



## RESEARCH CONFERENCES

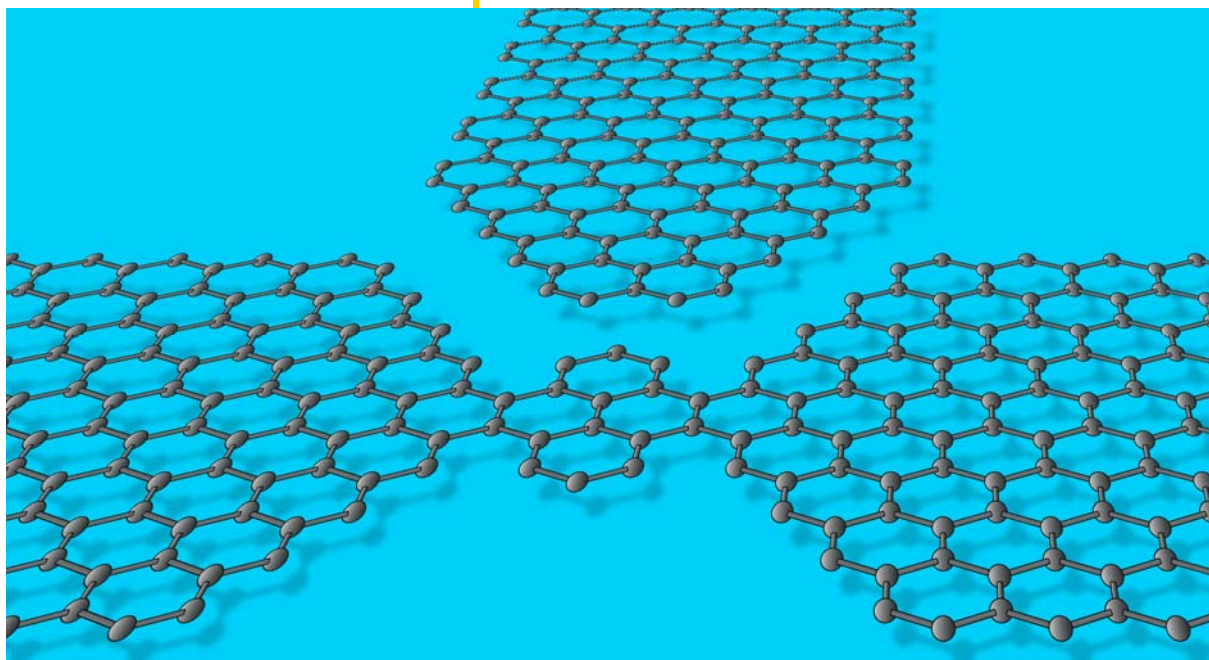
ESF-FWF Conference in Partnership with LFUI

# Graphene Week 2009

Universitätszentrum Obergurgl (Ötz Valley, near Innsbruck) • Austria  
2 - 7 March 2009

**Chair:** Vladimir Falko, Lancaster University, UK  
**Co-Chairs:** Andre Geim, University of Manchester, UK  
Allan MacDonald, University of Texas, Austin, US

[www.esf.org/conferences/09262](http://www.esf.org/conferences/09262)



## Conference Highlights

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*Please provide a brief summary of the conference and its highlights in non-specialist terms (especially for highly technical subjects) for communication and publicity purposes. (ca. 400-500 words)*

This conference was devoted to science and technology of graphene (atomically thin graphitic films), advances in its growth and chemical processing, manufacturing graphene-based devices, investigation of physical properties, and emerging applications of this new material including studies of optical properties of graphene and their applications in optoelectronics.

The early exploratory years of graphene research have created a massive interest in this qualitatively new two-dimensional electronic system). The fact that a material made of just one or two layers of atoms can withstand harsh mechanical treatment, thermal annealing, ambient chemical conditions, and still conduct electricity is, by itself, enough to catch the attention of many scientists and engineers. The unusual properties of electrons in graphene come on the top of this, as a bonus. For those who find pleasure in looking for extreme corners in physics, the 'flatland' of graphene offers a rich source of discoveries where some well (and some not so well) known effects acquire a new quality. Even the understanding of electronic phenomena requires a thorough revision. For example, the electrons in graphene mimic the behavior of two-dimensional relativistic particles, so called Dirac's fermions, though they move in graphene with velocity 300 time less than the speed of light.

The past five years of rapid development of graphene physics have been fun for participants and for observers in the larger community. At the same time, these few years have demonstrated what 'cross-fertilization' and 'technology transfer' mean in practice. The rapid progress that has been achieved in understanding graphene would not be easy (if possible at all) without the use of the full might of micro/nanofabrication techniques developed over the past decades in studies of semiconductor nanostructures, experience derived from the earlier graphite and carbon nanotubes studies, ready-to-use characterization technologies offered by large-scale facilities, and powerful theoretical tools designed earlier for studies of quantum transport and *ab initio* modelling of materials.

The ESF Conference Graphene Week 2009 has gathered physicist (theorists and experimentalists), chemists and engineers interested in the fundamental science and applications of this new material. It encompassed investigations of electronic properties of graphene, modeling of its band structure and mechanical properties, growth methods, and preparation techniques of graphene-based field-effect transistors: GraFET's. Topical sessions addressed the state of the art of characterization methods and modeling of specific properties of Dirac-type charge carriers in monolayer and bilayer graphene, electronic transport and kinetics including classical and quantum regimes, and discussing new functionalities offered by graphene-based microstructures.

I hereby authorize ESF – and the conference partners to use the information contained in the above section on 'Conference Highlights' in their communication on the scheme.

# Scientific Report

## Executive Summary

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(2 pages max)

The Conference programme incorporated 17 invited reviews, 28 contributing talks, and about 70 poster presentations in two poster sessions where most of the presented have been young researchers (junior postdocs or PhD students from over 20 different countries). 47% of the spent budget has been spent on the invited speakers, 53% - on young participants. The participation by female researchers was about 15%, higher than the average in physical sciences. The conference has generated a huge interest: over 200 applicants for about 90 places available for the contributing speakers and poster presenters.

The initially announced list of invited speakers has slightly evolved during the preparation of the conference, the result of availability of speakers and the appearance of new results in literature. The list of invited talks included:

M Crommie (Berkeley) – on STM of graphene  
L Vandersypen (TU Delft) – on graphene ribbons  
T Seyller (Erlangen) – on SiC synthesis of graphene  
T Heinz (Columbia NY) – on graphene optics and transport  
A Castro Neto (Boston) - on corrugations in graphene  
P First (Georgia Tech) – on graphene grown on SiC  
M Potemski (HMFL-CNRS Grenoble) – on infrared optics of graphene and graphite  
A Ferrari (Cambridge) – on Raman spectroscopy of graphene – experiment  
D Basko (SENG Grenoble) – on Raman spectroscopy of graphene – theory  
G Flynn (Columbia NY) - on STM of graphene on various substrates  
A Balandin (UC Riverside) – on Raman spectroscopy and thermal transport in graphene  
S Bunch (Boulder) – on graphene ‘drums’  
K Kechedzhi (Rutgers) – on disordered graphene - theory  
T Chakraborty (Winnipeg) - on molecular adsorbents on graphene  
K Novoselov (Manchester) - on hydrogenated graphene – graphene  
C-N Lau (UC Riverside) - on thermo-mechanics of graphene  
K Ensslin (ETH Zurich) – on graphene quantum wires and dots.

The Conference programme included the following sessions:

Graphene Properties I,II,III & IV  
Quantum Transport I, II & III  
Graphene on SiC I & II  
Graphene Optics  
Graphene Properties & Devices I & II  
Graphene Nanostructures I

This covered all relevant new results in the field of graphene science and technology. It worked well, with a lot of questions and lively discussion during and after the talks. Two Poster sessions have been very intense, each lasting over 4 hours, deep into late night. The hall was full, down to the last available chair, and junior participants were active, indicating intense and successful learning. The Organisers have established the daily prize for the best question of the day, handed at every dinner, and this has been won by a number of young researchers in the audience.

## Scientific Content of the Conference

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(1 page min.)

- Summary of the conference sessions focusing on the scientific highlights
- Assessment of the results and their potential impact on future research or applications

This conference was devoted to science and technology of graphene (atomically thin graphitic films), advances in its growth and chemical processing, manufacturing graphene-based devices, investigation of physical properties, and emerging applications of this new material including studies of optical properties of graphene and their applications in optoelectronics.

Topical sessions addressed graphene synthesis by mechanical and chemical exfoliation as well as epitaxial growth on metals and semiconductors, followed by ARPES, Super TEM, STM and AFM studies of graphitic films and intercalated graphite. C. Oshida (Waseda Univ Tokyo) has shown that graphene can be successfully grown on Ni films and, then, separated by chemical processing into a two-dimensional polycrystalline membrane. T. Seyller (Erlangen), P. First (Georgia Tech) and U Starke (MPI\_FKF Stuttgart) have reviewed the recent progress in graphene synthesis from SiC. Their new results have shown that silicon carbide technology does offer a viable (though expensive) route towards manufacturing large-area graphene wafers with decent transport characteristics. These talks have also identified the obstacle for using such material for transistor operation: the control of carrier density in graphene by electrostatic gates is hindered by charge transfer from SiC to graphene.

Manufacturing and transport studies of graphene p-n junctions, nanoribbons and quantum dots has been reported in several talks. The talk by Andrea Young, a PhD student from Columbia Univ NY has reported an outstanding technological breakthrough: the development of suspended gate devices, which enabled him to avoid suppression of graphene mobility by an additional dielectric material deposition upon the flake, thus, achieving ballistic regime in p-n-p junctions. Yong has reported an impressive observation of the Fano resonances in a p-n-p device and has shown how the phase jump in the oscillations of p-n-p device resistance as function of gate voltage at a relatively weak magnetic field can be related to the Berry phase  $\pi$  specific to chiral electrons in graphene.

Two sessions have been devoted to the optical properties of graphene: Raman and infra-red spectroscopy, with the inelastic (Raman) light scattering been shown the most effective non-invasive tool to distinguish single layer and bilayer flakes from multilayer graphitic films. The talk by A. Ferrari (CAPE Cambridge) reviewed the identification of different optical phonon modes in the Raman spectrum of graphene and reported the first observation of strain effect on the optical phonon energy in graphene flakes, a very thorough experimental work. Marek Potemski (HMFL Grenoble) has reported the results of spectroscopic studies of multilayer graphene grown on SiC, which indicated that loose graphitic layers grown in SiC resemble very much monolayer graphene.

The report by S. Bunch (Univ Colorado), on graphene 'drums' has addressed the use of graphene as non-penetrable membranes for capturing gases in nanoscale traps. Using helium trapped in a micron-size trench covered by a monolayer graphene flake he has demonstrated that helium atoms diffuse faster via a SiO<sub>2</sub> substrate than pass through the flake, which proves unique mechanical properties of graphene and shows that it can be used as a micro-mechanical platform for various nanoscale experiment. Jeanie Lau (UC Riverside) has reported the first direct observation of a negative thermal in-plane expansion of graphene. Her report of the observation that, for the range of temperatures between 10 and 400K graphene flake area shrinks upon heating was a complete surprise for all participants, and the observation itself sheds a new life at what happens with graphene-based devices upon thermal annealing.

## Forward Look

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(1 page min.)

- Assessment of the results
- Contribution to the future direction of the field – identification of issues in the 5-10 years & timeframe
- Identification of emerging topics

The conference has demonstrated that, after 5 years passed since discovery of graphene, the interest in this material is growing, and that pilot studies of graphene by few pioneers have created a solid base for a new field of research by numerous research groups in Europe and overseas, and is, now, transforming into a serious world-wide effort in a new carbon-based technology. The studies of electronic properties of this material have shown that it has great potential for electronics and optoelectronics applications, which attracts attention from industrial laboratories. For example, one of the conference participants, Dr B Shaagan head Electronics section in the Office for Naval Research in USA, which is, now, funding several projects in graphene-based technologies.

The reports on the characterisation techniques – invasive and non-invasive – show that most of the standard tools used in semiconductor studies and industry can be applied to graphene for characterisation and processing, with a very high efficiency. This experience will enable many more new groups to enter this new research field, both in academia and industry, giving boost to the search for new functionalities of graphene during the next decade.

The reports on the mechanical properties of graphene have highlighted the unique strength of this, only one atom thick, layer on the one side and its sensitivity to the details of the thermal processing protocols on the other. The research direction of graphene micro- and nano-mechanics seems to have a bright future, and the report by Prof. Lau at the conference (later published in Nature) has been a real breakthrough in understanding unique thermo-mechanical features of graphene. This direction seems to be an interesting research area for the coming 5 years.

The reported work on the growth of graphene on SiC give hope that this material can be manufactured on large-area wafers and processed into devices using the scalable top-down manufacturing techniques. The reports by T. Seyller and H. Weber (from Erlangen) have indicated that SiC synthesis of graphene is becoming a substantial research effort worldwide. There was recently a further advancement, stimulated by the Graphene Week reports on SiC growth technology: the observation of the metrological precision quantum Hall effect in SiC synthesised graphene: A. Tzalenchuk *et al*, arXiv:0909.1220. This means that graphene can be used for making the resistance standard based upon the quantum resistance unit  $h/e^2$ , which is one of the long-term goals in standardization and metrology.

The Conference has also been used by the participants to forge new collaborations and prepare bids for funding of graphene research, to the EU and ESF, through the Eurocores programme Eurographene. The Conference will also have a continuation: in 2010, there will be Graphene Week USA in Washington, and there is a plan to hold one more Graphene Week in Obergurgl, in 2011.

- Is there a need for a foresight-type initiative?
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The Conference Chair Prof. Falko has initiated a proposal for the Eurocores programme 'Eurographene', which has been successful, and, now, includes 23 funding agencies from 20 countries and is, currently, at the second stage of selection process. Now, there is a plan to hold one more Graphene Week in Obergurgl, in 2011, for which the application has been filed to the ESF.

## Atmosphère and Infrastructure

▪ *The reaction of the participants to the location and the organization, including networking, and any other relevant comments*

The Conference worked well, with a lot of questions and lively discussion during and after the talks, thanks to the excellent infrastructure of the Conference Centre in Obergurgl and the effort of the ESF Conference office Ms Alessandra Piccolotto. The conference has been heavily oversubscribed, due to the huge interest to this new subject, and the attendance of the meeting has gone up, from the estimated 70 participants to 115 attended senior and young scientists. Ms Piccolotto has managed to find additional accommodation outside the Centre for those willing to attend, filling up the conference to the last chair in the conference hall.

Two Poster sessions have been very intense, each lasting over 4 hours, deep into late night. The Centre is very well suited for that. The conference hall was full, down to the last available chair, and junior participants were active, indicating intense and successful learning. The Organisers have established the daily prize for the best question of the day, handed at every dinner, and this has been won by a number of young researchers in the audience.

### Sensitive and Confidential Information

This report will be submitted to the relevant ESF Standing Committees for review.

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**Date & Author:**



**8 Sept 2009, Prof. V. Falko**