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Editorial

MXenes – The fastest growing materials family in the two-dimensional world

The structural and compositional variety combined with tunable surface characteristics have rendered MXenes as one of the most versatile 2D material families with numerous rapidly expanding application domains. MXenes are typically synthesized by selective etching of layered carbide and nitride precursors, such as MAX phases, which have the general formula $M_{n+1}AX_n$ (n = 1–4), where M is an early transition metal, A is an element of group 13 to 15 of the periodic table, and X is carbon and/or nitrogen. Consequently, MXenes commonly have four structures: M_2XT_x, $M_3X_2T_x$, $M_4X_3T_x$, and $M_5X_4T_x$, where T_x stands for surface terminations, such as —O, —OH, —Cl or —F [1–3]. They can also be sorted as mono-MMXenes, double-M (M′ and M″) MXenes, and double-X (C and N-carbonitrides) MXenes. Double-metal MXenes have been reported in two different forms, depending on the distribution of M′ and M″ metals: 1) solid solution MXenes where the M-sites are randomly occupied by two kinds of metal atoms, 2) ordered MXenes where the M′ and M″ elements are separated into different layers ($M_3X_2T_x$, $M_4X_3T_x$ structures) [1,4]. 2D $M_{1.33}C$ sheets with ordered metal divacancies have also been synthesized [5]. Surface-terminations allow further control of properties, beyond the base structure and composition. Therefore, the MXene family is a promising platform for a multitude of applications [6–8]. More than 30 stoichiometric carbide and nitride MXenes and numerous solid solutions have already been reported and many more will certainly emerge soon. MXene-based research is growing quickly worldwide, with publications originating from about 70 countries, but China leading the world in the number of publications, according to Web of Science. So, it is natural that the first two International Conferences on MXenes were hosted by China. Following the 1st Conference on MXenes, which was held at Jilin University in Changchun, China, the 2nd International Conference on MXenes organized by Beijing University of Chemical Technology in May 2019 attracted more than 450 participants, more than double the attendees of the first conference, indicating the quickly growing interest in this family of materials. The 2nd International Conference on MXenes attracted scientists, researchers, and academics from different scientific disciplines. The conference covered the rapidly developing domains of MXenes, which have now expanded from energy storage to the frontlines of biomedical science, catalysis, sensors, environmental remediation, optics and separation science.

The purpose of this special issue of *Chinese Chemical Letters* is to celebrate this conference and share with the readers the latest cutting-edge research in the field of MXenes. The selected articles include 7 reviews and 16 original research papers, which cover the frontlines of MXene research from synthesis to characterization, properties of MXenes and their applications in supercapacitors, batteries, electro and photo-catalysis, sensors, medicine, electromagnetic interference shielding, and other fields.

Several articles describe synthesis and characterization of MXenes and MXene-derived materials. N. Chen *et al.* elaborated on the synthesis of high-quality Ti_3CNT_x MXene from high-yield Ti_3AlCN ceramics using the Al segregation control (https://doi.org/10.1016/j.cclet.2019.10.004). J. Xu *et al.* communicated a simple way to achieve high yield of few-layer $Ti_3C_2T_x$ flakes with enhanced pseudocapacitor performance by decreasing the precursor particle size (https://doi.org/10.1016/j.cclet.2020.02.050). C. Wang *et al.* reviewed the recent advancements achieved in the preparation and synchrotron radiation X-ray absorption spectroscopic characterization of cation-intercalated MXenes (https://doi.org/10.1016/j.cclet.2019.08.045). The intercalation of foreign substances between MXene layers produces intercalated MXene-based layered composites (IMLCs) and has been effective for controlling the layer-stacking issue. In this context, S. Wu *et al.* summarized the most recent advancements in the IMLCs development and their widening applications in various domains including energy storage, catalysis, sensors, and biomedicine (https://doi.org/10.1016/j.cclet.2020.02.046). S. Zhao *et al.* reviewed the progress in MXene-derived hybrid nanomaterials fabricated by the partial or complete oxidation of MXenes for advanced energy conversion and storage applications (https://doi.org/10.1016/j.cclet.2019.11.045).

In the area of energy storage, H. He, *et al.* reported the application of V_2CT_x nanosheets with accordion-like morphology as electrodes for supercapacitors in safe and widely available seawater electrolyte (https://doi.org/10.1016/j.cclet.2019.08.025). C. Li *et al.* proposed a simple method involving combustion synthesis and acid treatment to prepare accordion-like $Ti_3C_2T_x$ with open structure and high crystallinity, which was employed as an anode material in lithium-ion capacitors (https://doi.org/10.1016/j.cclet.2019.09.056). To address the restacking of MXene nanosheets, which limits their capacitance, Y. Yang *et al.* synthesized porous $Ti_3C_2T_x$ by introducing ice as a spacer using a facile freeze-drying method (https://doi.org/10.1016/j.cclet.2020.02.027). Y. Fang *et al.* constructed a flexible cross-linked porous $Ti_3C_2T_x$-reduced graphene oxide film (https://doi.org/

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10.1016/j.cclet.2019.08.043) with enhanced capacitive performance. Concerning battery electrodes, the MXene-based hybrid composites received substantial attention, where MXenes functioned as substrates for active materials due to their metallic conductivity and 2D morphology. C. Wei *et al.* described scalable construction of SiO/wrinkled $Ti_3C_2T_x$ MXene composite by a simple electrostatic self-assembly strategy and its use as anode for high-energy lithium-ion batteries. Significant improvement of rate capability and cyclability was achieved thanks to the synergistic mishmash of SiO and highly conductive wrinkled $Ti_3C_2T_x$ (https://doi.org/10.1016/j.cclet.2019.12.033). C. Wen *et al.* used a simple hydrothermal method and high-temperature calcination to synthesize nanostructured $Ni/Ti_3C_2T_x$ hybrid, which had an ultrahigh specific capacity when used as cathode of a lithium-oxygen battery (https://doi.org/10.1016/j.cclet.2019.09.028). L. Qin *et al.* described a simple *in-situ* approach to convert multi-layered Nb_2CT_x into hierarchical Nb_2CT_x/Nb_2O_5 composite using a hydrothermal method. The produced electrode exhibited an excellent rate performance and stable long-term cycling (https://doi.org/10.1016/j.cclet.2020.03.006).

For the application of MXenes in electrocatalysis, C. Cui, *et al.* discussed the use of spontaneously immobilized Pt over porous MXene/MAX hybrid for hydrogen evolution reaction (HER) catalyst application (https://doi.org/10.1016/j.cclet.2019.08.026). J. Yin *et al.* discussed a simple approach to utilize hierarchical Pd nanoparticles loaded MXene/polymer nanocomposites for the electrocatalytic detoxification of 4-nitrophenol and 2-nitrophenol (https://doi.org/10.1016/j.cclet.2019.08.047). The use of MXene as co-catalyst and hybrid catalyst for electrocatalytic reduction of N_2 (NRR-reaction) was covered by J. Sun and coworkers. The review highlighted the latest strategies for efficient NRR reaction, along with the shortcomings and future challenges perceived by MXenes in the electrocatalytic NRR (https://doi.org/10.1016/j.cclet.2020.01.035). The improvement on the electrocatalytic CO reduction and oxygen evolution reaction (OER) by the efficient use of MXene as either a direct or an in-direct catalyst was collectively presented by Y. Zhang *et al.*, from the standpoints of both experimental and theoretical investigations (https://doi.org/10.1016/j.cclet.2019.12.010).

The use of MXenes in environmental remediation has been represented by studies of catalytic detoxification and clean energy production. Here, X. Xie *et al.* demonstrated the use of $Pd/Ti_3C_2T_x$/graphene hydrogels in catalytic hydrogenation of nitroaromatic compounds (https://doi.org/10.1016/j.cclet.2019.10.012). T. Xu and coworkers proposed a ternary $BiOBr/TiO_2/Ti_3C_2T_x$ system for the photocatalytic degradation of rhodamine B (RhB) dye (https://doi.org/10.1016/j.cclet.2019.11.038).

To widen the range of MXene applications, J. Hu *et al.* demonstrated the use of $Ti_3C_2T_x$ as an additive to enhance the mechanical properties of aluminum (https://doi.org/10.1016/j.cclet.2019.09.004). X. Fan proposed $Ti_3C_2T_x$-bonded carbon black films with a porous structure as a promising MXene-based EMI shielding film with lightweight and good flexibility (https://doi.org/10.1016/j.cclet.2020.01.030). X. Wang and coworkers discussed the use of MXene as a substrate in the electrocatalytic sensor. The research showed the electrocatalytic capability of $Ti_3C_2T_x$/PEDOT:PSS hybrid materials to sense methanol vapors with high sensitivity (https://doi.org/10.1016/j.cclet.2019.11.031). In regard to the electrochemical sensors, the mini-review from R. A. Soomro *et al.* discussed the analytical superiority of MXene-based sensors and projected MXenes' future use in a variety of photoelectrochemical and biomedical devices (https://doi.org/10.1016/j.cclet.2019.12.005). The recent progress in the biomedical and theranostic applications of MXenes was discussed by Y. Wang *et al.*, and the role of intrinsic chemistry, surface chemistry and functionalization of MXenes for applications in nanomedicine has been emphasized (https://doi.org/10.1016/j.cclet.2019.11.016).

This special issue features the latest articles which focus on synthesis and diverse applications of MXenes. The large collection of articles presented in this special issue expresses well the vibrancy of the field and gives an overview of recent progress in a wide range of applications, such as supercapacitors, batteries, electro- and photo-catalysis, sensors, medicine and electromagnetic interference shielding. We hope that the comprehensive reviews and interesting cutting-edge science presented in this special issue will improve the understanding of this fascinating family of materials and expand horizons of utilization of MXenes.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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