EDITORIAL

Focus on 2D materials beyond graphene

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Focus on 2D materials beyond graphene

Inspired by the success of graphene, especially its intrinsic shortcoming of a zero band-gap, research on 2D layered semiconductors has triggered tremendous worldwide interest over the past few years. These materials exist in bulk form as stacks of strongly bonded layers with weak interlayer attractions, allowing their exfoliation into atomically thin layers. Unlike graphene, 2D layered semiconductors have suitable band-gaps varying around 1–2 eV. In addition, single-layers of 2D layered semiconductors are only three atoms thick, extremely flexible and transparent. Because of their distinct properties, these 2D materials promise applications in various fields, such as, electron devices [1], optoelectronics [2], catalysts [3], chemical and biological sensors [4], energy storage devices [5], and solar cells [6] etc.

With the rapid development of 2D layered semiconductors in recent years, this focus collection aims to highlight the remarkable contributions made by leading scientists in this important research area and the broad impact of 2D layered semiconductors. In this focus collection, there are a total of 19 articles, both original papers and review articles, ranging from the controllable growth of 2D materials and their fundamental properties, to their diverse applications in electron devices, optoelectronic devices, bio-sensors, and theoretical simulations.

The successful application of these 2D materials relies on the controllable growth of their size, thickness and crystallinity [7]. Transition-metal dichalcogenides (TMDs) are representative 2D semiconductors with tunable band-gaps and reasonably good mobility. Xie and his co-workers adopt MoO$_2$ as a precursor for growing MoS$_2$ using chemical vapor deposition (CVD). By optimizing the ratio between MoO$_2$ and sulfur, they are able to control the shape of 2D MoS$_2$ flakes and achieve centimeter scale MoS$_2$ [8]. Lu et al present a method to reduce the thickness of WTe$_2$ using a thermal annealing process at 600$^\circ$C to decrease the thickness of WTe$_2$. Furthermore, the authors also perform detailed investigations on the relationship between the initial thickness and thinning rate and surface roughness [9]. In addition to the thickness of 2D materials, Long et al reduce the size of WS$_2$, along the lateral direction, to quantum dots by the liquid exfoliation method. This WS$_2$ composite material shows excellent nonlinear optical properties in terms of a low onset threshold, low optical limiting threshold, and high two-photon absorption coefficient [10]. Zhang et al adopt a conventional mechanical exfoliation method to prepare TMD nanosheets on transparent substrates. By using optical microscopy, they are able to identify the thickness of TMDs through the observation of optical contrast. This approach is in good agreement with other methods of identification [11].

Graphene is the first 2D material to be discovered. Recent progress on growth and transfer methods have enabled more applications in electronic and energy devices. In this focus collection, Sun et al present a solution-assisted method to complete an ultrafast transfer and fabricate freestanding and smooth GO thin films. This GO thin film can be used as the counter electrode of dye-sensitive solar cells and humidity sensors [12]. Meng and co-workers demonstrate a Si-compatible graphene growth technique. They use Ir as the catalyst, which contains a carbon precursor and precipitant to the top Si surface [13]. Zhou et al work on the growth of a carbon nanotube on graphene substrate for interconnecting applications. The
high temperature growth process forms covalent bonding between the carbon nanotube and graphene, which minimizes the electrical contact resistance [14]. It is quite important to develop a catalyst-free and transfer-free method for practical applications of graphene. Ning et al present a comprehensive review on the updated works in this respect. They summarize four representative methods, including sacrificial metal assisted CVD, catalytic assisted CVD, pattern assisted direct deposition, and a catalytic metal-free method [15].

The unique structural, chemical, and mechanical properties of 2D materials enable various applications. For example, boron nitride is a highly impermeable and ultrathin nanosheet; even the smallest molecule cannot penetrate through it. Zhang et al utilize a boron nitride nanosheet as a passivation layer of Ni foil, exhibiting excellent electrochemical corrosion resistance [16]. Black phosphorus (BP) is a 2D semiconductor with unique physical properties, but its chemical instability hinders its wider application. Luo et al present a detailed study on the kinetics of BP under various well-controlled conditions, revealing the synergetic effect of water and oxygen on BP oxidation [17]. Wang et al perform molecule dynamics simulations of nanoindentation experiments to investigate the mechanical induced phase transition of MoS2. During indentation, the loading force decreases sharply and then increases again at a certain deflection, which is shown to be caused by the changing lattice structure of monolayer MoS2 and corresponds to a phase transformation [18].

2D semiconductors have the potential to scale down to the nanoscale and have a lower power consumption compared to conventional 3D semiconductors due to their ultrathin body, atomic scale smoothness, dangling bond-free surface, and sizable band-gap. Zhou et al investigate the effect of metal deposition on the work function of MoS2. The Schottky barrier at the metal–MoS2 interface can be tailored by both types and thicknesses of the deposited metal. This paves the way towards future high performance MoS2 device applications [19]. Zeng and co-workers study the stability and electronic properties of a GeS monolayer. In particular, the electric field and in-plane strain were used to tailor its electronic band-gap. Upon applying an electric field, the band-gap of the GeS monolayer is greatly reduced, and a semiconductor–metal transition happens under a certain level of external electric field [20]. Liu et al demonstrate the use of high-k ZrO2 as a gate dielectric of MoS2 transistors, which shows a high on/off ratio, low operating voltage, and excellent channel modulation capability for low-power devices [21]. Shu et al carry out a detailed investigation on the effect of water absorption on a MoS2 transistor, which can be used for humidity sensors [22]. The combination of 2D channel materials and neuromorphic computing configuration can further reduce the power consumption of basic data processing. Hu et al demonstrate a neuron transistor based on a MoS2 flake, which has summation and threshold functions similar to biological neurons and may act as a basic neuron unit in neuromorphic hardware [23].

The wide distribution of band-gaps of 2D materials enables the broad photoresponse region. Peng et al demonstrate the hybrid structure of a graphene nanodot array and gold nanoparticles for broadband infrared absorption enhancement [24]. Wu et al fabricate In2Se3 photodetectors in a ferroelectric field-effect transistor structure. High performance photodetectors have been achieved with a broad photoresponse spectrum (visible to 1550 nm) and quick response (200 μs). These studies present a crucial step for further practical applications of 2D semiconductors [25].

The large specific area of 2D materials enables them to possess excellent electrochemical properties, which can be used for energy storage and electrochemical sensors. In this focus collection, Meng et al successfully fabricate cobalt oxide (Co3O4) nanosheets directly grown on Ni foam through a simple hydrothermal method. The resulting self-standing electrochemical electrode presents a...
high performance for the non-enzymatic detection of glucose, including a short response time (< 10 s), ultra-sensitivity, excellent selectivity and a low detection limit. These results indicate that Co₃O₄ nanosheets wrapped onto Ni foam are a practical, low-cost and high performance electrochemical electrode for biosensing [26].

This present focus collection presents state-of-the-art studies on 2D materials research, including not only controllable growth and fundamental properties but also various applications. We hope that this focus collection provides important insight into a number of recent studies in related areas, and stimulates the development of these disciplines. Throughout the whole process of this focus collection, the editorial of the Institute of Physics (IOP) have provided us with very strong support and great cooperation. We also thank all of the authors for their contribution to this focus collection.

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