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Editorial

Expanding the Horizon of Two-Dimensional Layered Materials

Mingsheng Xu*

Department of Polymer Science and Engineering, State Key Laboratory of Silicon Materials, Zhejiang University, China

***Corresponding author:** Mingsheng Xu, State Key Laboratory of Silicon Materials, Zhejiang University, Hangzhou 310027, China, Tel: 86-571-87951308; Fax: 86-571-87951592; Email: msxu@zju.edu.cn

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The identification of graphene, a single layer carbon atom arranged in a two-dimensional (2D) hexagonal crystal lattice, among mechanically exfoliated graphite sheets and the subsequent discovery of its unique electronic properties [1] in 2004 have led to an extraordinary amount of interest from both academia and industry. While the absence of a band-gap in pristine graphene does not support its use as a digital electronics, its ultrahigh carrier mobility makes it an excellent candidate for fast optoelectronics, specifically radio-frequency transistors and wavelength-tunable photodetectors. The silicon-integrated graphene photodetectors that operate at mid-infrared frequencies have potential applications for medical examinations. Once the challenge of scalable production of high quality graphene is solved, graphene due to its flexibility, high carrier mobility and transparency would soon be used as transparent conductive electrodes in touch screens, display devices and so on, possibly replacing rare metal indium tin oxide (ITO) electrode.

The accumulated knowledge on graphene is now being applied to the exploiting of graphene-like 2D materials (2DMats) [2]. These 2DMats include the transition metal dichalcogenides (TMDs), transition metal oxides, insulating hexagonal boron nitride (*h*-BN), topological insulators such as bismuth telluride (Bi_2Te_3) and bismuth selenide (Bi_2Se_3), silicene and others 2D compounds.

TMDs consist of hexagonal layers of metal atoms (M) sandwiched between two layers of chalcogen atoms (X) with MX_2 stoichiometry. Depending on the combination of chalcogen (typically S, Se, or Te) and transition metal (typically Mo, W, Nb, Re, Ni, or V), TMDs occur in more than 40 varieties, and these show a wide range of important properties such as half-metallic magnetism, superconductivity, or charge density wave. TMDs can be semiconducting (e.g., M = Mo, W) or metallic (e.g., M = Nb, Re). For the semiconducting TMDs a transition from an indirect band gap to a direct band gap happens as the thickness of TMDs is decreased to a monolayer. This generates the appearance of strong light-emitting in the monolayer TMDs. Electronic and spintronic devices exploit the electric charge and the spin of electrons in semiconductors, respectively. Successful manipulation of spins could impact the exotic field of quantum computing. Unlike graphene, the monolayers of the semiconducting TMDs lack inversion symmetry. This results in strong spin-orbit splitting and open possibility for spintronic devices. Another property of electrons, namely, their valley degree of freedom, in a semiconductor where they occupy multiple conduction band minima (valleys) with equal energies but at different positions in momentum space could be exploited for potential applications of valleytronics or valley-based electronic applications through the coupling between spin and valleys in the TMDs. TMDs are now the hottest topic under investigation of the 2DMats beyond graphene.

Silicene is the silicon-based counterpart of graphene, but the atoms are arranged in a bucked honeycomb structure rather than a planar structure like graphene. According to theoretical studies, this buckled geometry makes silicene strikingly different from graphene. The buckling creates new possibilities for manipulating the dispersion of electrons in silicene and opening up an electrically controlled sublattice-asymmetry band gap. Although there are reports on ordered silicon phases on the Ag (111) surface and on other surfaces, no one has synthesized free-standing silicene so far. Because modern microelectronics are primarily based on the exploitation of the properties of Si and an enormous amount of knowledge is available to assist in the design and fabrication of Si-based devices, silicene might provide a fruitful new avenue of research in Si-based nanoelectronics.

Due to their distinct chemical and crystalline structures, these graphene-like 2DMats exhibit strikingly different properties from graphene and from each others. By combining two or more types of different 2DMats into heterostructures or other artificial structures, new phenomena may appear. For example, fractional quantum Hall effect has been observed in graphene coupled to *h*-BN [3]. Derivatives of 2DMats further expand the field of 2D technologies. For instance, graphene-based materials include graphene, graphene oxides, reduced graphene oxides and functionalized graphene with polymers or other nanostructures such as nanoparticles and nanowires. These hybrid materials have a wide range of potential applications including in *supercapacitors*, *lithium*-ion *batteries, catalysts, mechanical reinforcement, gas barrier, electromagnetic* interference *shielding and thermal management.*

In addition to the strong research interest in the use of 2DMats for electronics, optics, structural materials, catalyst, energy generation and energy storage *applications, there are also efforts on exploring their applications in biomedicine [4] including biosensors, bioimaging, drug/DNA delivery and photothermal therapy*. For example, graphene now is attracting great interest in ultrafast and inexpensive DNA sequencing [5,6]. The using of graphene may achieve single-base resolution in electronic DNA sequencing due to its thickness comparable to the base-separation in a DNA strand as well as its

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ultra-sensitivity to conductance change as its interaction with the individual DNA bases. We believe the exploration of 2DMats beyond graphene for biomedical applications will be rapidly increased soon.

The Europe's graphene flagship project, [7] aiming to fund academic research on graphene and other 2D layered materials and ignite possible technological breakthroughs towards transferring this knowledge to industry, has trigged a wave of investments around the world not only for graphene technology but also for exploiting new layered 2DMats and their own interesting properties. The field of 2DMats beyond graphene is likely to grow at a rapid pace in the near future. More works are needed to done to better understand performance limits of the 2DMats and to develop new technologies to incorporate a 2DMat into industrial products. The whole family of 2DMats may open up new possibility for novel applications that could change many aspects of modern life.

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