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Editorial

MXenes: The Revolutionary Material Powering the Future of Energy Storage

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Since the discovery of MXene in 2011 by Yuri Gogotsi and his team at A. J. Drexel University, these materials have garnered significant attention from researchers worldwide for diverse applications, particularly in energy storage [1]. This editorial explores MXene's role as an electrode material for supercapacitors, highlighting its superior properties compared to other materials.

The transition metal nitrides, carbides, and carbonitrides family of 2D materials known as MXenes are rewriting the fundamental limits of supercapacitors with their combined properties of metallic conductivity, hydrophilicity, mechanical flexibility, and large surface area [2]. With such an impressive list of properties, it is no surprise that the key to their dominance of the energy storage field lies in the atomic-architecture [3], the MXene sheets are only a few atoms thick, consisting of transition metal atoms sandwiched between carbide or nitride atoms, and their surface termination groups can be precisely tuned to obtain the electrochemical properties required [4], [5]. As reported by Tongming et al., -OH terminations in MXene increase its surface area by further delaminating MXene layers than other terminations, which directly improves its electrochemical properties as the increased surface area provides more active sites for the material to achieve higher specific capacitance [6]. These delaminated sheets provide both EDLC and pseudo capacitance as their surface-active sites allow for both redox reactions and surface charge storage. These properties enable the successful use of MXene in supercapacitors, because they possess an interlayer spacing of few nm, which is suitable for the intercalation of ions, and a negatively charged surface that provides natural affinity for cations, which is favourable for the charge storage mechanism [3], [7]. MXene-based supercapacitors remain electrochemically reversible and structurally intact at high scan rates and offer charge storage in seconds instead of hours, and they allow for millions of charge-discharge cycles with minimal degradation. Recent studies have shown that MXene supercapacitors can achieve an energy density of more than 100 Wh/Kg and a power density of more than 100 W/Kg, which was thought to be unachievable [4], [8]. MXene supercapacitors are currently competing with batteries in terms of energy density, power density, and energy storage capacity. The mechanical robustness of the material makes it possible to fabricate freestanding films up to 1,000 µm thick without the use of current collectors or binders, thereby increasing the loading of active chemicals and reducing inactive ones [3], [9]. The hydrophilic nature of MXenes makes them functional with an electrolyte solution, and their surface terminations can be tailored to optimize the ions, which further increases their specific capacitance.

MXene is a game-changer in the practical applications of supercapacitors across all application sectors, as MXene supercapacitors outperform batteries in terms of braking energy and charge-discharge cycles both of which are critical for a vehicle lifetime in electric automobiles [4], [5], can be charged within a few seconds, can be integrated into portable and flexible energy storage systems in consumer electronics due to their flexibility and ultrathin nature, and can be made stretchable, allowing for the creation of wearable devices that maintain performance after excessive strain. The materials science behind these achievements is equally revolutionary. MXene can be precisely tailored at the atomic scale by choosing the appropriate MAX phase, etching conditions to tune surface terminations, such as longer etching in HF will result in more -F terminations, while lesser time etching results in more -OH or -O terminations, interlayer spacing engineering, and heterostructures with other two-dimensional materials. These modifications to MXene can be optimized for many applications, making it applicable in such a wide range of fields. Advances in MXene synthesis have enabled single-flake sizes larger than 100 µm with atomic-scale thickness control, and more recent delamination techniques yield MXene solutions at concentrations as high as 50 mg/mL, suitable for industrial-scale processing [6], [7], [10].

Looking forward, the future of the MXene supercapacitor revolution is being accelerated by 3D-printed MXene architectures that enhance ion transport pathways, hybrid MXene-graphene heterostructures that combine the most desirable properties of both materials, and solid-state MXene supercapacitors with unprecedented energy densities. As production moves from lab batches to industrial numbers, costs will come down and allow for broader adoption. Costs are expected to go down as production moves from lab batches to industrial quantities, making wider adoption more likely. The combination of performance and characteristics of MXenes could enable supercapacitors to go to a standard energy storage solution for all sectors of the global economy, ushering in a new era of energy storage where the limitations of traditional energy storage technologies are eliminated.

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Biography

Mr. Nitin Kumar Gautam is a PhD scholar in the Department of Physics at UPES, Dehradun (India), working under the supervision of Dr. Shalendra Kumar and Dr. Aditya Sharma. His research focuses on advanced materials for energy storage applications, especially in supercapacitor technology. He holds a Master of Science (M.Sc.) in Physics from Dr. B.R. Ambedkar University, Agra, India (from 2021 to 2023). His work has been published in reputed international journals. His research aims to enhance energy storage efficiency through material design and electrochemical characterization.

Dr. Aditya Sharma is working as Associate Professor in Physics, UPES, Dehradun, India, from November 2023 to till date. He was associated with Manav Rachna University Faridabad, India, as an Assistant Professor & In-Charge of University Instrumentation Centre (2018-2022). Dr. Sharma worked as Visiting Research Scientist in the X-ray open laboratory of the Korea Institute of Science and Technology (KIST), Seoul, South Korea (2015-2018). He had been associated, as a post-doctoral research fellow, in the Spectro-Nano-scope group at Pohang Accelerator (synchrotron) Laboratory (PAL), South Korea (2013-2015). Dr. Sharma received his PhD degree from Dr. B.R.A. University, Agra, Uttar Pradesh, India, in 2013. He worked as junior/senior research fellow under the Inter University Accelerator Centre (IUAC), New Delhi, India, sponsored research project (2007-2010). Dr. Sharma received his M. Sc degree (2005) and B.Sc degree (2003) from Vikram University, Ujjain, and DAVV, Indore, Madya Pradesh, India, respectively. His current research endeavors revolve around energy harvesting, storage and conversion through developing Battery/Super-Capacitor devices, Solar-Cell devices, up-conversion persistent luminescent Nanomaterials, Photo/Electro Catalyst and ion-beam induced modification of thin films and multilayers (deposited using RF/DC sputtering). He has guided several PhD/M.Sc students and received research project grants for energy harvesting/storage nano- materials/ thin films. He is serving as editorial board member and guest editor in several scientific and academic journals.

Dr. Shalendra Kumar is a Professor in the Department of Physics at UPES, Dehradun, India. Previously, he served as a visiting faculty at King Faisal University, Saudi Arabia. He completed his M.Sc. and Ph.D. in Physics at Aligarh Muslim University (AMU), India. Following his Ph.D., Dr. Kumar embarked on postdoctoral research as a Korean Research Foundation fellow from February 2008 to March 2009. He then served as a Research Professor under the prestigious Brain Pool Program at Changwon National University, South Korea, from April 2009 to January 2012. Subsequently, he joined the Beamline Division at Pohang Light Source II as a Research Scientist, where he worked from February 2012 to April 2013. Returning to Changwon National University, he resumed his role as a Research Professor from December 2013 to July 2015. From December 2015 to June 2016, Dr. Kumar was a visiting Professor at Universidade Federal do Maranhão, Brazil. He later joined Amity University Haryana, Gurgaon, as an Assistant Professor, a position he held from August 29, 2016, to November 1, 2019. Dr. Kumar's research is centered on experimental investigations of functional oxide materials, including ferrites, colossal magnetoresistance (CMR) compounds, lead-free piezoelectrics, multiferroics, and dilute magnetic semiconductors (DMS), across various forms such as bulk, thin films, and one-dimensional nanostructures. Additionally, his work focuses on the development of nanostructures for energy storage applications, including Li-ion and Li-S batteries, supercapacitors, and solar cells. With an impressive h-index of 55 and over 11,000 citations, Dr. Kumar has published more than 300 research papers in international peer-reviewed journals. He holds 6 US patents and has delivered over 100 conference presentations worldwide. He has been a Guest Editor in several journals.

