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Focus on Graphene

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EDITORIAL

Focus on graphene

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Abstract. Graphene physics is currently one of the most active research areas in condensed matter physics. Countless theoretical and experimental studies have already been performed, targeting electronic, magnetic, thermal, optical, structural and vibrational properties. Also, studies that modify pristine graphene, aiming at finding new physics and possible new applications, have been considered. These include patterning nanoribbons and quantum dots, exposing graphene's surface to different chemical species, studying multilayer systems, and inducing strain and curvature (modifying in this way graphene's electronic properties). This focus issue includes many of the latest developments on graphene research.

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1. Graphene, the wonder material

Graphene was discovered in 2004 at the Centre for Mesoscopic and Nanotechnology of the University of Manchester, UK, directed by A K Geim (see [1, 2]). This new material is the first



Figure 1. Left: optical image of graphite debris on top of a silicon oxide wafer. Right: optical image of a graphene flake on a silicon oxide wafer, with single and multilayer graphenes clearly visible (courtesy of A K Geim).

isolated monoatomic membrane, made solely of carbon atoms arranged in a two-dimensional honeycomb (hexagonal) lattice [3]–[5].

The method employed in the original isolation of graphene is simultaneously surprising and ingeniously simple on the surface [1, 2]. Such simplicity appears at a time where highly sophisticated technology is commonly used for nanofabrication and nanopatterning in nanosciences. The exfoliation method, as it is called, can now produce two-dimensional membranes with areas as large as 1 mm^2 , about ten times the diameter of a human hair (an example of a graphene flake is shown in figure 1).

Graphene physics is currently one of the most active research areas in condensed matter physics. This special issue includes many of the recent developments on graphene research. A recent contribution to a discussion of the status and prospects of graphene physics has been published [5, 6].

2. Recent developments: theoretical

It is now well understood that the low-energy electronic properties of graphene are described by a two-dimensional Dirac equation for massless particles. Therefore, the approach based on the continuous model is suitable in the case of the effect of super-lattices imposed on the graphene material by an external potential, due to either a periodic arrangement of magnetic stripes or a periodic structured surface (induced by trenches) [7]. The continuous approximation is also suitable for studying the transport properties of ribbons in magnetic fields, with or without the effect of some types of disorder [8, 9].

Bilayer graphene is another interesting system in itself [9]. The possibility of inducing and controlling a spectral gap in the bilayer using external gates suggests [10] that this system can be an alternative to graphene. There is however a puzzling experimental issue regarding the value of the gap in the bilayer, since values obtained from dc and optical measurements do not coincide. In addition, if the layers are rotated relative to each other, a system termed *twisted bilayer*, the electronic dispersion exhibits a linear dispersion relation (contrary to the parabolic one in the Bernal stacking configuration) and, in addition, shows no gap in the presence of a perpendicular electric field [11].

For the study of edge states, some types of impurities [12, 13], and for dots with special geometries, the tight-binding description is preferred over the Dirac equation representation. It is particularly interesting when it comes to understanding the effect of disorder in the bilayer system due to vacancies. In the presence of this type of disorder, peculiar semi-localized states emerge [12, 14].

Ab initio methods are well suited for studying the adsorption of molecules and metals at the surface of graphene. This allows us to understand the doping of graphene sheets as well as the modification of the band structure due to adsorbed molecules (although the *bands* obtained from the *ab initio* methods have, strictly speaking, no physical justification). Combining different and complementary approaches is particularly useful in some problems. One example is validation of the tight-binding parametrization of hopping integrals using density functional theory (DFT). This type of approach was used to parametrize hopping integrals under the effect of tensile strain [15].

In the field of the quantum Hall effect in graphene, understanding the lifting of the $n = 0$ Landau level degeneracies at large magnetic fields (observed experimentally) is required and some mechanisms have been proposed, such as random hopping [16].

The detailed understanding of the Raman spectrum of graphene layers [17] is crucial for understanding some electronic properties of graphene layers, such as for example the modification of the electronic spectrum under the effect of strain [18, 19]. The many-body effects in the phonon spectrum of graphene were also considered [20]. This study shows that many-body effects lead to important modifications of the spectrum of flexural phonons close to the Brillouin zone center, which can be important in suspended graphene (for graphene on top of a substrate, these modes are most likely quenched).

Concerning the fingerprints of the effects of Coulomb interactions in the electronic properties of graphene, they have been shown to be quite elusive (an exception being the recent observation of the fractional $1/3$ quantum Hall plateau). It is therefore important to understand why this is so. Contributions including many-body interactions in graphene are useful as a way to suggest effects where their presence can manifest themselves [21].

Graphene systems such as bulk crystallites, nanoribbons, and quantum dots and antidots are also important fields of study [22]. Extended defects, off-diagonal disorder (random hoppings and substitution atoms) [13, 23] and random mass effects [24] are some topics included in this special focus issue. Magnetism at the zigzag edges of graphene dots and its possible application to spintronics [25] need deeper investigation, with special emphasis on how roughness of the edges affects the magnetic properties predicted for ordered ribbons.

The electronic properties of graphene dots [25] and ribbons [26, 27], with particular emphasis on the charge transport in graphene ribbons with rough edges and variable width, have also been analysed [28, 29].

3. Recent developments: experimental

The possible applications of graphene layers vary. Nanotransistors have now been built where the p–n junctions [30] created with top gates (which can now be made suspended—a clear advantage) allow *in situ* control of the polarity of the junction and the amount of doping. Radio-frequency devices, non-volatile memories, transparent electrodes in solar cells and liquid crystal displays are other examples of devices for which graphene-based prototypes have already been built. Working as a transparent electrode, graphene can advantageously replace more traditional

materials, such as indium tin oxide (ITO) and fluorine tin oxide (FTO). Single molecule sensors, stress sensors, flexible electronic devices (a foreseen technology in the field of organic conductors) and spintronics devices are other fields of active research with potentially important applications.

The transport properties of graphene p–n–p and n–p–n junctions measured at zero and finite magnetic field shed new light on the charge transport in these systems [31].

The thermal properties of graphene were recently measured [32]. The high thermal conductivity ($\sim 3000\text{--}5300\text{ W m}^{-1}\text{ K}^{-1}$) depends on the lateral dimensions of graphene flakes, and a simple theoretical model was developed [32]. Understanding the mechanism for heat transport in suspended graphene [32], where phonons play the key role, is an important achievement, especially because production devices made of graphene, if ever made, will be working at room temperature.

Anti-dots were also studied experimentally [33]. The formation of transport gaps, the manifestation of weak localization [34, 35] in the magneto-resistance and geometric size effects were reported [33]. This raises the importance of finding a method to pattern graphene ribbons in a controlled and reproducible way, with special emphasis on the control of edge roughness.

4. Future developments

There are many relevant questions still to be answered. For instance, understanding the limiting factors of electronic mobility—which could be due to short-range scatterers, ripples, charge impurities or something else—remains an important open question.

Another relevant issue is the effect of bending in free suspended graphene. Being suspended, the back gate both dopes and distorts the graphene membrane. Its effect on the spectrum and on the electronic transport of material is now being studied in detail. The spontaneous ripple formation in suspended graphene (strongly connected to the elastic properties of the membrane [36]), where the ripples have an almost perfect sinusoidal profile and whose presence is reversibly controlled by temperature (with the negative thermal expansion of graphene playing an important role), might also prove to be an important avenue of investigation.

Also, conditions for the appearance of the fractional quantum effect in graphene, and understanding why the quantum Hall effect is not observed in suspended graphene with contacts in the Hall bar geometry, need further research.

One of the ultimate quests in current graphene research pertains to the development of a transport gap. One straightforward option to induce such a gap consists of patterning graphene nanoribbons, but this method only works for ribbons with armchair edges, and the state-of-the-art technology is still unable to cut ribbons with atomic precision. Additionally, the edges are known to be rather rough, which would certainly create states in the gap of the otherwise pristine graphene ribbon. Better experimental methods to control the size, shape and degree of roughness in graphene ribbons are needed.

5. Conclusion

The papers published in this focus issue touch upon some of the important theoretical and experimental issues presented and discussed above.

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