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Graphene: Emerging matter in two dimensions

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Abstract. We briefly review recent advances in graphene science and technology in the context of the contributions to this special issue.

Graphene is the name given to a flat monolayer of carbon atoms tightly packed into a two-dimensional (2D) honeycomb lattice, and is a basic building block for graphitic materials of all other dimensionalities (nanotubes or stacked into bulk graphite). Theoretically, graphene (or '2D graphite') has been studied for sixty years [1], and is widely used for describing properties of various carbon-based materials. In the eighties, it was realized that graphene also provides an excellent condensed-matter analogue of (2+1)-dimensional quantum electrodynamics [2], which propelled graphene into a thriving theoretical toy model [3]. On the other hand, although known as an integral part of 3D materials, graphene was presumed not to exist in the free state, being described as an 'academic' material [3,4] and was believed to be unstable with respect to the formation of curved structures such as soot, fullerenes and nanotubes. Suddenly, the vintage theory model turned into reality, when free-standing graphene was experimentally discovered [5] by the group of Andre K. Geim from Manchester in 2004 who also made the first graphene-based field-effect transistor – and especially when the follow-up experiments [6, 7] by the same group and the groups of Philip Kim and Horst L. Stormer of the Columbia University measured transport characteristic of graphene and found that its charge carriers were massless Dirac fermions. Nowadays, in many laboratories worldwide graphitic monolayers and bilayer (commonly refereed to as graphene) are available for experimental studies by extracting them from bulk graphite by micromechanical cleavage [5–7]. The most recent technological development [8,9] in the graphene research has been that of Eli Rotenberg (Lawrence Berkeley National Lab) who excelled in growing monolayer and bilayer graphene on a silicon carbide substrate (following earlier reports [10]) and performed angle-resolved photoemission measurements confirming the features of the electronic band structure of these materials [8,9].

Graphene is the first known truly two-dimensional solid but its uniqueness also rests on the fact that graphene has a singular band structure: its valence band and conduction bands touch each other [1]. In the absence of doping, the Fermi level in graphene lies at an energy which belongs to the both bands and corresponds to the Bloch states in the corners of the hexagonal Brillouin zone of the honeycomb crystal. This defines graphene as a gapless semiconductor, making a continuous variation of carrier density from electrons to holes possible. Moreover, the sublattice composition of the electronic Bloch states in graphene is locked to the direction of their propagation making charge carriers in both monolayer and bilayer material 'chiral'. Previously, such behaviour has only been associated with relativistic massless spin-1/2 particles, such as neutrinos. It has also been noticed that the chirality of carriers in graphene is associated with the Berry phase π in monolayers [4] and 2π in bilayers [11,12], which manifested itself in the unusual sequencing [3,11] of the plateaus in the recent quantum Hall effect measurements [6,7,13].

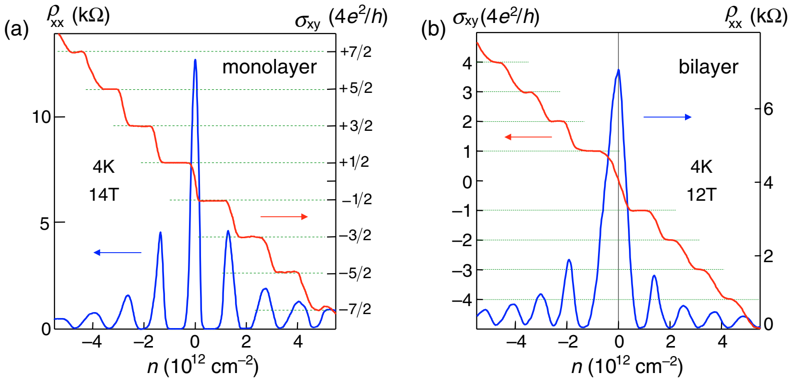

Fig. 1. Observed quantum Hall effect in (a) monolayer garphene and (b) bilayer graphene.

The absence of a gap between conduction and valence bands in graphene gives rise to another interesting effect: the apparent existence of a minimal conductivity ($\sim e^2/h$) in a sheet with a nominal zero electron density [5]. A 'conductivity without charge carriers' represents challenging issue for theorists stimulating studies of the effect of various types of defects, electron-electron interaction and interference on the transport properties of realistic graphene structures [14–20].

Another unique feature of the new material [22] is that the electron transmission through the interface between n- and p-doped graphene resembles optical refraction at the surface of metamaterials with negative refractive index [23]. In optics, interfaces between materials are used in lenses and prisms to manipulate light beams. So far, interfaces have played a rather different role in semiconductor electronics, where the central place was for a long time occupied by the p-n junction. Owing to the large band gaps in conventional semiconductors, a depletion region near the n-p junction makes it almost impenetrable for electrons. In contrast, the p-n junction in graphene is highly transparent to the charge carriers [24,25] and, most unusually, the straight n-p interface in graphene is even able to focus electric current [22]. Using the analogy with optical metamaterials, a ballistic stripe of p-type graphene separating two n-type regions may act as an electrostatically controlled lens for electrons [22].

The above examples give only a brief snapshot of the recent discoveries that make the investigation of graphene a hot and exciting topic. The Conference 'Graphene Week 2006' in Dresden was the very first international meeting dedicated to science and technology of, exclusively, this atomically thin, truly two-dimensional gapless semiconductor. This meeting has been co-organized by Igor Aleiner and Boris Altshuler of Columbia University in New York and Vladimir I. Fal'ko of the University of Lancaster. Representatives of most of the research groups which contributed (by that time) to the spectacular progress in this field were present at the meeting. The Conference participants reported on the development of graphene-based electronics, the direction currently attracting the main attention worldwide. Papers included in this issue of the European Physical Journal cover the following topics:

Development of techniques for growth of graphene, microfabrication of graphene-based transistors, and their characterisation using transport measiurements and ARPES (reports by A. Bostwick et al.; Y.-W. Tan et al.; and Echtermeyer et al. in this issue);

Experimental studies of quantum transport, including weak localisation and the first experimental realisation of graphene-based superconducting proximity-effect transistor (H.B. Heersche et al. in this issue);

Theoretical studies of disorder and electronic transport in monolayer graphene, including analysis of mobility, dominant scattering mechanisms, weak localisation (reports by K. Kechedzhi et al.; V.V. Cheianov; P.M. Ostrovsky et al.; M.P. López-Sancho et al.; and A. Cortijo and M. Vozmediano in this issue);

Properties of electrons in bilayer graphene – at zero magnetic field, peculiar sequencing of Landau levels in monolayers and bilayers, far infrared magneto-absorption spectra (E. McCann et al.; D.S.L. Abergel et al.; and F. Guinea et al. in this issue);

Theory of the quantum Hall effect in graphene (J.K. Pachos et al.; Y. Hatsugai et al.; and H.A. Fertig and L. Brey in this issue);

Theoretical and experimental investigation of electron-phonon interaction and observation of optical phonons in Raman spectroscopy (J.-N. Fuchs and P. Lederer; S. Piscanec et al.; and D. Graf et al. in this issue);

Spin scattering and spin physics of quantum dots (D. Huertas-Hernando et al.).

Whether or not graphene will find its way into practical electronics remains to be seen. This depends on new functionalities this material may offer due to its unusual electronic and mechanical properties. At present, the field enjoys an explosive growth of research in fundamental physics and technology issues, and the number of experimental and theoretical groups working on graphene worldwide is growing, whereas the research gradually extends into other directions outside electron properties. From the time of the meeting (during the period of preparation of this issue) graphene studies have progressed further, with tens of new publications appearing each month, and a new review on the subject recently published by A.K. Geim and K.S. Novoselov.

Finally, on behalf of all the organisers and participants of the International Conference 'Graphene Week 2006', we thank Max-Planck-Institut for the Physics of Complex Systems in Dresden for financial support which has made possible this timely meeting, and also express our gratitude to Ms. C. Poenisch, the Conference Secretary for her effort in the organisation of this event.

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