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PERSPECTIVE

Graphene and other two-dimensional materials

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Over the last few years, research on graphene [1–3] has progressed significantly, and as a result, a number of real-life applications of graphene have been realized [4, 5]. This carbon allotrope (for a review on other forms of carbon, see [6]) resulted in a number of novel physical phenomena already discovered (ranging from new types of quantum Hall effect to universal optical conductivity) and dramatically expanded the range of possible applications for such materials (from transparent conductive coating to ultrafast photodetectors). Currently, there are hundreds of products in the market that have graphene playing a significant (sometimes, dominant) role in improving the properties and the functionalities of the products. For example, graphene and other 2D materials can be used to design microwave shields and absorbers with predefined properties [7]. In addition, due to the absence of a band gap and the very high mobility of the charge carriers, graphene can be used for broad-band, ultrafast optoelectronic devices [8] and optical modulators [9]. Moreover, new details about graphene continue to be discovered on a regular basis.

The most important benefit of graphene has been that it paved the way for the discovery and study of more two-dimensional materials [10]. There are dozens of such materials [11] with different characteristics available currently: insulators, semiconductors, semimetals, and metals. Recently, superconductivity [12] and ferromagnetism [13–15] have been observed in two-dimensional materials. In the monolayer form crystals often behave very differently compared to their 3D counterparts. Thus, for instance, monolayers of many transition metal dichalcogenides (TMDC) act as direct-band-gap semiconductors, whereas they exhibit indirect band gap in the bilayer or thicker forms [16], which makes such materials particularly suitable for optoelectronic applications [17]. Further, the catalytic properties of MoS_2 can be enhanced by assembling monolayers into the hierarchical structure [18–20].

The multitude of 2D crystals resulted in the concept of van der Waals heterostructures [21–24]. With saturated chemical bonds, the 2D crystals can interact with each other only through the van der Waals forces, thus preserving the major electronic and structural characteristics of the individual crystals.

In the simplest possible manner, such a concept was used to encapsulate atomic crystals sensitive to environment. Thus, graphene encapsulated with hexagonal boron nitride (hBN) demonstrates electronic properties [25] comparable to those of the suspended devices [26–29]. Such encapsulation proved crucial when studying the properties of air-sensitive materials, for instance, $NbSe_2$ for superconductivity [13] or $MoTe_2$ for silicon photonics applications [30].

More complex heterostructures have been achieved with two graphene monolayers separated by a thin layer of hBN. In such structures, the interaction between electrons in the two layers led to Coulomb drag [31] and electron-electron correlation effects [32]. Furthermore, if the hBN layer is sufficiently thin, tunnelling current can be observed in the heterostructures [33–35]. Since the work function of graphene can be readily controlled by an external gate (due to the low density of states in graphene), such tunnelling devices can work as tunnelling transistors, as demonstrated by several groups [36, 37]. Interestingly, the tunnelling current in such heterostructures is strongly dependent on the misorientation between the two graphene electrodes. If the two graphene layers are crystallographically aligned, tunnelling can occur with momentum conservation. This effect, however, depends resonantly on the gate and bias voltages and leads to a negative differential resistance [38–41]. If the two electrodes are crystallographically misoriented, the momentum conservation can only be realized by scattering on impurities [34–42] or phonons [34, 43, 44], since the difference in the momentum between the initial (source) and the final

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(drain) states can be damp to a third particle (phonon) of to the lattice, as in the case of scattering on impurities.

Generally, the ability to control the electronic characteristics and even the electronic structure of such devices by modifying the relative angle between the crystals in the stack is a unique characteristic of the van der Waals heterostructures. Even in the simplest case of graphene on hBN, the difference in the lattice constants between-graphene and hBN lead to the appearance of a moire pattern with a period of 14.5 nm if both types of crystals are aligned. Electron scattering on such a structure lead to a strong spectrum reconstruction and appearance of the secondary Dirac points both on electron and hole sides [45–49]. Furthermore, in a magnetic field, when the integer number of the magnetic flux quanta occupy an integer number of moire unit cells - pronounced Brown–Zak oscillations become observable up to room temperatures [50]. Similarly, the relative angle between two different TMDC crystals is crucially important for the observation of the indirect excitons [51]. Furthermore, not only the electronic structure but also the phonon structure can be modified by stacking different crystals together [52].

Probably, the dominant effect when assembling van der Waals heterostructures is the charge transfer due to difference in the workfunction of the adjacent crystals. The formation of such an atomically thin p-n junction can be used, for instance, in developing novel photodetectors [53–55].

It is clear that the concept of van der Waals heterostructures is extremely interesting and will enable the study of many more exciting phenomena and the development of novel devices for various applications. Furthermore, as more and more 2D materials are being theoretically and experimentally discovered (for instance, the direct-bangap materials GeAsSe and SnSbTe [56]), the range of possible heterostructures increases dramatically as well. Furthermore, combinations with other nanostructured objects (such as γ-AlOOH nanosheets [57]) can expand the functionality of such devices even further. However, significant amount of effort is needed to convert the laboratory-scale applications of these stacked-crystal materials to real-life applications.

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