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Review

From two-dimensional materials to heterostructures

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ABSTRACT

Graphene, hexagonal boron nitride, molybdenum disulphide, and layered transition metal dichalcogenides (TMDCs) represent a class of two-dimensional (2D) atomic crystals with unique properties due to reduced dimensionality. Stacking these materials on top of each other in a controlled fashion can create heterostructures with tailored properties that offers another promising approach to design and fabricate novel electronic devices. In this report, we attempt to review this rapidly developing field of hybrid materials. We summarize the fabrication methods for different 2D materials, the layer-by-layer growth of various vertical heterostructures and their electronic properties. Particular interests are given to in-situ stack aforementioned 2D materials in controlled sequences, and the TMDCs heterostructures.

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1. Introduction

To meet the ever increasing demand for economical and high-performance devices, researchers have never ceased to search for new materials to incorporate them into the next generation devices. Recently, graphene-like two-dimensional (2D) materials have gained broad attention due to their unique properties that could have fundamental applications in novel devices [1–3]. The 2D layered material is now one of the most active fields in materials science, condensed matter physics and chemistry. The most common 2D material family members include graphene, hexagonal boron nitride (h-BN) and transition metal dichalcogenides (TMDCs).

Graphene [4–8], is so far the thinnest material in nature. Its abundant superior properties have been discovered progressively [9]. The development of fabrication methods and the ability to implant monolayer graphene into novel devices have initiated the pursuing of many other 2D materials through mechanical exfoliation, chemical isolation and vapor deposition [10–12]. Recent developments have demonstrated the possibility to create 2D atomically thin nanocrystals and these 2D atomic crystals exhibit unique properties complementing those of graphene [13,14]. Hexagonal boron nitride (h-BN) proves to be an ideal substrate for graphene-based devices due to its atomically smooth surface that is insulating and has small lattice mismatch. Both the fabrication techniques and the properties of individual materials have been studied extensively in recent years [15–19]. Moreover, profound implications in valleytronics, field effect transistors, catalysis, and energy storage have been found in TMDCs for their versatile physical and chemical properties [20–25]. Other 2D materials such as germanane [26], silicene [27], and Hafnium honeycombs [28] have been discovered. Additionally, the layered semiconductors (Bi_2Se_3, GaSe) and oxides (TiO_2, MoO_3) can also be classified into the 2D family [29].

Stacking the 2D materials on top of each other brings us a unique opportunity to expand the 2D material family to generate new hybrid materials. If we can fabricate them in a controlled fashion, this approach will pave a way towards creating materials with tailored properties. Indeed, several studies have shown that combining more than one thin layer materials together can generate interfaces with properties significantly different from that of a single component [30–33]. A bandgap of 53 meV at the Dirac point of graphene can be opened by placing monolayer graphene on top of h-BN due to the inequivalent carbon sites on BN [34]. Such strategy broadens practical applications of graphene in electronic devices. However, the weak adsorption and small built-in potential in graphene based optoelectronics always give rise to low extrinsic quantum efficiency (EQE, the ratio of the generated number of charge carriers to the number of incident photons) [35]. Vertical stacking transparent graphene layer with the protypical TMDC MoS_2 gives rise to high efficient photocurrent which benefit from both the parallel geometry of external field with respect to current direction and the weak electrostatic screening effect of graphene. Particularly, the TMDCs heterostructures represent ideal p-n diodes by vertically stacking p- and n-type TMDCs, such as WSe_2 and MoS_2. In contrast, creating the p–n diodes in single component TMDCs is difficult due to the selectively doping the particular areas into p- or n-type semiconductor, or complicated due to the controllable growth in-plane p–n junction [36]. Prominently, vertically stacked TMDCs heterostructures can form type II band