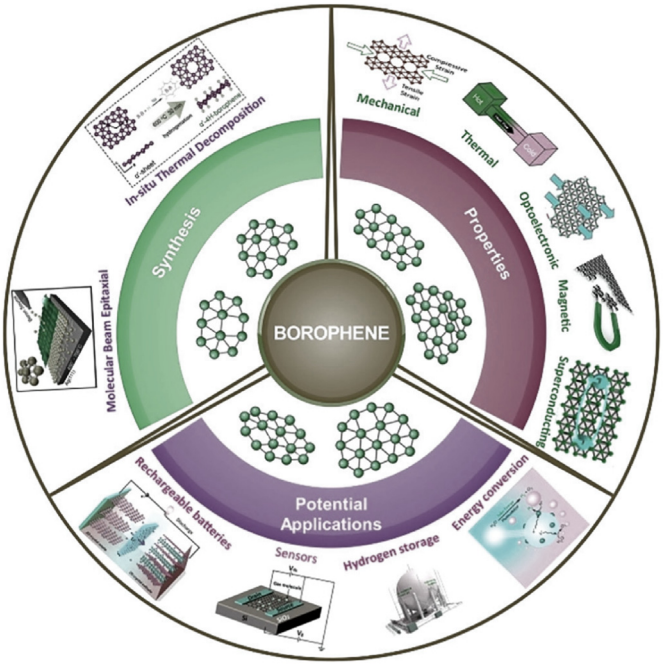


Fig. .15. Illustrates the exploration of catalytic applications, presenting the synthesis, properties, and potential applications of borophene [16].

borophene's exceptional thermal conductivity positions it for thermal management applications in electronic devices, where it can enhance heat dissipation and improve overall performance [213]. Borophene's high carrier mobility and conductivity make it ideal for integration into transistors, sensors, and other electronic components, driving advancements in device performance [109]. Table 11 highlights the transformative potential of borophene and other 2D materials, bridging fundamental research with practical applications.

6.1. Electronics application of borophene

Borophene, a 2D material of boron atoms in a honeycomb lattice, is attracting attention for advanced electronics due to its high carrier mobility and tunable band structure. These properties make it especially promising for next-generation transistors and logic gates [337]. Borophene's remarkable mechanical flexibility, exceptional electrical properties, and large surface area position it as a versatile nanomaterial with diverse potential applications. These unique characteristics make it well-suited for the development of flexible energy storage devices, such as lithium-ion batteries and supercapacitors. Borophene plays a critical role in the advancement of wearable and portable electronics. It contributes to innovations in technologies such as touch screen displays, electronic papers, foldable organic light-emitting diodes (OLEDs), and field-effect transistors (FETs), as illustrated in Fig. 16.

Kaneti et al. [16] provide a comprehensive review of borophene synthesis, properties, and its intriguing anisotropic metallic behaviour, along with flexible mechanical and optical characteristics. Guha et al. [196] introduced the clustered-P1 borophene allotrope, which exhibits a bulk silicon-like band gap. This property makes it well-suited for high-performance transistors tailored to specific electronic applications. Borophene's nearly perfect lattice structure contributes to its unique electronic properties and remarkably high carrier mobility, making it a compelling material for high-speed electronic components [169]. Works by Wu et al. [37] further emphasise these extraordinary properties and suggest a link between borophene's lattice structure and its electronic performance. Borophene's potential applications in electronics are underscored by Yng et al. [126], while Joshi et al. [9] explore its growing significance and multifaceted applications in energy storage devices. Seoane et al. [347] investigated non-planar transistors, suggesting that advanced materials such as borophene could significantly enhance transistor performance. Andreou et al. [301] emphasises the importance of field-effect transistors (FETs) in digital and high-frequency applications, setting the stage for potential borophene integration. Borophene's tuneable band structure enables the customisation of electrical properties, a feature particularly valuable for logic gate applications [348]. Yng et al. [126] further highlight the versatility of borophene, extending its potential across diverse fields, including electronics. Franzon et al. [349] explore molecular electronics, suggesting potential benefits for enhancing Field-Effect Transistors (FETs) – a key component in flexible devices. Vishwakarma et al. [350] investigated borophene-based heterolayers for applications in flexible devices and sensors. Bhavyashree et al. [100] provide insights into the distinctive characteristics and properties of borophene, which make it suitable for various applications. Wang et al.'s [4] comprehensive review highlights the properties of borophene and its promising applications in batteries, supercapacitors, sensors, and catalysis. Joshi et al. [9] focus on the applications of borophene in energy storage devices, aiming to find more effective solutions. Borophene's exceptional mechanical flexibility is crucial for wearable electronics. It allows components to seamlessly integrate into soft and stretchable substrates for comfort and wearability, while also promoting device durability [351]. Tian et al.'s [352] study on boron nanowires under strain highlights borophene's potential for flexible applications. Li al.'s work [353] demonstrates outstanding flexibility and stretchability, aligning with the demand for flexible devices. Gillan et al. [354] emphasises the necessity of durable, environmentally friendly materials for stretchable electronics. Borophene's potential extends beyond transistors

Table 11
Recognising Borophene's and 2D materials Potential, Synthesis Challenges and Addressing the applications.

Application	Key Findings	Ref.
High-performance electrical devices	Tuneable tribotronic dual-gate logic device using 2D materials and a triboelectric nanogenerator.	[315]
Low-voltage operation with well-behaved characteristics	Flexible vertical Schottky barrier transistors and logic gates based on graphene-organic-semiconductor-metal heterostructures.	[316]
Analog conductance modulation and CMOS compatibility	Tuneable and reconfigurable logic gates based on an electrolyte-gated transistor array co-integrated with neuromorphic synapses.	[317]
Advanced logic gate design with tuneable properties	Frequency-tuneable logic gates based on graphene nano-waveguides utilising voltage-dependent chemical potential.	[318]
Gas sensing applications for environmental monitoring and air quality assessment	Borophene-based gas sensor with high sensitivity, fast response, selectivity to NO_2, flexibility, and stability.	[29]
Photodetector technology for light sensing and imaging applications	Successful growth of structurally stable borophane on copper foils, enabling photodetector applications with a wide wavelength range and high photoresponsivity.	[319]
Enhancement of energy-conversion devices	Boron-doped molecules in energy-conversion devices outperform conventional carbon analogues.	[320]
Enhanced energy conversion efficiency in solar cells	Importance of light management in optoelectronic devices; nanostructures enhance energy conversion efficiency in solar cells.	[321]
Enhanced light transmission and improved coupling	Biomimetic nanostructure fabrication technique increases light transmission efficiency in optoelectronic devices.	[322]
High-performance sensing applications	Fabrication and sensing properties of ceramic NEMS sensors for high sensitivity.	[323]
High sensitivity biosensing applications	Potential of NEMS-based biosensors for high sensitivity and real-time detection of analytes.	[324]
High-performance actuation applications	Efficient and fully integrated actuation with programmable electromechanical coupling in NEMS.	[325]
Flexible and robust wearable devices	Introduction of textile-based electronics that are flexible, robust, and unobtrusive.	[326]
Wearable displays and biomedical devices	Emerging research areas of e-skin and textile electronics, highlighting their potential in wearable displays and biomedical devices.	[327]
Healthcare, communications, and personal electronics	Importance of lightweight, miniaturised, and flexible wearable energy and sensor devices.	[328]
Thermal energy storage in solar thermal propulsion systems	Use of boron phase-change material for thermal energy storage in solar thermal propulsion systems.	[329]
Efficient use and conservation of waste heat and solar energy	Importance of thermal storage technology for efficient use and conservation of waste heat and solar energy.	[330]
Reinforcement of aluminium alloy components	Boron carbide reinforcement in aluminium alloy composites for enhanced mechanical properties.	[331]
Enhancement of flexural properties in composites	Addition of nitrile rubber powder to boron phenolic composites improved flexural properties.	[332]
Enhanced power conversion in solar cells	Incorporating Boron-dipyrromethene (BODIPY) sensitisers into polymeric solar cells improved power conversion efficiency.	[333]
Efficient energy transfer in light-harvesting systems	Highly efficient energy transfer within a light-harvesting system composed of BODIPY fluorophores.	[334]
Enhancement of light-emitting properties in lighting systems		[335]

(continued on next page)

Table 11 (*continued*)

Application	Key Findings	Ref.
	Synthesis and characterisation of BODIPY dyes with improved light-emitting properties.	
Integration into polymeric solar cells for enhanced energy conversion efficiency	Investigation of near-infrared absorbing boron-dibenzopyrromethenes as sensitisers for polymeric solar cells.	[333]
Potential applications in solar cells and lighting systems	Exploration of unspecified aspects of boron-based materials.	[336]
Potential use of boron-rich solids in high-efficiency thermoelectric devices	Promising properties of boron-rich solids for high-efficiency thermoelectric energy conversion.	[337]
Application of thermoelectric materials in waste heat recovery systems	Use of thermoelectric materials for converting waste heat into electricity or for cooling and heating applications.	[338]
Integration of thermoelectric nanocomposites	Development of thermoelectric nanocomposite materials with increased Seebeck coefficient and low thermal conductivity.	[339]
Integration of borophene in wearable devices	High-performance properties of borophene for biosensing, bioimaging, and cancer treatment applications.	[30]
Application of borate glasses in tissue engineering	Potential use of borate glasses in bone and soft tissue engineering for improved biocompatibility.	[340]
Gas Separation Membranes	Development of hierarchically microporous membranes for highly energy-efficient gas separations.	[341]
Biosensors, Bioimaging, Cancer Treatment, Theragnostics	Borophene's potential in biosensing, bioimaging, cancer treatment, and theragnostic applications.	[30]
Biosensors, Therapeutics	Emerging use of borophene in biosensors and therapeutics.	[74]
Bioimaging, Photodynamic Therapy, Immunotherapy	Use of BODIPY in fluorescence bioimaging, photodynamic therapy, and immunotherapy.	[342]
Diagnostic and Therapeutic Agents	Potential of boron in designing diagnostic and therapeutic agents.	[343]
Polymer Electrolyte Membrane (PEM) Fuel Cells	Improvement of PEM hydrogen fuel cells with graphene sheets and h-BN as catalyst substrates.	[344]
Polymer Electrolyte Membrane (PEM) Fuel Cells	Potential of Ru catalyst for producing high-purity hydrogen for PEM fuel cells.	[345]
Direct Borohydride Fuel Cells	Performance of direct borohydride fuel cells with low Pt/C catalyst loading.	[346]

to advanced sensors, energy storage devices, and even quantum computing [157]. Borophene's flexibility can revolutionize wearable devices like smartwatches and fitness trackers, enabling them to monitor vital signs, motion, and environmental factors when embedded in clothing or worn on the skin [355]. Chen et al.'s [201] study on fabric-based triboelectric nanogenerators emphasises borophene's potential for energy harvesting and various sensing capabilities in wearable healthcare electronics. This opens avenues for self-powered wearable devices. Borophene's optical transparency and flexibility make it a compelling material for creating flexible displays, enhancing device portability, and durability [356]. This aligns with the emphasis on readability, low power consumption, and slim form factors – crucial features for wearable displays found in applications like writing tablets and electronic skins, as discussed by Montbach et al. [357]. While the integration of borophene into wearables is still in its early stages, the material's mechanical flexibility, electrical conductivity, and optical properties position it as a game-changer. Borophene's potential in flexible displays, energy harvesting, and sensing promises to transform wearable electronics.

6.2. Sensors and photodetectors application of borophene

Borophene, the lightest known 2D material [358], is gaining interest for its remarkable sensitivity in sensing applications, particularly in gas

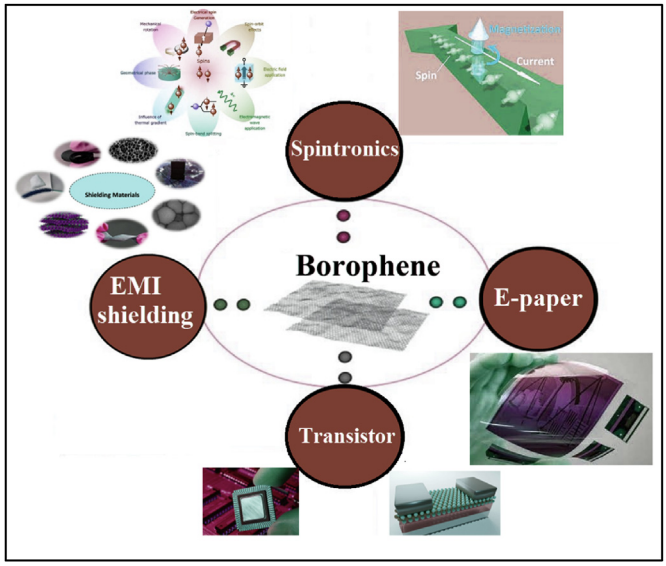


Fig. .16. The versatile nanomaterial borophene, with its remarkable mechanical flexibility and superior electrical properties, revolutionises electronics applications.

sensors and photodetectors [29]. Advancements in experimental synthesis on various substrates, such as Ag and Cu [359,360], have led to the emergence of hydrogenated borophene for electronic devices. Theoretical studies emphasise borophene's strength and flexibility due to its unique boron-boron multicentre bonds [28,29], suggesting potential in advanced wearables. Inspired by the skin's ability to sense pressure, researchers are developing wearable pressure sensors for medical interfaces [9,80,361]. While various nanomaterials have been explored, challenges such as narrow detection ranges persist [362,363]. Borophene, especially the semiconducting α'-4H-borophene, offers promise for high-performance sensors with versatile applications, including health monitoring, phonation detection, human motion detection, e-skin capabilities, and human-machine interfaces. In the realm of sensing, studies by Hou et al. [364], Yu et al. [313], and Chen et al. [365] highlight borophene's high sensitivity, rapid response, and selectivity. Borophene-based sensors have shown effectiveness in detecting nitrogen dioxide (NO_2) and other nitrogen-containing gas molecules. Tai et al. [73] introduced a novel heterostructure of hydrogenated borophene and graphene, synthesised through controlled thermal decomposition. This borophene-graphene heterostructure functions as a highly sensitive humidity sensor with rapid response and long-lasting stability. Surpassing pristine graphene sensors by nearly 700 times in sensitivity, this sensor stands out as the most sensitive among reported 2D material-based sensors. Furthermore, its flexibility retains stability after bending, suggesting its suitability for wearable electronics. The superior performance is credited to a well-established charge transfer mechanism upon H_2O molecule adsorption, paving the way for diverse applications. Chuang et al. [366] proposed borophene-MoS_2 sensors with exceptional sensitivity, surpassing individual borophene or MoS_2 sensors by over 90 or 70 times, respectively. These sensors exhibit rapid response, long lifespan, flexibility, and outstanding selectivity for water vapor. They highlight multifunctional applications in human breath diagnosis and non-contact switch sensing systems, suggesting their potential in healthcare and human-machine interaction. Liu et al. [367] created borophene-BC_2N heterostructures, forming an overly sensitive humidity sensor with a wide detection range (11–97%) and ultra-fast response times. Compared to pristine borophene or BC_2N quantum dots (QDs), this sensor demonstrates exceptional sensitivity (up to 22,001% at 97% relative humidity), stability, flexibility, and selectivity. It finds practical applications in smart diaper monitoring, wireless respiratory behaviour tracking, and speech recognition. Hou et al. [364] developed a high-performance

pressure sensor using two-dimensional semiconducting borophene. The sensor exhibits a sensitivity of 2.16 kPa-1, operates across a broad pressure range (0–120 kPa), detects pressures as low as 10 Pa, consumes approximately 0.6 μW of power, and maintains high reproducibility (over 1000 cycles). It serves as wearable electronic skin for health monitoring, voice and motion recognition, wireless detection, and integration into smart robots for human-machine interface. A study demonstrates the fabrication of a high-performance chemiresistive sensor based on hydrogenated borophene [267]. This sensor exhibits exceptional sensitivity, fast response, selectivity, flexibility, and long-term stability (Fig. 17). It demonstrates a low detection limit, wide detection range, and rapid response/recovery times, outperforming sensors based on conventional 2D materials. Applications include wearable electronic skin for health monitoring, voice and motion recognition, and integration into smart robots for human-machine interfaces (Fig. 17a). The sensor's exceptional selectivity to nitrogen dioxide (NO_2) highlights borophene's potential for high-performance sensing applications (Fig. 17b).

Borophene's excellent electrical conductivity and rapid carrier mobility enable swift and precise light signal detection [368]. Its versatility across UV, visible, and infrared regions make it suitable for applications ranging from data communication to environmental monitoring [259]. Liu et al. [319] synthesised stable few-layer β_{12}-borophane on copper foils using a chemical vapor deposition method. Their photodetector, based on a β_{12}-borophane–silicon junction, displays exceptional performance: high photoresponsivity (0.48 A W–1), specific detectivity (4.39×10^{11} jones), and external quantum efficiency (162%) across a wide wavelength range (365–850 nm). It also demonstrates rapid response and recovery times (115 and 121 ms) under UV light (365 nm) at a reverse bias of 5 V. The Jones is a unit used to measure specific detectivity in photodetectors. It represents the ability to detect weak signals against background noise. Higher Jones values indicate better detection performance. Liang et al. [369] synthesised α'-4H-borophene on GaAs substrates, exhibiting a semiconductor nature with a bandgap of 2.48 eV. Fabricated into a photodetector with GaAs, it exhibited high photoresponsivity (0.31 mA·W−1) and specific detectivity (10^8 Jones), along with rapid response times (117 ms) under near-infrared light. This demonstrates the high sensitivity and low power consumption of the borophene/GaAs photodetector, showing promise for efficient device applications. In another study, Liang et al. [370] synthesised high-quality freestanding α-rhombohedral borophene nanosheets using a probe ultrasonic approach in various organic solvents. The nanosheets achieved optimal quality in ethanol, with an average lateral size of 0.54 μm and a thickness of approximately 1.2 nm. Photoluminescence spectra revealed a significant quantum confinement effect, leading to an increased band gap compared to boron powders. Moreover, a non-volatile memory device incorporating nanosheets with polyvinylpyrrolidone demonstrated excellent rewritable behaviour and stability, highlighting their potential for advanced electronic applications. Wu et al. [371] successfully fabricated vertical borophene-graphene heterostructures on Cu substrates using chemical vapor deposition with hydrogen as the carrier gas and $NaBH_4$ as the boron source. The borophene-based photodetector demonstrates superior broadband photoresponse across UV to IR wavelengths, outperforming standalone borophene or graphene detectors. This study confirms the integration of borophene in nanoelectronics to enhance performance and expand its applications. While the potential of borophene in sensing is promising, its development faces obstacles such as scalable fabrication, long-term stability, and seamless integration [40]. However, ongoing research is actively addressing these challenges. Studies by Yadav et al. [30], Xie et al. [164], and Hou et al. [158] provide insights into borophene's biomedical potential, challenges, and opportunities across various fields.

6.3. Optoelectronic, photoelectric energy harvesting, solar cells and lightning application of borophene

Borophene exhibits unique optical transparency across a broad

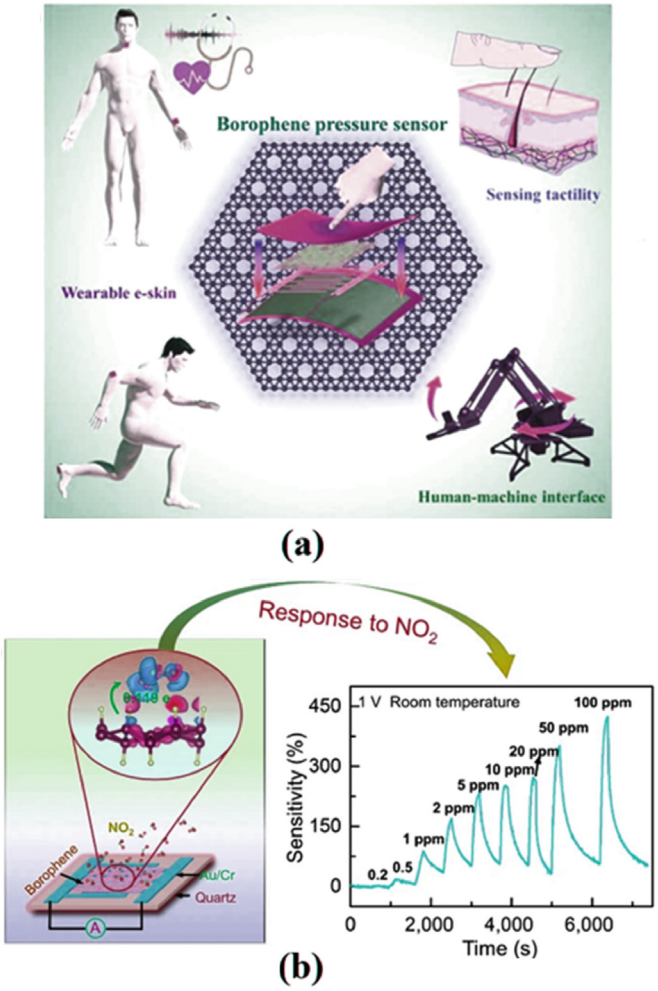


Fig. .17. Effectively summarise the key features and applications of the respective, a) wearable pressure sensors [364], b) Gas sensing with borophene [29].

spectrum. This characteristic, combined with its efficient electrical conductivity, makes it a promising transparent conductor. Adamska et al. [348] highlighted that the optical transparency of borophene is influenced by energy and thickness, indicating potential tunability for a range of optoelectronic applications. Displays and LEDs: The potential significance of borophene in light-emitting diodes (LEDs) and displays is highlighted by Kang et al.'s work on transparent dielectric structures [372] and Xiang et al.'s design of transparent and flexible OLEDs [373]. These applications rely heavily on transparent conductive materials. Successful fabrication of photodetectors using β_{12}-borophane and borophene's application in ultraviolet detection demonstrate its significance in photon detection [374]. Borophene's unique combination of optical transparency and light interaction positions it favourably for solar cell applications. Lu et al. [375] demonstrate improved light harvesting in BODIPY dyes, while Zhao et al. [336] explore borophene surface modification in perovskite solar cells. Furthermore, Veschetti et al.'s [376] research on high-efficiency boron emitter n-type silicon solar cells suggests the potential of borophene-based solar cells for enhanced energy output. Vázquez et al.'s [377] study on organic solar cells integrating boron compounds emphasises potential efficiency enhancements. Borophene's ability to absorb light across a broad spectrum positions it as a promising material for enhancing solar cell performance. Research by Abasi et al. [378] and Sachdeva et al. [379] highlights the suitability of borophene for LEDs, solid-state lighting, and other photonics applications. These studies highlight borophene's anisotropic nature,

strain-tuneable properties, transparency, and low absorbance in the visible region. The ability to customise borophene's optical properties could pave the way for the creation of energy-efficient lighting systems with adjustable features to enhance user comfort [165,380]. Borophene's unique combination of light-absorbing, emitting, and tuneable optical properties positions it as a compelling material for enhancing solar cells and revolutionising lighting systems. While borophene shows promise for optical applications, challenges in scalability, stability, and cost-effective production methods need further research [165]. Borophene-based solar cells promise to outperform traditional materials due to their broader light absorption spectrum, including infrared wavelengths. Their atomic-scale thickness and low density pave the way for lightweight and flexible solar panels [169].

6.4. Nanoelectromechanical systems (NEMS) application of borophene

Borophene, a 2D honeycomb lattice of boron atoms, is poised to revolutionise nanoelectromechanical systems (NEMS). Borophene's unique combination of properties makes it ideally suited for NEMS applications. Borophene's inherent flexibility rivals that of graphene, enabling it to bend and stretch at the nanoscale. This makes it a valuable material for flexible NEMS designs and composites. Borophene's exceptional electrical conductivity, as highlighted by Mortazavi et al. [12] and Joshi et al. [9], allows it to serve as a conductor within NEMS components. This enables seamless integration of sensing, processing, and response functions in NEMS devices [381]. Atomic-scale ultrathin structures enable the development of ultra-compact NEMS devices. Roukes et al. [382] and Sachdev et al. [383] further emphasise the importance of stability and single-atom thickness for compact, robust NEMS. Additionally, this minimal thickness minimises the mass of NEMS components, resulting in fast mechanical response times – crucial for high-frequency operation and increased sensitivity [384,385]. Borophene's combination of flexibility, conductivity, and atomic-scale thickness makes it highly suitable for designing precise NEMS devices, including resonators and sensors [386–388]. However, it is crucial to recognize that challenges persist in areas like synthesis and stability. Ongoing research endeavors are diligently focused on overcoming these hurdles, paving the way for borophene to fulfill its potential in NEMS and beyond..

6.5. Energy storage, thermal management and thermoelectric application of borophene

Borophene, a two-dimensional honeycomb lattice of boron atoms, exhibits remarkable properties that could revolutionise energy storage and thermal management. Recent research extensively explores borophene's ultrahigh thermal conductivity and its potential applications. Synthesis studies on various metal substrates investigate the impact of factors such as elemental doping, defects, and mechanical strains [16]. Borophene's thermal conductivity surpasses that of most known materials, making it exceptionally efficient at dissipating heat [12]. Studies on boron arsenide, a related material, demonstrate ultrahigh thermal conductivity comparable to diamond [389,390]. This underscores borophene's potential for enhanced thermal management, which is crucial for preventing overheating and degradation in devices like lithium-ion batteries [391]. Borophene's properties make it a compelling candidate for various energy storage applications, including alkali metal ion batteries, hydrogen storage, supercapacitors, and catalysis [4]. Predicted superconductivity in borophene promises zero electrical resistance, enabling more efficient energy storage [392]. Research into doped metal borohydrides suggests the possibility of high-temperature superconductivity, which could be a significant breakthrough for energy storage solutions [393]. Elemental boron demonstrates superconductivity at high pressures, highlighting the potential of borophene-based superconductors [392,394]. This innovation could revolutionise power transmission networks and help overcome challenges in overhead transmission lines [395,396]. Borophene's ultrahigh thermal conductivity is essential for preventing overheating in increasingly compact and powerful electronic devices [420]. Borophene's ultrahigh thermal conductivity surpasses that of most known materials, improving thermal management in devices such as lithium-ion batteries [12]. Tian et al.'s [389] studies highlight boron arsenide's ultrahigh thermal conductivity, which is comparable to diamond. Li et al.'s [390] research confirms the superior thermal conductivity of cubic boron arsenide, surpassing that of silicon carbide. This suggests borophene's effectiveness in dissipating heat, which is crucial for energy storage processes. It helps mitigate overheating and thermal degradation, extending the system's lifespan and reliability [391]. Borophene exhibits intrinsic superconductivity due to its metallic state and strong electron-phonon coupling. Its transition temperature (T_c) can reach up to 34.8 K with modifications. Bilayer borophenes are also superconducting, even without metal substrates. These properties make borophene promising for energy storage applications with zero resistance [392]. Doped metal borohydrides' research suggests high-temperature superconductivity, with critical temperatures reaching as high as 110 K [393]. Strain and carrier doping are crucial for optimizing borophene's energy storage potential. This 2D material is an intrinsic superconductor with a transition temperature (Tc) near 19.0 K. Tensile strain can boost Tc to 27.4 K, while hole doping raises it to 34.8 K. Controlling these factors allows us to tune borophene's superconductivity, potentially leading to advanced energy storage devices. Further research is needed to fully unlock this potential [173]. Additionally, elemental boron exhibits superconductivity at high pressures, offering another avenue for advancing superconducting technology [394]. Borophene-based superconductors have an impact on power transmission networks, suggesting the use of underground lines to tackle challenges associated with overhead transmission [395,396]. Borophene's ultrahigh thermal conductivity is crucial for thermal management in electronic devices, preventing overheating as components shrink and power increases [397]. In the pursuit of sustainable energy, borophene emerges as a promising candidate for revolutionising thermoelectric applications, advancing the efficient conversion of heat into electricity [162]. The study emphasises borophene's electronic and optical properties, positioning it in various energy-related fields, from energy storage to hydrogen storage [398]. Werheit et al. [337] recognise boron's potential in high-efficiency thermoelectric energy conversion, emphasising its transport properties in boron-rich solids. Zhou et al.'s [160] findings reveal borophene's exceptional thermal conductivity, surpassing even graphene, which is crucial for efficient energy conversion. Yang et al. [399] discovered that borophene exhibits low thermal conductivity, emphasising its significance in improving the efficiency of the Seebeck effect. He et al. [400] investigated α′-borophene with various gas functional groups, emphasising customised modifications for achieving high thermoelectric ZT. Incorporating nano amorphous boron into thermoelectric materials, as demonstrated by Yang et al. [401], reduces thermal conductivity, improves charge transport, and achieves high ZT values. Higher ZT value indicates a more efficient thermoelectric material. Therefore, achieving a high ZT value implies that the material has a high efficiency in converting heat to electricity, making it desirable for various applications such as waste heat recovery, portable power generation, and refrigeration. Zulkepli et al. [402] discuss the tuneable electronic properties of borophene, offering flexibility for tailoring thermoelectric materials to specific conditions. They highlight the potential for modifying borophene to achieve desired thermomechanical characteristics, enhancing its adaptability [155]. Borophene's atomic-scale thickness and low density make it attractive for developing lightweight thermoelectric devices [403]. Jang et al. [402] proposed a cost-effective, energy-efficient technique for fabricating thermoelectric devices that align with borophene-incorporated devices. Mele et al. and Yu et al.'s reviews on oxide thin films and novel carbon-based thermoelectric materials provide insights that are relevant to borophene-based devices [403,404].

6.6. Composite materials for aerospace and automotive application of borophene

The aerospace and automotive industries require materials that achieve an optimal balance between strength and lightness. Advanced materials play a crucial role in achieving these performance goals. Research on boron carbide-reinforced aluminium composites demonstrates superior strength-to-weight ratios, making them ideal for lightweight aircraft applications [331,405]. These enhancements demonstrate that boron-based materials can reduce weight and maintain structural integrity. Borophene, with its two-dimensional honeycomb lattice of boron atoms, emerges as a promising candidate for enhancing composite properties [406]. Enhanced strength and reduced weight are highly beneficial for composites. Chamis et al.'s [407] study on adhesively bonded metal and resin matrix fibre-composite hybrids suggests ways to enhance strength and stiffness while minimising density increases. This approach could be explored in conjunction with borophene-based materials. Borophene, a 2D material with unique properties, has the potential to revolutionise composites for aerospace applications, where lightweight and robust materials are essential. Forest et al. highlights the benefits of boron/aluminium composites, including high strength, stiffness, and conductivity, while acknowledging challenges in production cost [408]. Borophene's exceptional properties along with affordability can make it an attractive material. Studies by Mortazavi and Zhang emphasise borophene's remarkable tensile strength (range from 13.5 GPa nm to around 22.8 GPa nm dependent on the atomic configurations and the loading direction), exceeding traditional materials [161,200]. This strength improvement is crucial for reinforcing structures in aerospace applications. Zhang et al. [200] further highlights borophene's flexibility, surpassing that of graphene. This enhances its adaptability for various composite applications within aerospace designs. Research by Balasubramanian et al. [340], B. S. et al. [405] and Liu et al. [409] demonstrates the effectiveness of aluminium-boron carbide composites and the use of boron carbide and titanium diboride particles with ceramic matrix composites. These existing applications highlight the potential for borophene to further improve composite performance. Borophene's atomic-scale thickness and low density make it ideal for reducing the weight of composites without sacrificing strength, a key requirement in aerospace [410]. Meschut et al.'s [411] work on lightweight car body structures using boron steels combined with aluminium alloys demonstrates a focus on weight reduction. Similarly, borophene's potential within composites could offer further advancements for both aerospace and automotive industries where lightweight materials are crucial. Zhou et al.'s [160] findings on borophene's exceptional thermal conductance underscore its potential for efficient heat dissipation – a critical factor in aerospace and automotive applications where temperature control is essential. Borophene's unique combination of strength, lightweight properties, and thermal management capabilities make it a versatile material with the potential to revolutionise composites across diverse sectors.

6.7. Application of borophene in medical devices

Borophene, a hexagonal structure of boron atoms with conventional covalent bonds, attracts significant research interest across diverse fields, including biomedicine. Borophene's features position it as a candidate for applications ranging from biosensors for gas detection to precise tumour therapy via boron neutron capture therapy (BNCT) using ionised 10B [186]. Methods for improving 2D nanomaterial preparation, evolving alongside graphene synthesis, apply to borophene. Fabricated using top-down or down-top strategies with distinct precursors and metal substrates, borophene's structural properties play a pivotal role in biosensors and therapeutic applications [74]. Exploring the structural properties of boron and borophene reveals a covalent network structure for boron and a planar 2D structure for borophene. Borophene's clusters, resembling graphene, form trivalent and delocalised bonds, contributing to enhanced electrical and mechanical properties that distinguish it from other 2D nanomaterials. Borophene's mechanical properties, studied through uniaxial stress tests, reveal critical strains and stresses in different directions [259]. Withstanding higher stresses than silicene or black phosphorus, borophene exhibits robust mechanical performance, positioning it favourably among 2D nanomaterials with diverse potential applications. Despite structural similarities with graphene, borophene's biomedical applications, primarily biosensors, are underexplored [76]. Its quantum edge effect enables biosensing for cyanide or gas molecules, while its use in BNCT with the boron cluster C2B10 offers precise tumor therapy without harming healthy tissue [74]. Its mechanical flexibility, biocompatibility, and versatile surface properties have diverse applications in bioimaging, drug delivery, and biosensing [100]. Borophene's exceptional flexibility makes it ideal for wearable devices like smartwatches, fitness trackers, and health monitoring sensors [412]. Emphasising wear comfort in clothing underscores the market potential of biofunctional textiles [413]. The development of flexible bioelectrical sensing sleeves exemplifies borophene's potential in comfortable wearable electronics [414]. Li's focus on breathable materials underscores borophene's significance in ensuring user comfort [415]. Moving beyond wearables, borophene's surface properties can enhance visibility in bioimaging techniques like MRI and PET [416]. Boronic acid-based electrochemical sensors demonstrate borophene's potential in targeted diagnostics for health monitoring [417]. Molecular biosensors strengthen borophene's role in ultrasensitive diagnostics, particularly in cancer biomarker detection [165]. Biocompatibility of borophene is relevant in medical implants, where understanding host responses is crucial for successful integration [418]. Kabatas et al.' work on integrating boron-containing tags into proteins highlights borophene's potential in high-resolution imaging for medical diagnostics [419]. Borophene is transformative in diagnostics and therapeutics, a valuable asset for advancing healthcare technologies. Fig. 18 highlighting its role in biosensors and tumour therapy through BNCT. The hexagonal lattice structure of borophene illustrates its unique features for diverse biomedical functionalities.

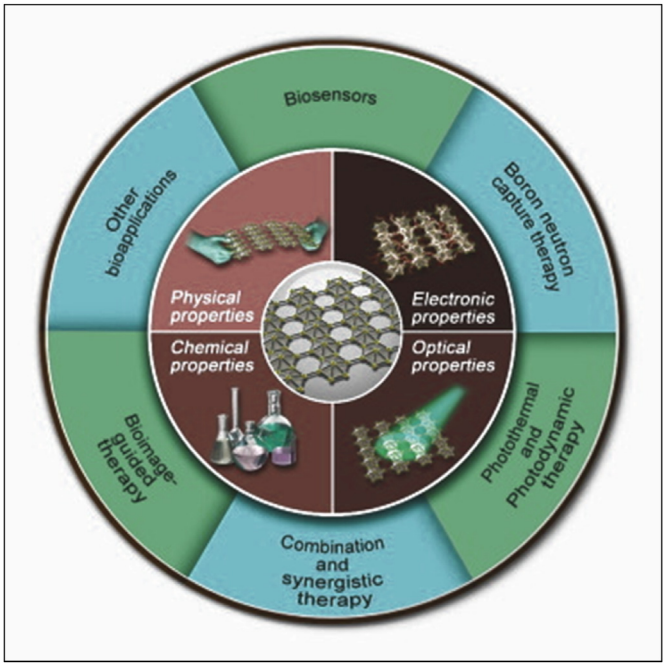


Fig. .18. Schematic representation displaying potential biomedical applications of borophene [74].

7. Conclusions and outlooks

Borophene, a 2D honeycomb lattice of boron atoms, has emerged as a revolutionary material with the potential to transform various scientific and technological fields. Its unique properties have sparked excitement and research interest across diverse industries. This article delves into the significance of borophene and its implications for future innovations. One of the most compelling aspects of borophene is its high carrier mobility and tuneable bandgap. These properties make it highly attractive for the development of faster and more efficient transistors and logic gates. By leveraging borophene's electronic properties, researchers aim to revolutionise electronics, paving the way for advancements in computing power and data processing. Furthermore, borophene holds promise for spintronics applications, offering opportunities for breakthroughs in data storage and manipulation. Beyond electronics, borophene's exceptional strength-to-weight ratio and thermal stability make it an intriguing candidate for aerospace applications. Lightweight yet robust, borophene-based materials could revolutionise the design of aerospace structures and components, leading to more fuel-efficient aircraft and spacecraft. Additionally, borophene's sensitivity to various stimuli positions it as a valuable material for gas sensors and environmental monitoring devices. Its ability to detect and respond to different gases could enhance air quality monitoring systems and contribute to pollution control efforts. Moreover, borophene's optical transparency and tunability open up exciting possibilities for advanced solar cells and innovative lighting systems. By incorporating borophene into these technologies, researchers aim to improve energy efficiency and explore new avenues for sustainable energy generation. Furthermore, borophene's potential for quantum applications is gaining attention. Its unique properties make it suitable for tasks such as radiation shielding and precise measurements in Earth sciences. As researchers delve deeper into borophene's quantum properties, they may uncover new avenues for exploration in fundamental physics and quantum technology. In conclusion, borophene's remarkable properties hold immense potential for a wide range of applications, spanning from electronics to aerospace, environmental monitoring, energy, and quantum technology. As research in this field continues to advance, we can anticipate even greater innovations and breakthroughs driven by this extraordinary 2D material. The future of borophene is bright, and it is poised to leave a lasting impact on science and technology.

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