

## 2D Carbides and Carbonitrides (MXenes) for Electrochemical Energy Storage: Batteries, Supercapacitors and More

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Nanomaterials, particularly two-dimensional (2D) materials, are among the most promising candidates that can be used to address some of the ongoing challenges in manufacturing batteries and supercapacitors and enable devices with superior performance metrics and lower cost. Two-dimensional metal carbides and nitrides (MXenes) are a very large yet quickly growing family of 2D materials with the formula of  $M_{n+1}X_nT_x$  where M is an early transition metal, X is carbon or nitrogen, and  $T_x$  refers to the surface terminations. Molecular dynamics and *ab initio* simulations, along with experiments, show that the electronic, optical, and, most importantly, electrochemical properties of MXenes distinguish them from other widely studied 2D materials. Chemical and electrochemical insertion of ions and molecules between the MXene layers allows modification of their properties, as well as electrochemical charge storage and harvesting, which use both double-layer and redox mechanisms. The high electronic conductivity (over  $20,000 \text{ S cm}^{-1}$ ), redox-active surfaces, cation intercalation in 2D slits, and rich chemistry of these materials, with more than 100 different compositions reported, have enabled their use as charge storage hosts and building blocks of passive cell components in various types of energy storage devices. Freestanding, binder-free films of  $\text{Ti}_3\text{C}_2\text{T}_x$  are capable of ultra-high-rate pseudocapacitive charge storage in protic electrolytes, delivering  $\sim 400 \text{ F g}^{-1}$  ( $1500 \text{ F/cm}^3$ ) at rates of up to  $100 \text{ V s}^{-1}$  and volumetric energy and power densities several times higher than conventional carbon-based capacitive electrodes. MXenes can intercalate a variety of monovalent and multivalent cations from aqueous or non-aqueous electrolytes and, therefore, can be used as electrodes for emerging new supercapacitor and pseudocapacitor chemistries. Their mechanical robustness and high conductivity expand their use as conductive additives in electrodes and also building blocks for conformal coatings to avoid dendrite growth in metal batteries. Yet, unlike most other 2D materials, the synthesis and processing of MXenes is scalable and cost-effective, and they can be processed in large batches from aqueous solution into various forms of powders, dispersions, and films. The combination of these properties and scalable synthesis not only renders MXenes as materials attractive for academic research but also as practical materials of choice for future charge storage applications.