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Two-dimensional transition metal dichalcogenide (TMD) nanosheets

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This special issue is about two-dimensional transition metal dichalcogenides (2D TMDs), a family of materials consisting of over 40 compounds with the generalized formula of MX_2, where M is a transition metal typically from groups 4–7, and X is a chalcogen such as S, Se or Te. Bulk TMDs have been widely studied over several decades because it is possible to formulate compounds with disparate electronic structures. In the bulk form, MX_2 compounds are layered materials (or van der Waals solids) in which there is strong intralayer bonding and weak interlayer bonding. Each individual layer of the TMDs consists of three atomic layers in which the transition metal is sandwiched by two chalcogens. Furthermore, the chalcogen atoms are saturated and therefore are not highly reactive. These features allow for the attainment of individual layers of the TMDs by several exfoliation or vapor deposition methods. The isolation of monolayers of TMDs leads to the dramatic changes in their properties, primarily due to the confinement of charge carriers in two dimensions (*x*- and *y*-directions) due to the absence of interactions in the *z*-direction. Thus, single-layered nanosheets are two-dimensional materials that possess dramatically different

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Manish Chhowalla

Manish Chhowalla is a Professor and Associate Chair of the Materials Science and Engineering Department at Rutgers University. He is also the Director of Nanotechnology for Clean Energy NSF IGERT Program and the Donald H. Jacobs Chair in Applied Physics (2009–2011). From June 2009–July 2010, he was a Professor in the Department of Materials at Imperial College London. Before Rutgers, he was a Royal Academy of Engineering Postdoctoral Research Fellow at the University of Cambridge after completing his PhD in Electrical Engineering there. Prior to his PhD, he worked for Multi-Arc Inc. (now Ion Bond) where he developed one of the first applications of "amorphous diamond" thin films. His technological interests are in the synthesis and characterization of novel low dimensional materials and their incorporation into devices for electrical, optical, thermal and mechanical applications.

Zhongfan Liu

Zhongfan Liu received his PhD from the University of Tokyo in 1990 and did his postdoc work at Institute for Molecular Science (IMS) in Japan from 1991 to 1993. He became an Associate Professor and then Full Professor at the Department of Chemistry of Peking University in 1993, and Changjiang Chair Professor in 1999. He was elected as the member of Chinese Academy of Sciences (CAS) in 2011 and the outstanding scientist of Ten-thousand Talent Program in 2013. His research interest focuses on low-dimensional carbon materials and novel 2D atomic crystals targeting electronic and energy conversion devices together with the exploration of fundamental phenomena in nanoscale systems.

fundamental properties compared to their bulk counterparts, making them potentially interesting for wide-ranging applications such as catalysis, electronics and photonics. This has generated a tremendous amount of interest in these promising materials.

Several key challenges must be addressed if 2D TMDs are to realize their full scientific and technological potential. Fundamental experimental and theoretical studies elucidating their electronic structure and vibrational properties can continuously provide new insight into the novel properties of 2D TMDs. Synthesis of high-quality and uniform TMDs over large areas continues to be an active research area. Fabrication methods tailored to different applications of TMDs are being studied. For example, chemical vapor deposition is being investigated for making large, highly uniform and electronic grade TMDs for fundamental condensed matter studies and electronics, while chemical exfoliation techniques are developed for large-scale production of nanosheets for catalysis and electrochemical storage applications. Efforts to tune the properties of TMD nanosheets by phase engineering, integration with other advanced materials to form novel composites, and functionalization during their preparation or post-synthesis are also ongoing. Finally, there is a substantial amount of effort being devoted to realize novel proof-of-concept devices for energy storage, electronics, photonics, catalysis and biomedical applications. The knowledge developed from the flurry of activity in TMDs and graphene has also inspired research into other atomically thin materials such as phosphorene, which holds promise for electronics and photonics. The following reviews are published in this themed issue.

Chaoliang Tan and Hua Zhang (DOI: 10.1039/C4CS00182F) report on recent advancements in large-scale based approaches to the synthesis of 2D TMD nanosheets and their integration with other advanced materials to form composites with functional properties. They describe 2D TMD-based composites with noble metals, metal chalcogenides, metal oxides, metal organic frameworks, organic molecules, and polymers to realize functional materials for batteries, electro- and photo-catalysis, electronics, sensors, and biomedicine.

Yi Xie and coworkers (DOI: 10.1039/C4CS00236A) review the role of the atomic and electronic structures of 2D materials for catalysis. They review works describing the characterization of defects and disorder in 2D materials using advanced analytical techniques. In addition, they also provide an overview of the literature related to various catalytic processes, including CO_2 reduction using 2D materials. Finally, they present two major challenges for catalysis with 2D materials.

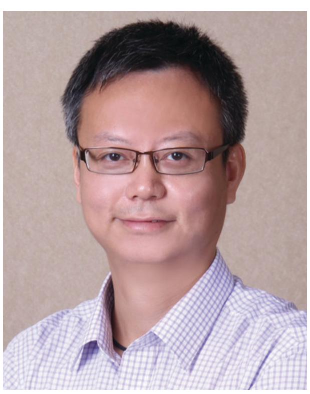
Yi Cui and coworkers (DOI: 10.1039/C4CS00287C) report on the versatility of 2D TMDs by describing physical and chemical tuning of their properties. Specifically, they review methods such as intercalation, alloying, confinement through decreasing dimensions, high pressure, integration with other materials to build heterostructures, and gating in order to tailor the properties of 2D materials in a controlled manner. Moreover, they go on to detail how these properties can be exploited in a variety of applications.

Damien Voiry, Aditya Mohite and Manish Chhowalla (DOI: 10.1039/C5CS00151J) review the different crystallographic phases that can occur in 2D TMDs. They report on how these phases are stabilized and how they can be controllably induced to realize new functionalities. They describe how phase engineering in 2D TMDs provides another parameter to control their properties.

Hua Zhang and coworkers (DOI: 10.1039/C4CS00399C) highlight the technologically relevant field of resistive memory devices based on 2D materials. In particular, they review recent works on graphene oxide/reduced graphene oxide and MoS_2 based resistive memories and their unique features that allow the realization of novel flexible and transparent resistive memory devices. Moreover, they also provide an overview on how facile integration of active 2D layers can lead to the enhancement of device performance.

Lianzhou Wang and coworkers (DOI: 10.1039/C4CS00300D) highlight recent advances in the implementation of 2D materials in biomedical applications. They highlight key properties of 2D materials that allow them to be utilized for biomedical applications as therapeutic, diagnostic, or theranostic agents in oncology. They also highlight key remaining challenges that must be overcome if 2D materials are to be implemented in biomedical applications.

Zhongfan Liu and coworkers (DOI: 10.1039/C4CS00258J) review recent progress on chemical vapor deposition of 2D TMDs. In particular, they highlight the deposition of 2D TMDs and their alloys using methods such as sulphurisation/decomposition of pre-deposited metal-based precursors, or the one-step reaction and deposition of gaseous metal and chalcogen feedstocks. They also elucidate how growth can vary between the commonly used SiO_2 substrates and single crystals such as sapphire or strontium titanate. They additionally summarize the affect of growth parameters such as temperature, gas flow rate and substrate to source distance.



Hua Zhang

Hua Zhang obtained his BS and MS degrees at Nanjing University in 1992 and 1995, respectively, and completed his PhD with Prof. Zhongfan Liu at Peking University in 1998. As a Postdoctoral Fellow, he joined Prof. Frans C. De Schryver's group at Katholieke Universiteit Leuven (Belgium) in 1999, and then moved to Prof. Chad A. Mirkin's group at Northwestern University in 2001. After he worked at NanoInk Inc. (USA) and Institute of Bioengineering and Nanotechnology (Singapore), he joined Nanyang Technological University in July 2006. His current research interests focus on the synthesis of two-dimensional nanomaterials and carbon materials (graphene and carbon nanotubes), and their applications in nano- and bio-sensors, clean energy, water remediation, etc.

Lain-Jong Li and coworkers (DOI: 10.1039/C4CS00256C) report on the latest developments in the synthesis of 2D TMDs using chemical vapor deposition. They highlight key progress that has been made thus far on alloying, substitutional doping, and integration of different TMDs. They also address remaining challenges that must be overcome in realizing high-quality and large-area 2D TMDs.

Hualing Zeng and Xiaodong Cui (DOI: 10.1039/C4CS00265B) provide a detailed tutorial review of the rapid progress being made in the fundamental understanding of exploiting inversion symmetry breaking in monolayer TMDs for accessing valley degrees of freedom. They highlight recent progress in using optical techniques for probing valley states, excitonic effects, and interplay between spin states and valleys.

Ping-Han Tan and co-workers (DOI: 10.1039/C4CS00282B) describe how Raman spectroscopy can be used to characterize the vibrational properties of a variety of TMDs. They report on how Raman spectroscopy provides fundamental insights into material properties such as interlayer coupling and spin–orbit splitting as a function of number of layers, affect of substrate, and external perturbations. Their work provides a foundation for understanding the basic properties of 2D materials using a readily accessible technique.

Wang Yao and coworkers (DOI: 10.1039/C4CS00301B) review theoretical work on 2D TMDs. They review the rich condensed matter effects that arise from the electronic structure of 2D materials. In particular, they highlight the origin of the direct band gap, substantial spin orbit coupling, and valley degrees of freedom. They explain the different multiscale models presented in the literature and theoretically explain experimental and calculation results.

Agnieszcka Kuc and Thomas Heine (DOI: 10.1039/C4CS00276H) report on theoretical work related to the elucidation of electronic properties. They highlight how the large spin–orbit coupling and giant spin–orbit splitting in odd numbers of layers make them well suited for spin-based devices. They describe how the materials behave in the presence of electric and magnetic fields. In particular, they describe that application of high magnetic fields can lead to Hall effects and even quantum spin Hall effects in some 2D TMD materials. They also describe valley-based effects using polarized light.

Peide D. Ye and coworkers (DOI: 10.1039/C4CS00257A) highlight recent and rapid developments on a related non-TMD 2D material called phosphorene or black phosphorus. They trace the history of the research on this material back to 100 years ago and provide insight into its unique properties. They describe how it can be exfoliated into monolayers and its novel electronic and optical properties.

This themed issue attempts to concisely provide an overview of the rapidly developing field of 2D TMD materials. We believe that the compilation of the reviews in a single issue will benefit experts and non-experts in the field. Finally, we would like to thank the authors for their contributions to this themed issue and the RSC editorial staff members for their strong support.