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Letter to the editor

MBENEs: A New Class of 2D Materials Beyond MXenes

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Abstract: Developing advanced materials is key to progress in energy, electronics, and environmental technologies. MBENEs, a new class of 2D transition metal borides (Mn+1Bn), offer exceptional electrical conductivity, thermal stability, and chemical resilience. Derived from MAB phases via selective etching, MBENEs differ from MXenes in their strong M–B bonds, making synthesis more challenging but promising for harsh-environment applications. Unlike graphene and MXenes, MBENEs combine metal-like conductivity with catalytic activity and structural robustness. Though current research on MBENEs is largely theoretical, early studies highlight their potential in catalysis, energy storage, and high-temperature electronics. Indeed, key challenges remain in scalable synthesis and surface property control to realize their technological promises.

शोधसार: उन्नत सामग्रीहरूको विकास ऊर्जा, इलेक्ट्रोनिक्स, र वातावरणीय प्रविधिमा प्रगतिको प्रमुख कुञ्जी हो। MBENEs (Mn+1Bn) नामक नयाँ वर्गका दुई-आयामी ट्रान्जिशन मेटल बोराइडहरूले असाधारण विद्यतिय सुचालकता, तापीय स्थायित्व, र रासायनिक प्रतिरोध प्रदान गर्छन्। MAB फेजहरूबाट छानिएको एचिङ प्रविधिमार्फत प्राप्त गरिने यी MBENEs, MXenes भन्दा फरक छन् किनभने तिनीहरूमा M–B बन्धनहरू बलिया हुन्छन्, जसले गर्दा तिनिहरुलाई संश्लेषण कठिन हुन्छ तर कठोर वातावरणमा प्रयोगका लागि सम्भावनायुक्त बनाउँछ। ग्राफिन र MXenes भन्दा फरक रूपमा, MBENEs ले धातु-जस्तै सुचालकता, उत्प्रेरक सक्रियता, र संरचनात्मक दृढता संयोजन गर्छन्। यद्यपि हालसम्मको अनुसन्धान प्रायः सैद्धान्तिक छन्, प्रारम्भिक अध्ययनहरूले उत्प्रेरक, ऊर्जा सञ्चयन, र उच्च तापमा काम गर्ने इलेक्ट्रोनिक उपकरणहरूमा तिनीहरूको सम्भावना देखाएका छन्। यस्ता प्रविधिगत सम्भावनाहरू साकार पार्न अझै पनि ठूला चुनौतीहरू, जस्तै ठूलो मात्रामा संश्लेषण र सतह गुणहरूको नियन्त्रण, कायम छन्।

INTRODUCTION

The development of new materials is essential for cutting-edge technology, enabling breakthroughs in energy, aerospace, electronics, tissue engineering, and environmental sustainability [1,2]. Novel materials with tailored properties boost innovation in devices and systems by overcoming the limitations of existing materials [1,2]. In this context, MBENEs (Cr_2B_2, Fe_2B_2, Mo_2B_2, W_2B_2, etc. based on first-principles calculations) a new 2D transition metal borides class, offer exceptional electrical conductivity, thermal stability, and chemical resilience [3,4]. These properties position MBENEs as promising candidates for next-generation applications in catalysis, energy storage, and harsh environment electronics, addressing critical challenges where other 2D materials like graphene or MXenes may fall short [3,5,6]. The emergence of MBENEs exemplifies the transformative potential of engineered 2D materials. In this regard, over the past three decades, research has surged into discovering and synthesizing numerous 2D systems with tailored properties for applications spanning sensing, robotics, electronics, energy storage, catalysis, and many more. Among these, graphene, transition metal dichalcogenides MXenes, and h-BN nanosheets got great consideration, and now the emerging class of MBENEs (a 2D transition metal borides, having general formula $M_{n+1}B_n$ where M = early transition metal, and B = boron) represent critical milestones. Thus, MBENEs are composed of metal boride nanosheets and are directly exfoliated from MAB phases (**Figure 1**). MAB phases are structurally analogous to the more

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established MAX phases from which MXenes are derived. In a typical MAB phase, a transition metal (M) is bonded to a boron sublayer (B), and the structure is interleaved with an (A) group element, commonly from groups 13 to 16. Through selective etching usually targeting the A-site element researchers aim to exfoliate the M–B layers, thereby yielding MBENE sheets. However, unlike MAX-derived MXenes, where the M–C or M–N bonds are relatively ionic and easier to disrupt, the M–B bonds in MAB phases exhibit stronger covalency and greater structural rigidity. This difference makes the synthesis of MBENEs greatly challenging, requiring innovative etching strategies and thermodynamically guided processes, including molten salt and electrochemical methods [4,6–8].

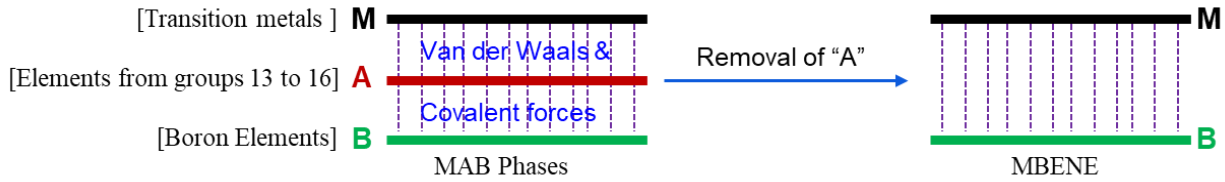

Figure 1. Schematic diagram showing the composition of MAB phases, MBENE, and the general strategy for conversion of MAB phases to MBENE

Each class of 2D materials offers distinct chemistry, structure, and functionality and possesses its advantages and shortcomings. In this line, MBENEs, introduce a different paradigm; combining the advantageous features of transition metals and boron in ultrathin, crystalline architectures. These materials, though still in their infancy, hold the promise of addressing some of the limitations faced by graphene, MXenes and h-BN nanosheets. Nevertheless, the attraction of MBENEs lies in their combination of robust thermal stability, high electrical conductivity, and chemical durability behaviors that make them mainly outstanding for harsh environments and high-performance applications. Compared to MXenes, which are often terminated with–F, –OH, or –O groups that enhance hydrophilicity and reactivity but also introduce structural instability in certain conditions, MBENEs provide a more chemically resilient alternative. The presence of boron, known for forming strong covalent bonds and contributing to high hardness and oxidation resistance, imparts greater thermal and chemical endurance to MBENEs. Therefore, MBENEs become promising candidates for next-generation electrocatalysts, high-temperature electronics, and protective coatings. In comparing MBENEs to MXenes, several important distinctions appear. MXenes first synthesized in 2011 have undergone extensive development, with over 30 distinct compositions reported and widespread application in supercapacitors, battery electrodes, electromagnetic shielding, and sensors [7,9]. The surface chemistry of MXenes, enabled by abundant terminal groups, is both a strength and a weakness. Although MXenes allow for functionalization and dispersion in aqueous media, these also contribute to oxidation degradation and electrochemical side reactions. In contrast, MBENEs are expected to be less reactive, thereby offering better longevity in operational devices. However, the trade-off is limited surface tunability, at least based on present research. In the same line, compared to graphene, MBENEs present an even more differentiated profile. Graphene, with its pristine sp^2-bonded carbon lattice, remains unmatched in terms of carrier mobility, mechanical flexibility, and chemical purity. Yet graphene's chemical inertness, although beneficial in some contexts, limits its ability to host active sites for catalysis or ion intercalation without defect engineering or heteroatom doping [5,10]. MBENEs, due to their transition metal centers and boron-based structure, naturally offer metal-like conductivity and catalytically active sites, especially when surface terminations or structural defects are introduced [2–4]. This makes them promising alternatives in energy storage and conversion technologies where graphene falls short. Nevertheless, the current state of MBENE research is largely exploratory. Moreover, the experimental reports are sparse, with only a handful of successful syntheses (e.g., Ti_2B and Mo_2B) documented whereas 100 s of methods have been developed for graphene production. In the case, of MBENEs most

studies remain computational and theoretical, using density functional theory to predict properties such as electronic structure, magnetic ordering, and thermodynamic stability [11]. These theoretical insights suggest that MBENEs can exhibit a rich diversity of behaviors, from metallic to semiconducting phases, and from nonmagnetic to ferromagnetic configurations, depending on the choice of transition metal and boron framework. The potential for tunable band structures via strain/doping further improves the importance of MBENEs. Importantly, to transition MBENEs from concept to technology, several challenges must be addressed. First, scalable and controllable synthesis methods are required to produce phase-pure, few-layer MBENE sheets with the defined morphology. Second, a deeper understanding of their structural, surface, and morphological properties, especially regarding possible terminations and their impact on properties, is very indispensable. Third and most crucial, application-specific optimization such as improving ion diffusion kinetics for battery electrodes, or maximizing surface area and active sites for catalysis must be undertaken.

In summary, MBENEs represent a compelling addition to the 2D material family, combining aspects of MXenes and graphene but carving out a unique identity defined by boron-rich chemistry and transition-metal functionality. Although, the theoretical promise of MBENEs is high, and their experimental progress, currently it is in a nascent stage, and gaining momentum widely in the materials science fraternity. Based on scientific progress, it is assumed that as synthetic techniques improve and mechanistic understanding deepens, MBENEs could become central to future materials platforms in energy, electronics, and beyond. Their arrival signals a continued diversification of the 2D materials landscape, offering new possibilities for designing functional matter at the atomic scale.

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