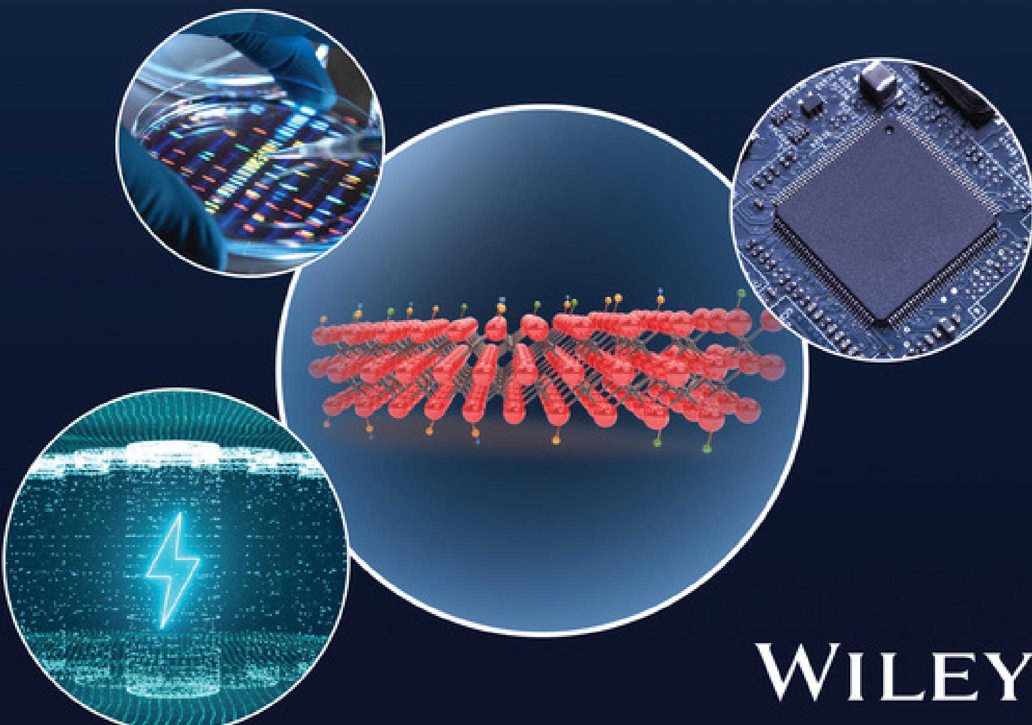
Transition Metal Carbides and Nitrides (MXenes) Handbook

Synthesis, Processing, Properties and Applications

Edited by
Chuanfang Zhang • Michael Naguib



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Preface

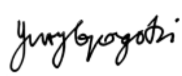
In 2011 came the first report telling a story of the discovery of MXenes, a two-dimensional (2D) transition metal carbide, $Ti_3C_2T_x$, obtained from selective removal of aluminum layers from a 3D-layered Ti_3AlC_2 MAX phase. This discovery was within a year followed by the realization of more MXenes, including Ti_2CT_x, $Ta_4C_3T_x$, and Ti_3CNT_x, and since then, the family of 2D carbides and nitrides has been growing at an unprecedented rate. There are currently more than 50 MXenes reported, including those with out-of-plane and in-plane ordering, solid solutions on both the M and X sites, and high-entropy compositions. Considering the possibility of having both single (Cl, Br, S, etc.) and multiple (O, OH, F, etc.) terminations on these laminates, this family is by far the largest and most diverse family of 2D materials.

Since 2011, more than 20 000 papers have been published by groups from more than 100 countries all over the world (six continents), and the number of publications appearing every year continues to increase. By the most conservative count (Web of Science), more than 70 000 researchers have co-authored MXene papers, following the initial discovery and exploring the enormously rich chemistry and large variety of MXene structures. The fast growth observed in the past five to six years is caused not only by an almost infinite number of new materials that can be synthesized but first and foremost by the unique properties of MXenes. Those include the very high electrical conductivity of $Ti_3C_2T_x$, a wide range of optical properties depending on the composition with absorption peaks from UV to IR wavelength ranges, etc. Biocompatibility and easy processability from aqueous colloids add another advantage. Over the past decade, a major progress has been achieved in increasing the environmental stability of MXenes, with M_3C_2 and M_4C_3 MXenes staying for a year or longer in aqueous solution without degradation, MXene supercapacitor electrodes lasting for 500 000 cycles in acidic electrolytes, and micron-thin films maintaining their conductivity after several years of storage in the ambient environment.

We stand at the crossroads of discovery and applications. While new MXenes are reported regularly and their fundamental properties are being explored, they are also tested for a vast array of potential applications. More than 4200 patent applications were known to be published at the end of 2022, according to Patsnap. Taking into account the 18-month gap between patent filing and publishing by patent offices, this number is much higher today. The initially explored area of application was energy storage, and the largest number of patents filed address energy, electrochemistry, and separation membranes. However, applications in optics and optoelectronics, as well as biomedical applications, are the fastest areas of growth nowadays. The area closest to commercialization may be electromagnetic interference shielding, where MXenes not only outperform all other materials in performance but also allow controlled reflection or absorption, depending on the choice of MXene and the film architecture, as well as modulation of shielding effectiveness. However, with many other applications being explored, it is difficult to predict where the first large commercial breakthrough will occur. What matters is that, due to their extreme properties, MXenes have already outperformed all known materials in a multitude of applications, from electromagnetic shielding to epidermal electronics and thermal management. By adding their simple processing from colloidal solution in water with no surfactant or additives needed, the chances are high for fast commercialization.

With properties outperforming many of those for currently applied materials, it is crucial to put extra emphasis on how the MXenes, and their precursors, are synthesized. This handbook contains 27 chapters covering synthesis and processing (14 chapters), properties (3 chapters), and applications (8 chapters). A clear emphasis is placed on the synthesis, chemistry, and processing of MXenes. In light of current challenges and demand for cost-efficient, scalable, and not the least sustainable synthesis procedures, the topic of this book *Transition Metal Carbides and Nitrides (MXenes) Handbook: Guidelines for the Synthesis, Processing, Properties, and Applications*, is timely. A comprehensive book that summarizes the current state-of-the-art of MAX and MXene synthesis, also providing details that may sometimes be overlooked in scientific publications, can provide a platform from which we develop MXene synthesis and processing further.

The potential of MXenes will be fully utilized once we have sustainable synthesis methods. While sustainability and materials are often discussed in terms of achieving desired material properties for specific energy and environmental applications, the technology to process the materials is sometimes overlooked. Sustainable MXene synthesis requires minimizing the environmental impact and consumption of resources. It entails principles such as reducing the use of hazardous chemicals (e.g. hydrofluoric acid), optimizing energy efficiency, and recycling raw materials and waste products (salt solutions). Moreover, this approach should also be used to manufacture MAX phases or other MXene precursors. By embracing this way of thinking and with more efforts invested in research on the processing of MXenes, they can play a key role in addressing pressing global challenges, from purification of water, air, and soil to clean energy and beyond.



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(*signed using $Ti_3C_2T_x$ MXene ink*)

Part I

The Introduction