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EDITORIAL

MXenes: Changing the World—a conference report and a look into the future

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Abstract
With the accelerated global interest in MXenes, the fastest-growing family of 2D materials, Drexel University hosted the 3rd International Conference, **MXenes: Changing the World**. This vibrant conference is the only one in the US solely devoted to MXenes, and the presentations and discussions brought together a significant number of top researchers with students. However, dedicated conferences and an increasing number of symposia are popping up worldwide as more applications and adaptations of MXenes are discovered and developed. We see the impact of this material and embrace its momentum as we look to the future.

MXenes are the fastest-growing family of 2D materials, which includes carbides and nitrides of transition metals and related compounds (Anasori and Gogotsi in Graphene 2D Mater 8:39–41, 2023). They have not only a great variety of structures and compositions, but also offer a wide array of useful and often unique properties, which lead to numerous potential applications (Anasori and Gogotsi in Graphene 2D Mater 7:75–79, 2022). Not surprisingly, dedicated MXene conferences took place on three continents in 2024, including the 1st EuroMXene Congress in Valencia, Spain, in July, the 3rd MXene Conference in Philadelphia, PA, USA, in August, and the 5th International Conference on MXenes in Xi'an, China, in October. There were also multiple MXene symposia at other conferences, such as the Materials Research Society (MRS) Spring meeting in Seattle and the European MRS (E-MRS) Fall meeting in Warsaw, demonstrating that the critical mass of researchers working on MXenes has been reached on several continents and announcing a formation of a MXenes community. This is a reflection of the groundbreaking discoveries in the field and penetration of MXenes into a wide variety of research fields, from energy technology to wearable and printable electronics, thermal management, communication, to aerospace and healthcare (Naguib et al. in Adv Mater 33:2103393, 2021).

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MXenes: Changing the World, the Third International Conference at Drexel University, was organized by the A.J. Drexel Nanomaterials Institute (DNI) and held at Drexel's College of Engineering, the birthplace of MXenes, from August 5 to 7, 2024. This editorial will summarize the conference events and also provide a summary of the key findings, and important research directions reported in conference talks and identified during panel discussions.

With resounding acclaim for this returned event, Drexel University welcomed over 250 attendees from around the world to celebrate this renowned family of materials with increasing interest and excitement. While about 90% of participants physically joined the meeting at Drexel (Fig. 1), virtual attendance allowed many attendees and presenters to participate from the other side of the globe. It also offered flexibility for the in-person attendees to remain engaged throughout the 3-day event. We saw a 74% increase in physical attendance from our prior meeting in 2022.

Sunday before the conference, an immersive 1-day MXene course was presented to a sold-out room of 50 participants who received a condensed overview of synthesis, characterization, and the electrochemical applications of MXenes, followed by laboratory tours and demos. The day began with a welcome address from Professor Yury Gogotsi, followed by presentations on the fundamentals of MXene synthesis, X-ray diffraction (XRD), Raman spectroscopy, and X-ray photoelectron spectroscopy (XPS) analyses of MXenes by postdocs and PhD students with the expertise in the field. Due to the interest and engagement of the attendees, discussions ran through the lunch break and reflected

the energy that brought these students to attend the course. For the second half of the day, groups of participants toured the DNI's laboratories (Fig. 2) and were presented with various demos to gain a deeper understanding of the developing capabilities of MXenes.

An evening reception gathered DNI alumni and current group members, those who presented at the conference, and others in the region who made the effort to connect with old classmates and the network of researchers under Prof. Gogotsi. Dozens of DNI alumni are currently in faculty positions around the globe and quite a few of them, including Michael Naguib (Tulane), Babak Anasori (Purdue), Kelsey Hatzell (Princeton), Majid Beidaghi (Univ. Arizona), Christopher Shuck (Rutgers), Vadym Mochalin (Missouri Tech), Ruocun (aka John) Wang (Univ. North Texas), and Mark Zhao (NJIT) are involved in MXene research in the US.

The welcoming energy of the celebration coursed through to the start of the conference on Monday morning with live music—a new MXene song (check YouTube) written and presented by Dr. Benjamin (Ben) Davis, a postdoctoral researcher at DNI and the Master of Ceremonies for our conference. A unique introduction to set the tone for the event. Welcome addresses were presented by Drexel's Executive Vice Provost for Research and Innovation, Prof. Aleister Saunders, and the Associate Dean for Research and Faculty Affairs, Prof. Caroline Schauer.

The first plenary lecture, "Defect Engineering of 2D MXenes at Ambient and Elevated Temperatures," was presented by Prof. Babak Anasori (Fig. 3, left) and was well received by the packed auditorium of attendees and participants who were eager for a day of diverse and important presentations on MXenes. Important keynote lectures from Prof. Michel Barsoum (Drexel) on MAX phases and Prof. Husam Alshareef (KAUST) on electronic applications of MXenes followed before breaking for lunch. Lunch was provided for each of the 3 days and kept the conference attendees together, offering a space for energized discussions and collaborative ideas to be shared. This was a truly meaningful component of each day.

Following lunch, an engaging panel, "The Place of MXenes in the Nanomaterials World," was expertly moderated by Prof. Paul Weiss of UCLA and included Prof. De-en Jiang from Vanderbilt University, Dr. Paweł Michalowski from Łukasiewicz Research Network—Institute of Microelectronics and Photonics in Poland, Prof. Po-Yen Chen from the University of Maryland, and Prof. Zahra Fakhraai from the University of Pennsylvania (Fig. 3, right). These experts discussed the importance and impact of MXenes and where they are making the greatest impact.

Midday brought the beginning of our parallel sessions on topics such as the Synthesis of MXenes, Optical and Electronic Properties, and Processing. Top researchers and junior scientists presented to engaged crowds, raising important issues, inciting inspiring discussions, and offering refreshing viewpoints (Fig. 4).

Monday concluded with all attendees reuniting for one final plenary lecture, "Inorganic, Organic, and Organometallic Surface Chemistry of MXenes," offered by Prof. Dmitri Talapin from the University of Chicago, followed by the first of two cocktail receptions and poster sessions. These casual events again were abuzz with deeper discussions and reflections on the day's presentations and, most importantly, connecting students with a network of senior scientists in academia, industry, and government.

Close to 100 posters were on display, filling the lobby of the Bossone Research Enterprise Center (Fig. 5). The array of posters presented the breadth of MXene capabilities and directions. While primarily from students, a number of posters were offered by visiting researchers, postdocs, and industry scientists. The displays remained throughout the conference and were a welcome feature of every break to conference-goers and Drexel affiliates passing through. Ten esteemed professors with varying expertise were selected to judge the posters, and awards were presented in a ceremony at the end of the event.

Tuesday, Day 2, was similar in format, starting with an outstanding Plenary Lecture, "Processing and Applications of 2D MXene Inks," by Prof. Valeria Nicolosi from Trinity College of Dublin. It was followed by Texas A&M University's Prof. Abdoulaye Djire's Keynote, "Operando Spectroelectrochemical Techniques for Elucidating the Mars-van Krevelen Cycle for Green Ammonia Production on Nitride MXene." After the morning coffee break, once again, parallel sessions were offered. Dr. Dhriti Nepal (AFRL), Prof. Chong Min Koo (SKKU, Korea), and Prof. Seon Joon Kim (KIST, Korea) spoke on applications of MXenes, while Dr. Anupma Thakur (Purdue), Prof. André Taylor (NYU), Dr. Mark Anayee (AFRL), and Prof. John Anderson (UChicago) continued the talks on synthesis. "Applications Making an Impact" was the panel that completed the morning sessions and provided an interesting discussion from experts in different fields working with MXenes: membranes, water, textiles, healthcare, and energy storage.

Following the Invited Talk by Prof. Andreas Rosenkranz from the University of Chile, "2D MXenes – Tribological Potential, Bottlenecks and Challenges," sessions on Processing, MXenes and Water, Energy Storage, Energy & Catalysis, and Optical and Thermal Properties filled the afternoon. "Where and How to Publish MXene Research" was the Editors & Publishers Panel that concluded the day's presentations and was perfectly moderated by Babak Anasori, Editor of *Graphene & 2D Materials*, and joined by Anita Lekhwani, Executive Publisher at *Springer Nature*, Emily Edwards, editor with *Cell Reports Physical Science*, Senior Editor, Yohan Dall'Agnese, from *Nature*, Michael Ghidiu, Associate Editor of *Nature Communications*, and

Fig. 1 The 3rd International Conference on MXenes brought together research leaders in the field and young researchers who are just starting their careers. Representatives from industry, government, and publishers participated as well

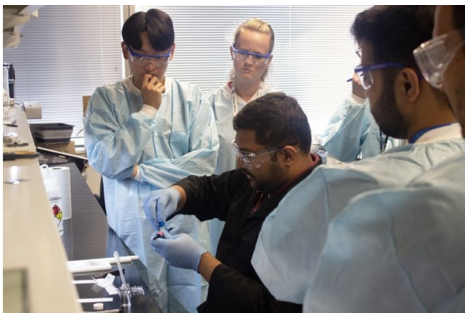

Fig. 2 The course participants were separated in several groups and were able to see the key steps in synthesis, processing, and characterization of MXenes. DNI instructors, Sokhna Dieng and Yash Athreya, wear black laboratory coats

April Rodd, Deputy Editor at Wiley in charge of *Small* and *Advanced Functional Materials* (Fig. 6, left). A truly fantastic discussion to mark the end of Day 2. Networking, cocktails, and the second night of posters ensued, once again delighting the diverse crowd of attendees.

On the final day of events, Wednesday, August 7, the morning opened with "The Future of MXenes" lecture by Drexel's own Prof. Yury Gogotsi, the Conference Chair. He offered a look ahead at where these game-changing materials can potentially take us. Prof. Mohammad Zarifi (the University of British Columbia) followed Gogotsi with his Keynote lecture on "MXene Guides Electromagnetic Waves in Communications and Shielding." Parallel sessions once again proceeded with presentations on Biomedical Applications, Environmental Applications (Water & Catalysis), Electronic Properties & Applications, and Emerging Applications with High Impact. As every day showed, the challenge was deciding which talks to hear. After many lectures on the capabilities of MXenes, and many questions about how it may be possible without the necessary quantity, a panel on scaling up was offered by industry scientists and entrepreneurs from Ballydel, Tesla, MXene Inc., and Nanoplexus. Drs. Brendan Delacy, Armin VahidMohammadi, Kyle Matthews, and Thomas Moissinac discussed the challenges, need, and impact of bringing MXenes to commercialization. The final Plenary lecture was presented by Prof. Michael Naguib from Tulane University. With no need for an introduction, as Michael was the student behind the discovery of MXenes, he presented on "MXene Nano- and Atomic-Scale Engineering for Electrochemical Energy Storage and Conversion" and responded to a final round of questions from the audience.

To summarize the results presented in talks, posters, and panel discussions, we should certainly consider MXenes as

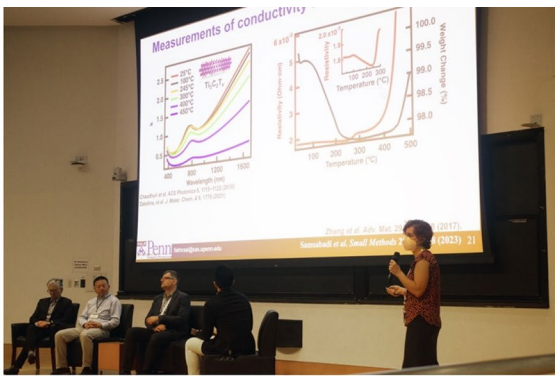

Fig. 3 Plenary lectures, like the one offered by Babak Anasori, provided broad overviews of key research areas, and the panel discussions kept the audience engaged

Fig. 4 Parallel sessions covered a wide variety of topics

an established family of materials that can advance technologies in all the above-mentioned fields. They show high commercial potential, and the manufacturing and scale-up activities have started.

Here, we list some of the useful properties and advantages of MXenes in various applications over other 2D materials as identified during the conference. This list is far from complete.

1 Physical properties

- Higher electronic conductivity (e.g., Ti_3C_2) compared to reduced graphene oxide (rGO) combined with ionic conductivity and hydrophilicity of graphene oxide (GO)
- Ti_3C_2 and Nb_4C_3 are stronger and stiffer than other solution-processed 2D materials
- Chemically tunable superconductivity, work function, and other physical properties
- Properties can be modulated using light, applied potential, and chemical environment

2 MXene colloids and dispersions

- Aqueous colloids with no surfactant or dispersion in polar organic solvents
- Hydrophilic particles form aqueous inks with no additives or surfactants
- Conductive ink produces films/traces with an order of magnitude higher electronic conductivity than carbons
- No binder burning or high-temperature reduction is needed
- No smearing, bleeding, or coffee-ring effect on paper or fabric

3 Energy storage

- Redox (pseudocapacitive) storage, in addition to double-layer capacitance
- Can accommodate large and multivalent ions between the layers
- It can be used as a conductive additive or current collector

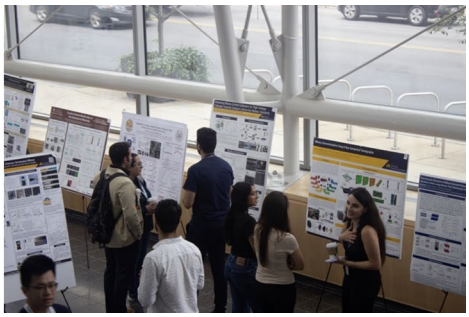

Fig. 5 Posters were discussed during every break and especially during the receptions on the first 2 days of the conference

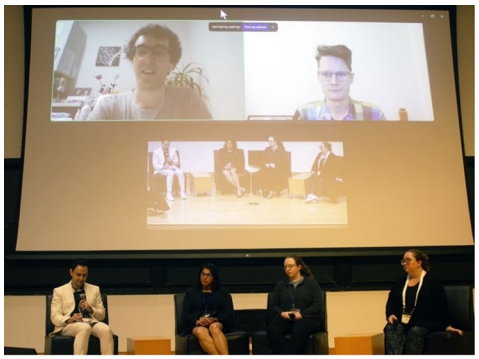

Fig. 6 The "Where and How to Publish MXene Research" panel represented a very broad range of editors and publishers, including scientist editors, professional editors, and journal publishers. Two of three national Agilent awards went to MXene researchers at Drexel this year

4 Light-emitting diodes and solar cells

- Transparent electron transport layers with tunable work function
- Flexible and stretchable (unlike ITO)
- MXenes can stabilize halide perovskites

5 Photonics

- The full palette of complementing (plasmonic) colors in reflection and transmission
- Electrochromic (> 100 nm/V)
- Electrochemically and chemically tunable colors
- Structural colors can be designed

6 Plasmonics and optoelectronics

- Close to 100% light-to-heat conversion at the peak wavelength
- Absorption peaks from UV to IR, depending on the composition
- MXenes absorbing in near-IR (Ti_3C_2) and IR (Nb_4C_3, Nb_2C) can be used in photothermal therapy of cancer or photothermal water desalination

7 Shielding

- Efficient shielding material in IR, THz, and microwave ranges
- Thin and flexible shielding or stealth
- More efficient than lead for X-ray shielding
- Microwave reflection (Ti_3C_2 and Ti_3CN) or absorption (Nb_2C), depending on the composition

8 Thermal management

- Ti_3C_2 has a thermal emissivity of polished metal with two orders of magnitude lower thermal conductivity—the best thermal protection, even at the thickness of 100–1000 times thinner than a human hair
- Films/coatings (200 nm coating drops the temperature by ~ 80 K)
- Excellent infrared (IR) stealth

9 Implantable and epidermal electrodes/electronics

- Higher conductivity of Ti_3C_2 compared to graphene-based films
- Lower impedance with tissue and skin than gold or platinum
- Excellent biocompatibility and no cytotoxicity for MXenes based on Ti, Nb, Ta, Mo, and other elements

10 Catalysis and electrocatalysis

- Catalytically active metals on the surface
- The entire basal plane is active (e.g., HER on Mo_2C)
- Single catalyst atoms can be incorporated into vacancies on M site

11 Adsorption

- Highly polar and charged surfaces and controlled interlayer-spacing allow the adsorption of molecules like urea that cannot be removed by carbon
- Adsorption affects the conductivity and enables gas sensing

There are still numerous fundamental and practical questions to be addressed, including but not limited to:

- Synthesis of hundreds of new stoichiometric 2D structures that have not yet been experimentally demonstrated, including lanthanide MXenes
- Better control of surface functionalization
- Understanding of the impact of surface chemistry (T_x) on properties
- Control of properties through surface chemistry
- Defects characterization and their impact on properties
- Defects engineering
- MXene interfaces (junctions in electronics, interfaces and interphases in composites)
- Mapping of variation of properties as a function of composition
- Sustainable large-scale synthesis of new MXenes
- Rational design of MXene hybrids, hydrogels, composites, heterojunctions, etc.
- Confirming theoretical predictions of properties, such as 2D magnetism

MXenes are also important building blocks for designing assembled multifunctional materials. They can be combined with other 2D materials, such as graphene derivatives, dichalcogenides, metal oxides, and polymers, to achieve multifunctionality and combinations of properties that are unavailable in any single material and are often mutually exclusive [4]. For example, they can combine metallic and ionic conductivity with extreme strength [5]. We encourage materials researchers and everyone looking for materials solutions to consider MXenes—they can provide answers to many problems, from fast battery charging to efficient water desalination, to making epidermal electronics widely used for health monitoring and medical diagnostics by every person, to providing submicrometer thin efficient insulation for our homes on Earth and, eventually, extraterrestrial habitats [6].

In the closing session, we presented 19 poster awards, which were generously supported by journals from leading publishers, including those from Springer Nature, Royal Society of Chemistry, MDPI, and Elsevier. Following this ceremony, Agilent formally presented Profs. Yury Gogotsi and Michel Barsoum with their Solutions Innovation Research Awards (Fig. 6, right). Drexel was extremely honored to receive two of the three national instrumentation awards (inductively coupled plasma (ICP) units with a mass spectrometer and a chromatograph) given in 2024.

An appreciated 23 sponsors supported the conference this year, ranging widely from large unrestricted funding to poster awards. We were honored to be endorsed by the Materials Research Society (MRS) and carry the support of The Electrochemical Society's (ECS) name throughout, as well. Many sponsors joined us in person and were a welcomed addition to our lobby area, co-mingling with attendees and participants in breaks and perusing the many posters that filled the space. Additionally, we were grateful to receive a grant from the US National Science Foundation (NSF grant 2416797) to support students from US universities in attending the conference, which covered registration for the course and conference, as well as accommodations for 43 students.

The 3rd International Conference at Drexel University, MXenes: Changing the World, was an ultimate success, with participation growing from the prior event held in 2022. Keeping up the momentum, planning for the next meeting in 2026 will begin soon.

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