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EDITORIAL

An Update from Flatland

For more than a decade after the discovery of the unique physical properties of graphene, two-dimensional (2D) materials have been attracting the attention of the nanoscale research community and beyond. This continuing interest is fueled by frequent reports of the discovery of new 2D materials, with silicene, germanene, and phosphorene already being intensely researched.[1] More than 20 carbides and nitrides of transition metals have also been added to the materials flatland in the past 5 years,[2] and 2D GaN grown under the cover of graphene has recently been reported.[3] However, 2D boron (borophene) has attracted the most attention this year (Figure 1), where the experimental synthesis[4,5] followed theoretical predictions.[6] This case has thus demonstrated the ability of modeling to guide the synthesis of new materials, which is one of the primary goals of the Materials Genome Initiative.[7] Borophene has been shown experimentally and theoretically to possess metallic properties,[8] potentially offering the thinnest metal sheets for applications such as interconnects, electromagnetic shielding, and transparent conductors, where 2D metals can outperform all other materials.[9] Realization of these applications in addition to fundamental studies of other charge transport phenomena such as superconductivity[10] will require the development of borophene transfer and processing methods that minimize chemical and structural degradation.

Two-dimensional materials offer additional opportunities for self-assembly and integration compared to zero-dimensional or one-dimensional structures, such as nanocrystals or nanotubes. Specifically, 2D heterostructures are attracting increasing attention because they enable researchers to combine the properties of individual 2D sheets and create layered assemblies with unique hybrid properties, including property gradients.[12] The race is now on to find practical applications afforded by these 2D systems.

Recent conferences on 2D materials have offered an excellent overview of ongoing efforts in the field and show that the 2D world stretches far beyond graphene. Even at Graphene 2016 in Genoa, Italy, about half of the talks were dedicated to materials other than graphene. In recent years, there have been growing numbers of 2D materials "beyond graphene" conferences, reflecting the widespread interest in this field. One such recent event was the International Conference on Electronic Materials (IUMRS-ICEM 2016) held in Singapore in early July, 2016. At a symposium on 2D materials and devices beyond graphene, many speakers spoke about their recent work on 2D materials including monolayer transition metal dichalcogenides (TMDs), phosphorene, and borophene, and their potential applications in electronics or optoelectronics.

Mark Hersam (Northwestern University) presented his collaborative work with Nathan Guisinger at Argonne National Laboratory on the synthesis of borophenes,[4] and Lan Chen (Chinese Academy of Sciences) showed that two types of 2D boron sheets can be grown epitaxially on Ag(111) substrates.[5] Wei Chen (National University of Singapore) talked about interface engineering of 2D black phosphorus and its photoreactivity to oxygen and water.[13] Lain-Jong Li (KAUST) presented impressive electron microscopy images on chemical vapor deposition (CVD) grown vertical and lateral heterostructures,[14] which was the theme of several other speakers.[15,16] Electronic screening effects between organic monolayers and 2D TMDs were also discussed.[11]

> The long-term sustainability of this field relies on the identification of practical applications where 2D materials possess competitive advantages.

Defects and grain boundaries play important roles in determining the properties of 2D materials, and several recent experimental imaging and computational results were shared by Jamie Warner (University of Oxford),[17] Arkady Krasheninnikov (Helmholtz Zentrum Dresden-Rossendorf),[18] Andrew Wee (National University of Singapore),[19] Shiwei Wu (Fudan University),[20] and other speakers. Xiaodong Cui (University of Hong Kong) explained the concept of spin-valley coupling in 2D TMDs,[21] and other speakers talked about the electronic structure, energy-level alignment, photoluminescence enhancement, and interlayer energy transfer in 2D heterostructures.[22,23] Other topics covered included mixed-dimensional heterostructures (Hersam),[24] integration of 2D TMDs with high-*k* dielectrics (Shijie Wang, Institute of Materials Research and Engineering, ASTAR), graphene plasmonics (Tony Low, University of Minnesota), and terahertz conductivity of 2D materials (Elbert Chia, Nanyang Technological University). Gianluca Fiori (Universita di Pisa) gave an overview on 2D materials for electronic applications.

With the continuing advent of new 2D materials and the nearly limitless possibilities for 2D heterostructures, it is evident that flatland remains rife with opportunities for fundamental research and discovery. Nevertheless, the long-term sustainability of this field relies on the identification of practical applications where 2D materials possess competitive advantages. While much of the early effort in this regard has focused on the utilization of 2D materials in common applications (*e.g.*, transistors, sensors, photovoltaics, and batteries),[25] it has historically been challenging to supplant incumbent materials in mature technologies. Consequently, it may prove to be more productive to focus on applications that exploit the unique properties in 2D materials that are not easily achievable in other materials systems. For instance, the atomically thin nature of 2D materials leads to incomplete electrostatic screening, which allows traditional two-terminal devices to be converted into gate-tunable three-terminal devices with unprecedented functionality. Emerging examples include gate-tunable diodes with antiambipolar transfer curves[26,27] and gate-tunable memristors as foundational elements of neuromorphic computing.[28] *ACS Nano* looks forward to continuing to report

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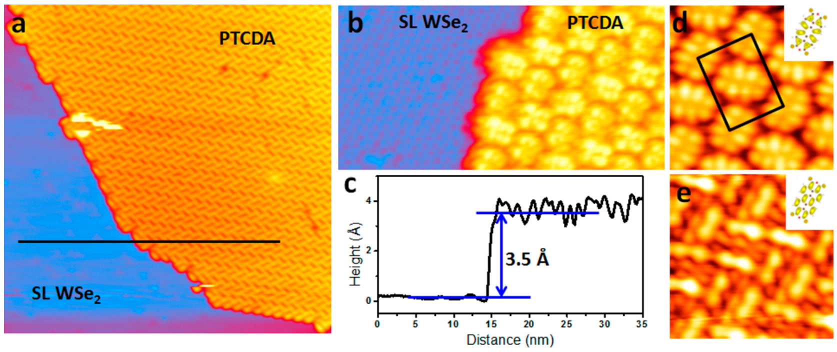

Figure 1. Submonolayer PTCDA self-assembled on SL WSe$_2$. (a) STM image of the PTCDA island on the WSe$_2$/graphite interface with a herringbone packing structure. (b) Atomically resolved STM image of the PTCDA island boundary. (c) Height profile corresponding to the dark line in panels and revealing the apparent height of the PTCDA layer to be 3.5 Å. (d,e) Bias-dependent STM image corresponds to the occupied and unoccupied states of PTCDA molecule, respectively. The corresponding calculated HOMO and LUMO orbitals are shown in each inset. Reprinted from ref 11. Copyright 2016 American Chemical Society.

the latest developments and to accelerate the advances in this rapidly evolving field by highlighting the challenges and opportunities in both the science and applications of 2D materials.

Announcements. At the end of August in Grenoble, France, at the European Conference on Surface Science (ECOSS), the three winners of the 2016 *ACS Nano* Lectureship Award received their plaques and gave intellectually stimulating talks (Figure 2).

We are sad for the loss of Nobel Prize winning Chemist and *ACS Nano* author, advisor, and supporter Dr. Ahmed H. Zewail of Caltech, who passed away on August 2, 2016.

Figure 2. *ACS Nano* Award Lecturers at the European Conference on Surface Science in Grenoble, France, earlier this month. Left to right: Prof. Christopher Murray of the University of Pennsylvania (Americas), Prof. Lifeng Chi of Soochow University (Asia/Pacific), and Prof. Andrea Ferrari of Cambridge University (Europe/Africa/Middle East). Photo credit: Paul S. Weiss.

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Notes

Views expressed in this editorial are those of the authors and not necessarily the views of the ACS.

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