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WELCOME

The recent emergence of graphene has generated a world-wide - and highly competitive - scientific enthusiasm, due to the extraordinary properties which are expected from graphene-based nano-objects and their derivatives. Its structural and chemical simplicity makes graphene a very convenient systems for fundamental research and for the development of nano-scale sciences. On the other hand, the numerous variations of the graphene based nano-objects allow a unique variability of properties (transport, mechanical, optical, chemical...) and an unusually high number of potential applications, spanning energy, nanoelectronics, or chemical industry. Graphene is also ideal for chemists who can modify its properties by functionalisation, grafting, adsorption and doping. Investigating graphene clearly requires the involvement of scientists in areas related to physics, chemistry, and materials sciences.

This growing interest, triggered by the numerous potential applications of graphene in future nanotechnology, motivates this interdisciplinary school on graphene. The school is aimed at PhD students, post-doctoral and young researchers in the first instance.

The school, initiated by the GdR-I « Graphene and Nanotubes », will deal with properties and characterisation of monolayers and multilayers of graphene and graphene-based nano-objects, from the points of views of physicists, chemists and material scientists. Both fundamental and applied aspects will be considered. It will offer participants both background lectures, essential for the interdisciplinary approach that is proposed, and specialised courses, which will include the most recent developments in the field. The lecturers of the school are researchers known for their pedagogic skills and internationally recognized for their expertise in the field of graphene. The participants will be encouraged to present their own work (also in adjacent fields) during poster sessions.

The Institut d'Etudes Scientifiques de Cargèse, where the school takes place, is organizing scientific meetings throughout the year. It is located on the west shore of Corsica, at the entrance of Cargèse, a small village of 800 inhabitants (50 km north of Ajaccio). Beaches are located in the vicinity of the Institute and on the opposite side of the village. Corsica is an island in the Mediterranean sea, 150 km south of the French coast and offering beautiful landscapes and historical landmarks.

It is our pleasure to thank Mrs Giovanna Chimini, director of the Institut d'Etudes Scientifiques, as well as Dominique Donzella, Nathalie Bedjai and Pierre-Eric Grossi for their help in the organisation of this school. We also wish to thank the members of the scientific committee and all those, cited later in this publication, who helped us very much. We also thank our sponsors.

We wish you a pleasant and scientifically fruitful stay in Corsica

Pertti Hakonen, Annick Loiseau, Didier Mayou

School Chairs

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Experimental and numerical simulation support

Nedjma Bendiab, Jean-Christophe Charlier, Laurence Magaud, Pierre Mallet, Vincent Renard, Antoine Reserbat-Plantey, Guy Trambly de Laissardière, Jean-Yves Veuillen. Horiba Scientific also contributes to the Raman experiment..

Administrative support at CNRS Grenoble

Martine Giglio, Cécile Némiche

Administrative support at Institut Néel

Marielle Lardato, Françoise Mollier Sabet, Patricia Poirier, Christine Zampaolo

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Schedule / second week

Monday 18		Tuesday 19	
A. LANZARA	8h30-9h30	A. Mac DONALD	8h30-9h30
<i>Break</i>		<i>Break</i>	
P. MALLET	9h40-10h40	A. LANZARA	9h40-10h40
<i>Coffee Break</i>		<i>Coffee Break</i>	
L. MAGAUD	11h-12h	C. BEENAKKER	11h-12h
<i>LUNCH</i>		<i>LUNCH</i>	
J. STROSCIO	15h30-16h30	J. STROSCIO	15h30-16h30
<i>Coffee Break</i>		<i>Coffee Break</i>	
E. OBRAZTSOVA	17h00-18h00	QUESTIONS	17h00-18h00
Wednesday 20		Thursday 21	
A. Mac DONALD	8h30-9h30	A. Mac DONALD	8h30-9h30
<i>Break</i>		<i>Break</i>	
M. ORLITA	9h40-10h40	J. CORAUX	9h40-10h40
<i>Coffee Break</i>		<i>Coffee Break</i>	
C. BEENAKKER	11h-12h	C. BEENAKKER	11h-12h
<i>LUNCH</i>		<i>LUNCH</i>	
POSTERS SESSION	15h30-17h30	P. PASANEN	15h30-16h30
		<i>Coffee Break</i>	
		QUESTIONS	17h00-18h00
Friday 22		Saturday 23	
J. CORAUX	8h30-9h30	DEPARTURE	
<i>Break</i>			
P. PASANEN	9h40-10h40		
<i>Coffee Break</i>			
P. KIM	11h-12h		
<i>LUNCH</i>			
P. KIM	15h30-16h30		
<i>Coffee Break</i>			
P. KIM	17h00-18h00		

ABSTRACTS OF LECTURES : first week

Hélène Bouchiat

Jean-Christophe Charlier

Walt de Heer

Andrea C. Ferrari

Jean-Noël Fuchs

Robert C. Haddon

Jean-Paul Issi

Annick Loiseau

Kostya Novoselov

Alain Pénicaud

Guy Trambly de Laissardière

IMPURITY SCATTERING AND QUANTUM TRANSPORT IN GRAPHENE

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Abstract.

Since the very first investigations of the electronic properties of graphene the nature of defects has been shown to play an essential role in determining the carrier density dependence of the conductance. Impurity scattering is characterized by two different times the transport and elastic scattering times which are both sensitive to the massless energy dispersion of graphene. The analysis of the ratio between these two times gives insight on the nature (neutral or charged) and range of the scatterers. We will discuss how to extract these two times from magneto-transport measurements in macroscopic samples and analyze their differences in monolayer and bilayer Graphene in relation with the different symmetry properties of their band structure and wave functions [1].

In the mesoscopic phase coherent transport regime, at low magnetic field and low temperature the physics is dominated by quantum electronic interferences leading to reproducible conductance fluctuations as function of Fermi energy or magnetic field. Their correlation energies and magnetic field turn to be related to the carrier density dependence of the diffusion coefficient specific of monolayer and bilayer graphene. We also show the existence of an important mesoscopic rectification which asymmetry in magnetic field gives information on electron-electron interactions [2].

Another way to probe coherence transport is to investigate s-graphene-s junctions, where S is a superconductor. We will review experimental work on proximity induced superconductivity in graphene and discuss the specificity of Graphene Josephson junctions in comparison with other systems [3].

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ELECTRONIC PROPERTIES AND QUANTUM TRANSPORT IN GRAPHENE : A COMPUTER SIMULATION APPROACH

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Abstract.

The outstanding structural and electronic properties of graphene promote graphene as a promising material for a wide range of nanoscience and nanotechnology applications. The goal of the present lecture consists in illustrating how computer simulations (first-principles modeling as well as lower accuracy techniques) can help to predict both the electronic properties and the quantum transport in graphene-based nanostructures.

More specifically, the electronic properties of graphene and few-layer graphene will be presented in the framework of various computer simulation approaches and compared to conventional graphitic forms [1,2]. In order to realize all kinds of graphene-based nanoelectronic devices, it is mandatory to tune the properties of graphene. Consequently, the confinement from 2D to 1D (graphene nanoribbons), the chemical doping, the introduction of point defects and the chemical functionalization will be considered as possible ways to achieve this goal. The intrinsic semiconducting character of graphene nanoribbons [3], as controlled by their topology, will be presented and compared to real graphene 1D systems presently synthesized experimentally [4]. Further, the spin-polarized density functional theory will be used to investigate spin-transport in graphene nanoribbons with topological disorder [5]. The effect of the introduction of isolated [6,7] or extended [8,9] defects in graphene on its electronic properties will be overviewed. At last, chemical modifications of graphene using hydrogen, fluorine and ozone [10] will also be investigated theoretically.

References

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EPITAXIAL GRAPHENE: DESIGNING A NEW ELECTRONIC MATERIAL

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Abstract.

In this series of three lectures, I will discuss the science and technology of epitaxial graphene on silicon carbide (EG).

The following topics will be addressed.

1. A brief history of graphene
2. Graphene-based electronics: why nanotubes were not good enough.
3. Early measurements of EG surface and transport properties
4. EG production beyond UHV: the confinement controlled sublimation method
5. Characterization: Surface probes and crystallography
6. Multilayered EG versus Few Layer Graphite
7. Transport properties of Si-face and C-face EG.
8. EG field effect transistors: path to the THz FET
9. Survey of recent measurements (STS, Optical, THz)
10. Modifying graphene: graphene oxide production and patterning
11. Templated EG growth: sidewalls and mesas.

Raman Spectroscopy of Graphene

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Abstract.

Raman spectroscopy is the most common and informative characterization technique in graphene science and technology. It is used to determine the number of layers, doping, strain, defects, functional groups, quality and type of edges [1-15]. I will outline the state of the art in this field, the recent developments and future directions of research, focussing on the link between Raman spectra and sample mobility, the quantification and identification of defects, and the role of electron-electron interactions.

References

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15. F. Schedin et al. ACS Nano (2010)

Introduction to the electronic properties of graphene

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Abstract.

1) General introduction and band structure of graphene: historical notes, fabrication (exfoliated, epitaxial, CVD, suspended graphene), crystalline structure (atoms, ripples, etc), band structure (tight-binding model), doping by electric field effect and density of states. Related systems: gapped graphene (boron nitride), graphene bilayer.

2) Low-energy effective description of electrons: massless Dirac equation, related effects of ultrarelativistic quantum mechanics (chirality, absence of backscattering, Klein tunneling, zitterbewegung, etc.), minimum knowledge about electron-electron interactions and screening.

3) Electronic transport (mainly diffusive and incoherent regime): phase diagram in the (temperature, backgate voltage), electron-hole thermal plasma versus degenerate metal, Einstein relation for the conductivity, transport and elastic scattering times, dominant scatterers, minimum conductivity, charge inhomogeneity near the neutral point (puddles), etc.

4) Electronic properties in a magnetic field: cyclotron motion, its quantization and appearance of Landau levels, Berry's phase, quantum Hall effect, lifting of spin and valley degeneracy at larger magnetic field, etc.

CHEMISTRY OF GRAPHENE

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Abstract

The potential of graphene as a novel electronic material has attracted significant attention in the scientific community. Covalent bond formation to graphene transforms the carbon centers from sp^2 to sp^3 thereby introducing a barrier to electron flow and opening a band gap.[1-4] Hence the chemistry of graphene represents an important frontier in the research on graphene-based materials and offers the promise of band gap engineering via synthetic procedures developed in organic chemistry. The present discussion will summarize the progress and the promise of the new field of graphene chemistry, which currently includes hydrogenation,[5] fluorination,[6] oxidation,[7] radical addition,[1] cycloaddition (nitrene addition, 1,3-dipolar cycloaddition, benzyne cycloaddition)[8-11] and complexation with metals.[12] Where appropriate, comparisons will be drawn with the chemistry of carbon nanotubes and fullerenes such as C₆₀, where curvature and topology play an important role.

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TRANSPORT PROPERTIES OF GRAPHENE IN AND OUT OF THE BULK

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Abstract

The carbon atoms have the unique capability of associating in different ways to form various architectures, some of them being unique. Following the discovery of fullerenes, these last twenty years uncovered some new forms of associations leading to a large diversity of nanostructured carbons with fascinating properties. As regards bulk carbons, the decade preceding the discovery of fullerenes, has paved the way for some physical properties which were found later to be displayed in these new nano entities. This mainly concerns the semiclassical and, more particularly, the quantum aspects of two-dimensional (2D) electronic transport and the behavior of phonons in low-dimensional materials.

The title of the talks reflects to what extent we would like to stress the obvious similarities as well as the differences observed in the transport properties of an isolated single layer graphene (graphene out of the bulk), or a few layers of graphene (FLG), supported or suspended, and those of a single (stage-1) or more (higher stages) graphene layers sandwiched between planes formed by other chemical species (graphene in the bulk), as it is the case for graphite intercalation compounds (GICs), and more particularly quasi-2D acceptor compounds (GACs), or even, in some cases, pristine HOPG.

These aspects will be discussed in relation with the electrical and lattice thermal conductivities

Transmission Electron Microscopy: a tool for visualizing the structure of C and h-BN monolayers and their defects with an atomic resolution

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Abstract.

This lecture will introduce the fundamentals of the structure characterization of graphene and derivative sp^2 structures by transmission electron microscopy (TEM). First part will introduce this technique and its different modes. Second part will focus on capabilities of this technique for identifying these structures with an atomic resolution. Finally, it will be shown how the tool can be used for studying various aspects of defects in graphene. In particular irradiation can modify the structure and induce the formation of configurations, which provide new insights in the bonding behaviour of carbon materials.

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Graphene and its chemical derivatives

K. S. Novoselov

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Abstract.

When one writes by a pencil, thin flakes of graphite are left on a surface. Some of them are only one angstrom thick and can be viewed as individual atomic planes cleaved away from the bulk. This strictly two dimensional material called graphene was presumed not to exist in the free state and remained undiscovered until the last year. In fact, there exists a whole class of such two-dimensional crystals. The most amazing things about graphene probably is that its electrons move with little scattering over huge (submicron) distances as if they were completely insensitive to the environment only a couple of angstroms away. Moreover, whereas electronic properties of other materials are commonly described by quasiparticles that obey the Schrödinger equation, electron transport in graphene is different: It is governed by the Dirac equation so that charge carriers in graphene mimic relativistic particles with zero rest mass. The very unusual electronic properties of this material as well as the possibility for it's chemical modification make graphene a promising candidate for future electronic applications.

Recent progress in graphene samples production allowed for a dramatic improvement in quality. Thus, mobilities of the order of 10^6 cm²/Vs can be routinely achieved in mono- and bi-layer graphene samples. This brought an influx of novel phenomena, previously non-observable in this material. The influence of electron-electron interaction become dominant and exhibit itself in spectrum modification, fractional quantum Hall effect, etc.

CHEMICAL ROUTES TO GRAPHENE AND GRAPHENE NANORIBBONS

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This lecture will review the different chemical routes that have been explored to obtain graphene. Chemical vapor deposition (CVD) and reduction of graphene oxide will not be covered here since they both constitute a rather large corpus by themselves and, as such, are the subject of specific lectures within this school. A brief introduction will attempt to define graphene, graphene nanoribbons and nanographene, and explain the need for chemical routes to graphene. The lecture will be centered upon the following topics: (i) Graphene from graphite (ii) graphene from graphite intercalation compounds, (iii) graphene nanoribbons from longitudinal opening of carbon nanotubes, (iv) nanographene and graphene nanoribbons from molecular precursors.

NUMERICAL INVESTIGATIONS OF QUANTUM TRANSPORT IN GRAPHENE

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Abstract

We present numerical methods that give powerful tools to evaluate electronic transport properties in the scheme of the Kubo-Greenwood formula. For large two-dimensional systems with static defects, the MKRT method [1,2,3,4] is a very efficient real-space recursion method. It has already been used successfully in the treatment of various disordered systems in graphene (see for instance [5,6]). For smaller systems, a reciprocal-space approach [7] allows to analyse the new terms in quantum diffusion with respect to classical Bloch-Boltzmann theory. These methods are applied to analyse the role of single vacancies and pair of vacancies in mono-layer and bi-layer graphene [8].

References

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ABSTRACTS OF LECTURES : second week

Carlo Beenakker

Johann Coraux

Philip Kim

Alessandra Lanzara

Allan Mac Donald

Laurence Magaud

Pierre Mallet

Alexander Obraztsov

Elena Obraztsova

Milan Orlita

Pirjo Pasanen

Joseph A. Stroscio

Andreev reflection and Klein tunneling in graphene

Carlo Beenakker

Instituut-Lorentz, Leiden University, The Netherlands

We will discuss two electronic processes in graphene, each having an analogue in relativistic quantum mechanics. Both processes couple electron-like and hole-like states, through the action of either a superconducting pair potential or an electrostatic potential. The first process, Andreev reflection, is the electron-to-hole conversion at the interface with a superconductor. The second process, Klein tunneling, is the tunneling through a p-n junction. Existing and proposed experiments on Josephson junctions and bipolar junctions in graphene are discussed from a unified perspective.

Literature: Rev.Mod.Phys. 80, 1337 (2008) [arXiv:0710.3848]

GRAPHENE PREPARATION ON METALS

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Abstract.

Thin graphite layers and even graphene can be readily prepared at the surface of transition metals as it is known for decades [1]. In the last few years this synthesis route not only appeared as one of the most promising for producing large area and high quality graphene [2], but also yielded a rich playground where to explore the physics of graphene in more or less interaction with a metal (see, e.g., ref. 3). This lecture will first address the history of the field, which has largely preceded the last six years of intense research focusing on graphene, and is most often little referred to. We will then present the structure of graphene on metals as a key to the understanding of graphene growth. Growth processes down to the atomic scale and the graphene morphologies that they yield will then be exposed. Finally, recent evolutions, including graphene growth on thin metal films followed by a transfer to arbitrary supports, will be presented.

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Interactions In GRAPHENE

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Abstract.

Electrons confined in two dimensions (2D) can exhibit strongly correlated states. Recent experimental discovery of integer and fractional quantum Hall effect in graphene amplified interest in correlated 2D electronic systems, owing to presence of the unusual topological phase associated with zero effective mass of charge carriers. In this talk, we will discuss the role of the many-body effects due to the electron-electron interaction in graphene manifested in electron transport phenomena. In particular, we will discuss the nature unusual spontaneous symmetry breaking Landau levels graphene under the extreme quantum condition, the appearance of unique low density insulating states and fractional quantum Hall states [1], employing extremely high quality samples obtained by suspending graphene and graphene on atomically flat defect free insulating substrate [2]. In addition, we will discuss the effect of electron phonon interaction that can be tuned by electron density especially at an extremely high carrier density achieved by electrolyte gating. [3]

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Electronic structure and chirality of graphene

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Abstract:

The peculiar electronic structure of graphene where quasiparticles have zero effective mass and follow the relativistic Dirac equations is at the basis of a variety of novel exciting properties of this two dimensional material.

I will present an overview on the electronic structure of graphene and its chirality and will show how the presence of Dirac quasiparticles leads to unusual many body interaction. I will then show how the linear dispersion of graphene can be easily modified by size dependent effects, substrate, doping and disorder, leading to gap opening and metal to insulator transitions [1-4].

The implications of this study on the properties of Dirac materials and their potential role for applications are discussed.

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Electron-Electron Interaction Effects in Graphene and Graphene Bilayers

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I will discuss the influence of electron-electron interactions on the electronic properties of graphene and few layer graphene systems, concentrating on the topics listed below and on issues raised by school participants.

1) Doped single-layer graphene is a Fermi liquid, but one with a few unusual properties, for example a Pauli susceptibility that is suppressed rather than enhanced by interactions.

2) ARPES in single-layer graphene reveals a plasmaron (plasmon+hole bound state) spectral feature which is strongest near the Dirac point and can be misinterpreted as evidence for a gap.

3) In very high mobility weakly doped bilayers, graphene can exhibit a series of broken symmetry states. The most interesting of these have broken time-reversal symmetry and a (quantized) anomalous Hall effect, but no spin magnetism.

4) When two-layers are twisted relative to each other, a large peak in the density of states, which favors broken symmetries, can sometimes occur at the Dirac point.

5) Broken symmetry states, quantum Hall ferromagnets, are also common in the quantum Hall regime in graphene systems. In bilayers a dipole allowed transition within the $N=0$ octet allows the quantum Hall effect to be studied with THz spectroscopy. An electric field applied perpendicular to a bilayer is particularly effective in driving quantum transitions between different ordered states.

Graphene in its environment : what can be learned from ab initio calculations

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Abstract. Graphene outstanding electronic structure comes from its honeycomb lattice. Here, we will describe how the environment can affect graphene properties. Indeed for most applications, graphene has to be supported and this can result in graphene-substrate interactions. Furthermore, several graphene layers can be stacked on top of each other leading here again to interactions.

Ab initio calculations results will be used to describe graphene – substrate (SiC and metals) interface atomic and electronic structures. Weak and strong interaction cases will be presented for both types of materials (strong interaction : Si face of SiC and Ru, weak interaction: C face of SiC and Ir).

Interface modification through defects (H) will also be discussed and finally, the effect of different stacking sequences (AA, AB, rotation angle) will be presented. Ab initio results will be compared to experiments, especially STM and ARPES.

STRUCTURAL PROPERTIES OF GRAPHENE ON SILICON CARBIDE PROBED BY SCANNING TUNNELING MICROSCOPY

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Abstract.

Graphene has recently attracted a great deal of attention, in particular for its unusual and fascinating electronic properties. Among the different methods for graphene elaboration, the graphitization of silicon carbide is very promising, because it is thought to be compatible with large scale production of graphene-based devices. Progress is underway to optimize the structural quality of the graphene layers and to increase their lateral size. However, a critical issue remains the control of the atomic and electronic structure of the interface between the first graphene layer and the substrate, which can impact the graphene low-energy properties.

In this lecture I will review the efforts made by our group to address this issue, using Scanning Tunneling Microscopy (STM). Our samples are grown in ultra-high vacuum, by thermal decomposition (Si sublimation) of 6H-SiC(0001) or 6H-SiC(000-1) surfaces. After a brief introduction to the experimental technique, I will show how STM experiments, with the support of Density Functional Theory, are able to capture at the nanometer scale many of the structural and electronic properties of the graphene layer(s) and of the interface with the SiC substrate. In particular, it is possible to probe, at least qualitatively, the reminiscent electronic graphene-interface coupling, for different interface reconstructions and in presence of possible rotational stacking disorder.

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FABRICATION AND OPTOELECTRONIC APPLICATION OF NANOGRAPHITE

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Nanosized graphitic materials attract great attention because of its unique physical properties. We present here recent results on fabrication of thin film materials consisting of graphite of nanometer thickness and on investigation of photo-induced phenomena allowing its optoelectronic application.

Chemical vapor deposition (CVD) technique has been used to fabricate thin films consisting of graphite of nanometer thickness with orientation of its basal crystal plane (0001) perpendicular or parallel to substrate surface. In case of a perpendicular orientation the obtained film material has a mesoporous structure formed by tiny flakes of nanometer thickness. The graphite films, having the orientation of its atomic layers parallel to a substrate, exhibit a quasi single crystal structure.

For both type of materials a current generation across the film has been observed under pulsed laser illumination. This phenomenon is discussed in terms of a photon drag effect and specific electronic properties of nanographite materials.

GRAPHENE NON-LINEAR OPTICAL ELEMENTS for NEAR and MID- INFRARED SPECTRAL RANGE

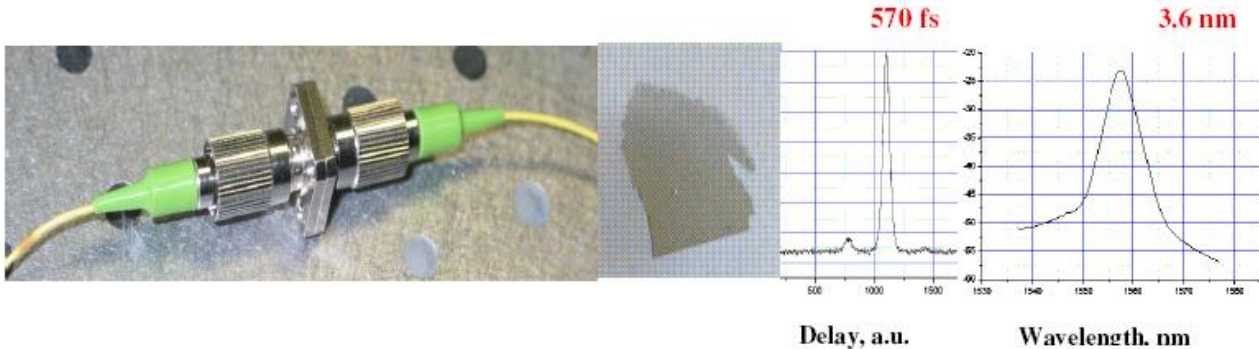
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Last few years single-wall carbon nanotubes became quite a popular material for the fast and working in a wide spectral range nonlinear optical elements – *saturable absorbers* [1-5]. In 2009 a single graphite sheet – graphene- also has demonstrated the remarkable nonlinear optical properties [6,7]. Its important advantage is a possibility to realize mode-locking regime in a much wider spectral range (at least up to 12 μm).

In this work we report the results on synthesis [8], characterization and application of a few graphene layer flakes for realization of the mode-locking regime with an output pulse duration of 570 fs in an Er fiber laser (with a working wavelength of 1.55 μm). A unique potential of graphene for formation in the first time the saturable absorbers for long-wavelength CO ($\sim 5\text{-}6 \mu\text{m}$) and CO₂ ($\sim 10 \mu\text{m}$) lasers is also discussed.

The work was supported by RAS research program and RFBR project-10-02-00792.

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MAGNETO-OPTICAL SPECTROSCOPY OF DIRAC FERMIONS

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Abstract

Recent results of optical spectroscopy of graphene-based materials will be reviewed [1]. We will focus on the optical response of massless as well as massive Dirac fermions in magnetic field, i.e. on basic aspects of cyclotron resonance of such particles. This brief theoretical discussion will be illustrated with experiments carried out on several carbon-based systems with Dirac-type particles - on multi- and single-layer epitaxial graphene on the SiC substrate, on graphene placed on the surface of bulk graphite as well as on bulk graphite itself. The presented experimental results will show how the infrared magneto-spectroscopy can be applied to visualize the electronic band structure of these systems and to estimate their quality in terms of scattering time or mobility.

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Graphene: Prospects for Future Electronics

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Abstract :

Graphene has attracted a lot of attention because of its unique electrical properties. Graphene holds the record of the highest carrier (electron and hole) mobility $> 100\,000\text{ cm}^2/\text{Vs}$ at room temperature. This exceeds by a factor of ~ 10 the state-of-the-art semiconductors lattice-matched to InP, currently regarded as the best high-speed materials. Consequently, there are high expectations on graphene devices operating up to the THz regime: photodetectors, mixers, amplifiers, frequency multipliers, and generators. In addition to excellent electrical characteristics, graphene has also outstanding mechanical and optical properties. It has a small mass, a large Young's modulus of elasticity, and it is 97.7% transparent on optical frequencies. All these combined make graphene a unique material, with potential for many electronics applications.

In my two lectures I will discuss the feasibility of graphene electronic devices from the industry point of view. In particular, I will review what is required to use graphene for high performance RF electronic circuits or as an alternative for transparent conductors.

All Graphenes Are Different!

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With the advent of scanning tunneling spectroscopy (STS), the local density of states can be mapped in real space to give insight into the role the local disorder potential plays in determining the 2-dimensional electron gas (2DEG) properties. In this talk I describe studies using scanning tunneling spectroscopy to examine various graphene systems with disorder potentials in the strong and weak limits. The amount of disorder depends on how the graphene was made. In the growth of graphene on the Si-face termination of SiC in UHV, local defects are found which contribute to strong inter- and intra-valley scattering [1]. Strong disorder is also found in exfoliated graphene on SiO₂. Using a back-gated exfoliated graphene device on SiO₂ we observe a Landau level spectrum and charging resonances [2] that are completely different from previous STS measurements on weak disorder graphene systems. Applying a gating potential allows us to obtain “STS gate maps” which show the graphene 2DEG breaking up into a network of interacting quantum dots formed at the potential hills and valleys of the SiO₂ induced disorder potential. Graphene grown on the C-face termination of SiC is shown to have weak disorder with Landau level line widths approaching thermal limits at 4 K [3]. Using a new STM system operating at 10 mK, we are able to resolve the graphene “quartet” internal structure of a single Landau level [4]. The quartet structure shows the complete lifting of the valley and spin degeneracies, which we determine as a function of magnetic field. Strong correlation effects are observed when a Landau level is placed at the Fermi-level. An enhanced exchange spin splitting occurs at odd filling factors corresponding to fully polarized Landau levels. Most surprisingly, the tunneling spectroscopy reveals a series of unexpected many-body states with half-integer filling factors.

*This work in collaboration with Y. J. Song, A. Otte, S. Jung, G. Rutter, N. Klimov, D. Newell, N. Zhitenev (NIST); Y. Hu, D. B. Torrance, P. N. First, W. A. de Heer (Georgia Tech)

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