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Editorial

Two-dimensional materials: new opportunities for electronics, photonics and optoelectronics

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The exciting progress in graphene research in the past 15 years [1,2] has further stimulated the exploration of other non-graphene two-dimensional (2D) materials [3], such as h-BN [4,5], transitional metal dichalcogenides (TMDs) [6,7], black phosphorene [8], etc. Research on these ultimately atomic thin 2D materials has grown exponentially owning to their fascinating properties and enormous potential in the fields of physics, chemistry, optics and photonics, material sciences, medicine and engineering. Despite that massive efforts and achievements have been made in the flatland world, the community is still constantly fueled by discoveries of new materials, properties and device functionality. By this Special Topic, it is therefore timely that *Science Bulletin* sheds a spotlight on this fast growing field and provides a timely perspective on the state of the art investigations.

The papers in this Special Topic presented the most recent progresses in 2D materials regarding to their new properties and promising applications. This Special Topic consists of one News & Views article, three original articles, and two review articles. In the short News & Views, He's group [9] reported the successful integration of high-performance, multifunctional devices in an asymmetric van der Waals heterostructures. Three research papers revealed the optical and electrical properties of several types of TMDs by theoretical calculation and experimental investigations. The two review articles summarized the research progress of 2D materials devices for synaptic electronics and neuromorphic systems.

Semiconductor heterostructures play a key role in the development of solid-state electronic and optoelectronic devices. Compared with homogenous components, heterostructures offer new functionality driven by charge and energy transfer mechanism. The versatile van der Waals integration of different isolated 2D crystals offers a great platform to probe new physics and device functionalities. In the News & Views by He's group from National Center for Nanoscience and Technology, China, He's group [9] introduced their recent progress on the integration of diode, photodetector, photovoltaic (PV) cell, transistor and non-volatile memory by designing an asymmetric heterostructures with graphene, h-BN, MoS_2 and $MoTe_2$. The switching of the multifunctional devices was operated under different bias conditions. Distinctive photocurrent behaviours and advantageous photodetection capabilities, including high photo on/off ratio ($\sim 4 \times 10^7$) and external quantum efficiency (~7.5%) were also demonstrated.

TMDs have emerged as an exciting class of 2D materials with rich physical properties and potential applications. Monolayer TMDs as the direct-gap semiconductor provide a new platform for nonlinear optical studies in the ultimate 2D limit. Gong et al. [10] theoretically investigated the two-photon transition and second-harmonic generation process in electron-hole continuum regime in monolayer 2D semiconductors. A two-photon selection rule reversal of circularly polarized light by the competition of two contribution from different bands was demonstrated. Furthermore, the valley-polarized current injection by the one- and two-photon quantum interference with the interaction was discussed in this paper.

Among the large family of compounds, the group-10 TMDs (e.g., $PtSe_2$, $PtTe_2$) have yet received enough attention compared with the semiconducting group-6 TMDs (e.g., MoS_2, $MoSe_2$) until the discovery of type-II Dirac fermions in their bulk crystals. However, the evolution of electronic structure of atomically thin $PtTe_2$ films still remains elusive. Zhou's group [11] from Tsinghua University has revealed that the $PtTe_2$ film evolves from a 2D metallic at 2 ML to a 3D Dirac semimetal at 4–6 ML thickness based on the angle-resolved photoemission spectroscopy (ARPES). The helical spin texture induced by the local Rashba effect in bulk $PtTe_2$ was reported in the meanwhile. Metallic $PtTe_2$ thin films with local Rashba effect provides new opportunities for the investigation of topological superconductivity.

To fully explore the potential of 2D materials in electronic and optoelectronic devices, a fundamental understanding of the charge transport mechanism is crucial. By using monolayer graphene as the barrier-free contact to MoS_2, Duan and his co-workers [12] showed that the field-modulated conductivity can be used to probe the electronic structure of the localized states with a high resolution up to 1 meV. A series of regularly distributed plateaus were observed in the gate-dependent transfer curves, and such plateaus can be attributed to the discrete localized states near the mobility edge based on the variable-range hopping theory. This method offers a general approach for directly

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probing the localized states and a direct evidence of the hopping transport origin in the MoS_2.

Among the versatile applications of 2D materials, the utilization of them in synaptic electronics and neuromorphic systems represent an exciting frontier. The versatility of 2D materials together with their extraordinary properties offers a wealth of possibilities for the unprecedented parallel, energy-efficient, fault-tolerant synaptic electronics and neuromorphic systems. A timely literature review on the recent advances based on 2D materials was articulated by Zhou's group from Fudan University [13]. A brief introduction of synaptic plasticity and learning behavior was given firstly, followed by a summary of the main 2D materials library and preparation process, ranging from the conductors, semimetals to semiconductors and insulators. Subsequently, synaptic devices and artificial neuromorphic network systems based on these 2D materials were discussed, including the electrostatic/electronic (ionic) neural synapses and neuromorphic network, electrochemical metallization/conductive bridge (ECM/CB) synapses and neuromorphic network, redox/valence change synapses and neuromorphic network, phase change (PC) synapses and neuromorphic network, thermochemical/joule heating synapses and neuromorphic network. At last, the opportunities and challenges faced by 2D-based synaptic devices and neuromorphic computing systems were summarized.

Apart from the TMDs, a new member of semiconducting 2D materials – black phosphorus (BP) – has attracted much attention since the first demonstration of few-layer BP field-effect transistor in 2014 [8]. Thanks to its high mobility, in-plane anisotropy and direct band gap, BP is considered to be a promising candidate for next-generation electronic and optoelectronic devices. Hence, a timely focused review on the BP electronics was presented by Liao's group [14]. The authors start with an introduction of fundamental properties of BP such as crystal structure, electronic structure and electrical properties, followed by the modulation and application of those properties. Then, the design for high-performance device was discussed, with a particular emphasis on interface engineering and device stability. Finally, the perspective on the future of BP electronics was offered, including synthesize high-quality wafer-scale crystalline, optimize interface quality, and enhance device stability.

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