Graphene Flagship – US NSF Workshop

2D Materials, Heterostructures and Devices

National Graphene Institute, Manchester, United Kingdom

10-12 October 2016

Workshop Report

Contents

Executive Summary

The second Graphene Flagship – US NSF Workshop gathered close to 120 participants that presented the newest research developments in their fields with the aim to identify complementarities and opportunities for collaboration between ongoing activities in Europe and the United States and discuss future plans. Participants have discussed a broad range of research topics related to 2D materials, allowing to highlight the complementarity of research activities and expertise across the Atlantic as well as to identify the main issues of common interest such as access to dedicated infrastructure and the need to define materials characterisation standards. In addition, reporting of research results so that they can be broadly accessible and used (including by the private sector) as well as the challenge to identify most promising materials amongst the broad family of 2D materials have been emphasized. Specific actions and opportunities proposed by the participants are summarized in the report. The newly established grant mechanisms that enable exchanges between EU and US research groups were welcomed and the first applications have already been received and approved. Several enquiries from both US and EU researchers are expected to result in proposals made to the respective funding sources in the near future.

Overview

The second Graphene Flagship – US NSF Workshop was held at the National Graphene Institute in Manchester (UK) during 10-12 October 2016. The workshop provided an open technical forum that brought together leading researchers from the US and Europe to discuss cutting-edge research in 2D materials, their heterostructures, and devices based on such materials. The aim was to facilitate scientific exchanges and discuss needs and mechanisms for future collaborations. This was a follow up to the first "US-EU Workshop on 2D Layered Materials and Devices" held on 22-24 April 2015 in Arlington (US)[1].

The meeting was co-organised by US and European researchers and was co-chaired by:

- **Professor James Hwang** and **Professor Anupama Kaul (US)**
- **Professor Vladimir Fal'ko (UK)**

The workshop gathered **117 participants** (28 from the United States and 89 from Europe), coming mainly from of academic institutions and private companies.

European participants included members of the Core 1 Project, Partnering Projects and Associated Members. As a part of the workshop, three Flagship work packages, '*Enabling Science*', '*Enabling Materials*' and '*Spintronics*' held an Open Division 1 meeting where current research activities and open questions were discussed. **US participants** included representatives of selected projects supported by National Science Foundation (EFRI 2-DARE)[2], by Air Force Office of Scientific Research (BRI)[3], by Semiconductor Research Corporation/Defense Advanced Research Projects Agency (STARnet)[4] as well as government and industry representatives.
Representatives from funding organisations including the European Commission, the U.S. National Science Foundation, U.S. Office of Naval Research and U.S. Army RDECOM – Atlantic were also present for planning of future collaborative programs.

The workshop focused on 2D materials beyond graphene and their heterostructures and addressed a series of topics including:

[1] http://engineering.utep.edu/useu2dworkshop/
[2] https://www.nsf.gov/pubs/2013/nsf13583/nsf13583.htm
[3] http://afrl.dodlive.mil/funding/
[4] http://www.darpa.mil/program/starnet

- techniques that can enable the scalable synthesis of these materials;
- controlling layer number and defect density;
- understanding doping mechanisms and optimizing contacts for device research;
- physical properties of planar and vertical heterostructures of 2D materials;
- developing predictive modelling and simulation techniques, including 2D material design and discovery;
- new *in-situ* and *ex-situ* characterization techniques to measure material properties.

The programme featured 36 invited plenary presentations that showcased the breadth of activities and topics covered by the respective research groups in the field of 2D materials synthesis, characterisation, production, devices, and applications. Two break-out discussion sessions addressed opportunities and needs to enhance cross-Atlantic collaborations.

This report summarises the main conclusion of the discussions and the envisaged way forward in terms of collaborations. For more details about the scientific content of the presentations, we refer to the Abstracts section.

Breakout sessions addressed a set of questions concerning the needs in terms of collaboration between European and US researchers and more specific issues related to materials and devices:

- What are the S&T topics that would benefit most from transatlantic collaboration?
- What benefits does such collaboration bring in each of those areas, on each side of the ocean?
- Is there a need / how would it complement existing schemes?
- What could such a mechanism look like?
- What level of interest should be expected?

2D materials creation strategies, supply, exchange and standards

- How to organise materials flow between groups – if any (sharing protocols and best practices)
- Are standards needed? Standardised characterisation?
- Is access to complementary facilities a desirable/feasible option?
- Who should be the target audience: academia, industry, or both?
- What are concrete goals to be achieved?
- How to measure progress?

2D devices application, innovation and commercialization

- What trans-Atlantic collaboration can do to accelerate innovation based on new devices?
- What could be the lowest lying fruits for trans-Atlantic collaboration?
- Would intellectual property rights be a problem for trans-Atlantic collaboration?
- Who should be the target audience: academia, industry, or both?
- What are concrete goals to be achieved?
- How to measure progress?

Common interests

Several breakout groups discuss the challenges that face 2D materials research and development and how the EU and US can collaborate in areas of common interest.

Collaboration between theory / experiments and materials / devices research groups could bring added value in general but also for collaborations between European and US researchers since specific complementary expertise exists across Atlantic namely in theory and computing (Europe) and devices (US). European competence on 2D materials multiscale modelling via molecular dynamics and electronic structure

calculations was noted as a special capability of interest for the US side, while the US "application-driven" approach and strong links with the information technology industry could bring important perspectives to the Flagship. It was also noted that device simulation should guide the development of new technologies.

Materials synthesis and, in particular, synthesis of materials with specific properties is a common challenge. Theoretical simulation could also contribute to identify the most suitable synthesis processes.

The **scalable growth of 2D materials** (including heterostructures) with focus on reproducibility and quality for devices (in particular electronic devices) was deemed crucial for developing new applications and systems solutions. In general materials variability should be distinguished from device performance.

The goal for materials growth is to move from exfoliated materials to synthetic materials that will include single layer device stacks and heterostructures.

Challenges related to materials need to be addressed in order to find solutions for:

- Low power consumption
- High performance computation
- Energy storage
- Applications beyond electronics including membrane applications and nano-biology.

There was a general agreement among participants that for some applications it would be advisable and beneficial to down select materials so that materials growers can focus on developing growth processes to provide the highest quality material possible. These processes being within one material system, e.g. transition-metal dichalcogenides (TMDs), could form the basis for growth of other TMDs.

Facilitating **access to infrastructure** dedicated to 2D materials synthesis and characterisation across the Atlantic would be highly beneficial for researchers as it would allow the best use of available resources and access to complementary expertise and facilities. Unique facilities and centres of competence for the investigation of 2D materials existing in the US or EU have been named as relevant for enhancing transatlantic collaboration. Some examples include large scale facilities optimized to probe nanoscale materials (e.g., tr-SARPES in Artemis-CLF, nanospectroscopy in Elettra-Trieste, capabilities at DOE, DOD and DOC nanoscience centers), high magnetic field laboratories, etc.

There are also potential collaborative opportunities with the NSF 2D Materials Innovation Platform based on the 2D Crystal Consortium at Pennsylvania State University (PSU)[5]. The PSU consortium's objective is to become a user facility and thus there could be many opportunities for collaboration. Other user facilities, if they exist, for other materials or processes such as liquid phase exfoliation, and graphene growth on SiC would have to be identified in both the US and EU.

Issues such as joint ownership of intellectual properties would need to be addressed in this context. It was generally recognised that IP issues can be a significant barrier to international collaboration.

Identifying and selecting the most promising 2D materials for new applications

It was stressed that the field of "2D materials beyond graphene" is still in its initial stages and fundamental understanding for all disciplines, physics, materials science, device integration, etc. is of utmost importance. Focusing on any material to understand and establish growth processes should not be confused with ignoring the longer term objectives. Rather, focusing on a few materials for a few specific applications will help accelerate the development of other potential 2D materials. The guiding principle should be "what do we need for the applications?" rather than "what can we do with this material"? The mutual development of a materials roadmap to address the needs of specific applications was also discussed as an important area to develop and expand the current published graphene roadmap created by the Graphene Flagship. Further discussions will be required to address the collaboration efforts between the US and the EU.

[5] https://www.mri.psu.edu/mri/facilities-and-centers/2dlm

Common challenges

Benchmarking and standardisation of materials produced by different techniques (and suppliers) was identified as a real challenge which is important to solve as to advance towards the industrialisation of graphene and other 2D materials-based products and technologies. Collaboration would be very important as to set common and accepted standards across the Atlantic and even worldwide. Such standards should concern reporting of materials properties, synthesis, measurements, material parameters, etc. Ideally the outcome would be a standardized library of benchmarked materials complemented by the database of validated materials properties (possibly engaging the US Materials Genome Initiative).

Specifications and standards are therefore an area where there are real opportunities to foster collaboration between the Flagships' efforts in standardization and the US National Institute of Standards and Technology (NIST). For this activity, it is not only important to agree on what techniques can be/should be used for characterization but it was also felt that it is important to create materials specifications required to meet a specific application. As an example, when materials performance parameters such as carrier type, concentration and mobility are reported, the details of device test structures (e.g., channel thickness, substrate, capping and/or gate oxide layer, metal contacts) and processing conditions (annealing temperature, etching recipe etc.) must be reported in order to properly compare results. This is true for many other performance measurements.

Health and safety issues are universal and although norms and regulations are different in Europe and in the US, the impact of 2D materials on health and environment is a topic that would greatly benefit from common approaches and collaboration.

Complementarities

The presentations and discussions during the meeting have revealed the following complementarities between the EU and USA activities:

- Complementary 2D material (2DM) growth expertise and approaches are used by several groups. While some EU and many USA teams excel in chemical vapor deposition (CVD) growth of TMDs and phosphorene on various substrates, EU effort also covers growth of hBN and graphene/hBN heterostructures, in particular using molecular beam epitaxy (MBE) of both graphene and hBN.
- Complementary approaches to the development of optoelectronic devices based on graphene/hBN/TMD structures are used by US and EU groups, which offers an avenue for productive collaborations.
- EU teams run a wide program in developing graphene and 2DM inks, and using them for printable electronics. This effort can be enhanced by the work done in the US on 'repairing' the exfoliated 2DM in liquid suspensions which increases performance. This complements well characterisation capability for developing standardised characterisation of powders available in US to the larger extent than in Europe.
- EU teams attempt unique developments of various quantum technology devices based on graphene/hBN heterotructures and newly studied 2DM, such as InSe. On the US side, several groups are working on devices based on phosphorene and TMD alloys.
- Numerous overlapping activities have been identified in the studies of optical and transport characteristics of 2DM, where complementarity appears through the mutual validations of new surprising results. Examples include four Nature Nantoechnology papers published in 2015, on the observations of single-photon emitters in 2D TMDs. Such mutual validation is a necessary part of scientific progress and passing the knowledge onto the application stage, and exchange of information would greatly speed it up.

Opportunities

- Development of widely accessible database of properties of various 2DM, using the platform of the Institute of Physics (IoP) Journal '2D Materials'.
- Speedy development of printable circuits for sensing and detection, with the fast-track towards commercialisation.
- Development of standardised characterisation of graphene and other 2DM, for building users confidence in the materials supply chain.
- Development of growth methods for 2DM heterostructures suitable for the following top-down fabrication of devices, with easy materials transfer between EU and USA research groups.
- Based on the recent observations of single-photon emission in 2DM, to develop new materials base for the electrically excited and controlled single-photon emitters suitable for applications in quantum cryptography devices.

Collaboration mechanisms

Exchange programs

The new exchange grant scheme for researchers supported by the NSF[6] and the Graphene Flagship[7] was welcomed as a very good opportunity to enhance collaboration and provide opportunities for European and US researchers. Complementary funding (travel money) besides mobility grants to establish long time collaborations between EU-US would be helpful, as would be a larger size for the EU mobility grants. The next step could also be to provide opportunities for more extended stays (6 months to 1 year) and include senior researchers as well. The proposal to support joint postdocs was also put forward.

Next workshop and meetings

Participants agreed that the organisation of joint workshops is important to maintain and build new collaborations.

It was recommended that the next meeting should be more focused and possibly smaller in scale (about 50 participants) or with extended breakout sessions. Some identified topics and common areas of interest are:

- Graphene Single Crystal Growth
- Single-crystal Growth of h-BN
- Nucleation and (low temperature) growth of TMD materials

It was suggested that the next workshop would be organised again the US (East coast) during the second half of 2017.

Suggestions for joint activities

- Demonstrate devices using the latest best synthetic materials
- Foster collaboration between materials groups and device groups including by co-authoring of papers within EU and EU-US
- Perform side by side comparison of exfoliated and synthetic materials
- Create a Roadmap for a materials synthesis technique down selection
- Develop materials selection strategies, specifically for "compound layer materials"
- Identify 'new' technologies that are not available in the US or EU and create co-development projects.
- Identify gaps in our knowledge (e.g. define key integration challenges) and have a concerted action to solve those problems. Push promising ideas to applications (instead of jumping to new topics)
- Transfer technology to startup or existing industrial partners
- Bring together spin-off companies across the ocean for collaboration

[6] https://www.nsf.gov/pubs/2016/nsf16102/nsf16102.jsp
[7] http://graphene-flagship.eu/transatlantic-collaboration-creates-new-research-opportunities

- Setup lists of equipment suppliers working on industrial tools and when they will be available
- Create a collaborative platform for scaling up two dimensional materials in order to prevent unnecessary repetition of research on growth of those materials
- Create a website to find partners to collaborate on specific topics. Interested partners could list their expertise and mention on which topics they want to collaborate.
- Create databases for materials properties, device performance and simulations specific for 2D materials.

Follow-up outcomes and conclusions

A first mobility grant has been awarded by the Graphene Flagship for an exchange visit expected in early 2017 between RTWH Aachen University (Germany) and Harvard University (US) with the latter being the host. Another proposal for a postdoc visit from ICFO (Spain) to the University of Columbia (US) has been approved.

From the US side, there has been several inquiries regarding the Dear Colleague Letter (DCL, NSF16-102, July 12, 2016) and formal proposals in the form of supplement to existing EFRI grant are expected in the near future.

New collaborations and contacts have been established during the workshop and eligible PIs are encouraged to consider applying for mobility grants and EFRI supplements to the respective funding sources.

Program

Day 1 – October 10th	
08:30-09:20	**Registration**
09:20	**Opening Session** *Chair: James Hwang*
09:30-09:55	**Atomically thin semiconductors and heterostructures** *Tony Heinz*
09:55-10:20	**Dynamics of photons, plasmons and electrons in 2D materials** *Frank Koppens*
10:20-10:45	**From black phosphorus to phosphorene** *Peide Ye*
10:45-11:10	**2DM heterostructures for tunnelling and optoelectronic applications** *Konstantin Novoselov*
11:10-11:30	Coffee break
	Session: 2D materials for devices *Chair: Alan Seabaugh*
11:30-11:55	**hBN growth @ WP 'Enabling Material'** *Annick Loiseau*
11:55-12:20	**(Mo,W)Te2 alloys: phase diagram and phase engineering** *James Hone*
12:20-12:45	**Transition metal trichalcogenides** *Francois Peeters*
12:45-14:15	Lunch & NGI tours
	Open meeting of Flagship Division One 'Enabling Science and Materials' *Chair: Jonathan Coleman*
14:15-14:40	**Overview of WP 'Enabling Research'** *Vladimir Falko*
14:40-15:05	**Ab initio modelling of 2D materials** *Matteo Calandra*
15:05-15:30	**Surface and interface transport in devices based on semiconducting TMDs** *Alberto Morpurgo*
15:30-15:55	**InSe: From nano-sheets to vdW heterostructures** *Amalia Patane*
15:55-16:20	Coffee break
	Open Division One meeting – continued *Chair: Tim Wehling*
16:20-16:45	**Spintronics in Graphene Flagship** *Bart van Wees*
16:45-17:10	**Spin-orbit and exchange proximity effects in graphene** *Jaroslav Fabian*
17:10-17:35	**Controlling spin dynamics in graphene** *Stephan Roche*
17:35-18:00	**Graphene in heterostructures with metals: superconductivity and magnetism** *Irina Grigorieva*
18:00-19:30	**Reception and Poster Session I**

Day 2 – October 11th			
	Open Division One meeting – continued *Chair: Pertti Hakkonen*		
09:00-09:25	**Overview of WP 'Enabling Materials'** *Mar Garcia-Hernandez*		
09:25-09:50	**Update on TMD growth** *Andras Kis*		
09:50-10:15	**Large Scale synthesis of TMD films and heterostructure** *Georg Duesberg*		
10:15-10:40	**Strains and electrons in two dimensional materials** *Francisco Guinea*		
10:40-11:00	Coffee break		
11:00-12:30	**Session: General discussions of collaboration mechanisms within and beyond US/EU research programs** *Panel: Jari Kinaret, Dimitris Pavlidis, Chagaan Baatar, Jennifer Becker* *Chair: Wide Hogenhout*		
	BoS1: A-J **(F3 main meeting hall)** *Chairs: C.Coletti/T.Heinz*	**BoS2: K-R** **(F1 discussion area)** *Chair: F.Peeters*	**BoS3: S-Z** **(F2 discussion area + BR)** *Chair: C.Stampfer*
12:30-14:00	Lunch & NGI tours		
	Session: 2DM Synthesis and Production *Chair: Wlodek Strupinski*		
14:00-14:25	**Top-down and bottom-up synthesis of 2D TMDs and their device applications** *Anupama Kaul*		
14:25-14:50	**Epitaxial growth of 2D Chalcogenides** *Joan Redwing*		
14:50-15:15	**High-mobility graphene from chemical vapour deposition on reusable copper** *Christoph Stampfer*		
15:15-15:40	**The growth of strained graphene and hexagonal boron nitride by MBE** *Peter Beton*		
15:40-16:05	**2D Materials Production via Liquid Phase Processing** *Stephen Hodge*		
16:05-16:30	Coffee break		
	Session: Applications of 2DM & heterostructures *Chair: Andrey Turchanin*		
16:30-16:55	**Electrons, phonons, and unconventional applications of 2D materials** *Eric Pop*		
16:55-17:20	**Electronic and photoelectronic properties of hybrid vdW heterojunctions** *Lincoln Lauhon*		
17:20-17:45	**Heterojunctions of 2D materials and their potential applications** *Huili Grace Xing*		
17:45-18:10	**Black phosphorus optoelectronics and electronics** *Fengnian Xia*		
18:10-19:30	**Reception and Poster Session I**		

Day 3 – October 12th		
	Session: 2DM applications *Chair: Cinzia Casiraghi*	
09:00-09:25	**Update on Progress, Prospects and Challenges on Flexible 2D Electronics** *Deji Akinwande*	
09:25-09:50	**Electronic, Electrodynamic, and Optoelectronic Technology with vdW Heterojunctions** *Donhee Ham*	
09:50-10:15	**2D Materials Nanosculpting and Bioelectronics Applications** *Marija Drndic*	
10:15-10:30	Coffee break	
10:30-11:15	**BoS4** (F3 hall): **Materials creation strategies, supply & exchange including standards** *Chair: Luigi Colombo*	**BoS5** (Discussion area F1): **2DM devices applications & 2DM innovation and commercialization** *Chair: Chun-Yun Sung*
11:15-12:15	**Session: Reports from break-out sessions and general discussions** *Chair: Ana Helman*	
12:15-14:00	Lunch & NGI tours	
	Session: Optics of 2DM & heterostructures *Chair: Alexander Tartakovski*	
14:00-14:25	**Exchange Field Effects in vdW Ferromagnetic Semiconductor Heterostructures** *Xiaodong Xu*	
14:25-14:50	**Scalable synthesis of WS_2 on graphene and hBN: an all-2D platform for light-matter transduction** *Camilla Coletti*	
14:50-15:15	**Superconductivity in 2D materials and heterostructures** *Gary Steele*	
15:15-15:40	**Moiré superlattice modulation of optical and topological properties in heterobilayers of TMDs** *Wang Yao*	
15:40-16:05	**Optical properties of semiconducting TMDs: Observations and puzzles** *Marek Potemski*	
16:05-16:30	**Conclusions and end of the meeting**	

Abbreviations: vdW = van der Waals; TMD = transition metal dichalcogenides.

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Book of Abstracts

Invited talks

Progress, Prospects and Challenges on Flexible and Emerging 2D Devices

Prof. Deji Akinwande
The University of Texas - Austin, United States

Short biography:

Dr. Deji Akinwande received the PhD degree in Electrical Engineering from Stanford University in 2009.
He is now an Endowed Associate Professor at the University of Texas at Austin. Prof. Akinwande has been honored with the 2016 Presidential PECASE award, the IEEE “Early Career Award” in Nanotechnology, the NSF CAREER award, the Army and DTRA Young Investigator awards, the 3M Nontenured Faculty Award, and was a past recipient of fellowships from the Ford Foundation, Alfred P. Sloan Foundation, and Stanford DARE Initiative. His recent results on silicene have been featured by nature news, Time magazine and was selected among the top 2015 science stories by Discover magazine. His work on flexible 2D electronics was highlighted among the "best of 2012" by the nanotechweb news portal and has been featured on MIT's technology review and other technical media outlets. He is a distinguished lecturer of the IEEE Electron Device Society and an Editor for the IEEE Electron Device Letters. He co-authored a textbook on carbon nanotubes and graphene device physics by Cambridge University Press, 2011, and was recently a finalist for the Regents' Outstanding Teaching Award, the highest teaching award from the University of Texas System.

Abstract:

This talk will provide an update on progress on 2D flexible electronics, devices, circuits, and systems over the past few years including prototypical materials such as graphene, TMDs and phosphorene. Their prospects and major challenges will also be discussed towards the goal of manufacturable flexible integrated systems, which is a major objective of international research and development efforts. Flexible devices with strain performance up to 8% has been achieved in realistic transistor structures and cut-off frequencies as high as 100GHz are accessible on flex substrates at sub-um channel lengths. Radio receiver systems including wireless communication have been demonstrated using 2D materials on soft substrates. In addition, new directions in employing graphene and 2D materials for wearable and bio devices will be highlighted. This includes graphene as a multi-functional ex-vivo electronic tattoo and graphene for in-vivo brain recording.

The growth of strained graphene and hexagonal boron nitride by molecular beam epitaxy

Prof. Peter Beton
University of Nottingham, United Kingdom

Short biography:
Peter Beton joined the University of Nottingham in 1988 as a postdoc and, following a period as a Royal Society University Research Fellow, was appointed to the academic staff in 1994. Following a period when he investigated quantum phenomena in electrical transport observed in semiconductor nanostructures fabricated using electron beam lithography, he set up a new programme on scanning probe microscopy. His research interests now lie at the intersection between materials science, physics, chemistry and device technology and his recent work has been focussed on supramolecular templates, random tiling, two-dimensional covalent networks, the growth of graphene and 2D materials and the deposition of polymers and polymer nanorings on metal surfaces.

Abstract:
Graphene grown by high temperature molecular beam epitaxy on hexagonal boron nitride (hBN) forms continuous domains with dimensions of order 20 μm, and exhibits moiré patterns with large periodicities, up to ~30 nm, indicating that the layers are highly strained. Topological defects in the moiré patterns are observed and attributed to the relaxation of graphene islands which nucleate at different sites and subsequently coalesce. In addition, cracks are formed leading to strain relaxation, highly anisotropic strain fields, and abrupt boundaries between regions with different moiré periods. These cracks can also be formed by modification of the layers with a local probe resulting in the contraction and physical displacement of graphene layers. The Raman spectra of regions with a large moiré period reveal split and shifted G and 2D peaks confirming the presence of strain. We also demonstrate direct epitaxial growth of high-quality hexagonal boron nitride (hBN) layers on graphite using high-temperature plasma-assisted molecular beam epitaxy. Atomic force microscopy reveals mono- and few-layer island growth, while conducting atomic force microscopy shows that the grown hBN has a resistance which increases exponentially with the number of layers, and has electrical properties comparable to exfoliated hBN. X-ray photoelectron spectroscopy, Raman microscopy and spectroscopic ellipsometry confirm the formation of sp^2-bonded hBN and a band gap of 5.9 $\pm$ 0.1 eV with no chemical intermixing with graphite. We also observe hexagonal moiré patterns with a period of 15 nm, consistent with the alignment of the hBN lattice and the graphite substrate.

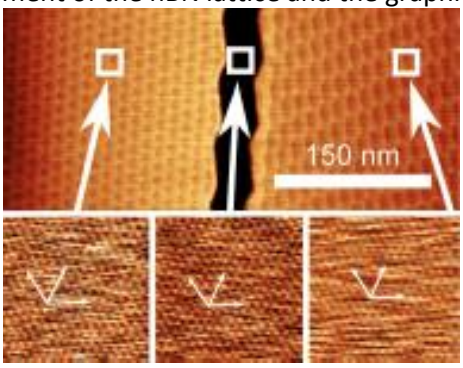

Figure: Moiré pattern formed by graphene grown by molecular beam epitaxy on boron nitride. Top AFM image shows a crack formed in monolayer graphene; on each side of crack graphene relaxes resulting in differences of local lattice constant and moiré period. The right side is anisotropically strained. Lower – contact mode images of regions on either side of the crack and of the BN surface within the crack. Lattices are aligned confirming epitaxial growth.

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Scalable synthesis of WS_2 on graphene and h-BN: an all-2D platform for light-matter transduction

Dr. Camilla Coletti
Center for Nanotechnology Innovation @ NEST, Istituto Italiano di Tecnologia, Italy

Short biography:

Camilla Coletti received her MS degree in electrical engineering from the University of Perugia (Italy) in 2004 and her PhD degree in electrical engineering from the University of South Florida (USA) in 2007. From 2008 to 2011 she was first a Max Planck postdoctoral fellow and then an Alexander von Humboldt postdoctoral fellow at the Max Planck Institute for Solid State Research of Stuttgart (Germany). From 2011 to 2016 she worked first as a postdoc and then as a researcher at the Center for Nanotechnology Innovation @ NEST in Pisa (Italy), where she personally set-up and developed a laboratory for the CVD synthesis and the characterization of graphene and other 2D materials. Since April 2016 Camilla Coletti is the Principal Investigator of the research line 2D Materials Engineering (TT1 Researcher) of the Istituto Italiano di Tecnologia (Pisa). She is the IIT responsible for the work-package Enabling Materials (WP3) of the European Flagship Project. Currently, her main research interest is the synthesis and study via surface science techniques of two-dimensional materials and heterostacks for optoelectronic applications. She is author of about 50 peer-reviewed publications, holds 2 international patent, authored 4 book chapters, and gave more than 30 invited/keynote talks.

Abstract:

By exhibiting a measurable bandgap and exotic valley physics, atomically-thick tungsten disulfide (WS_2) offers exciting prospects for optoelectronic applications. The synthesis of continuous WS_2 films on other two-dimensional (2D) materials would greatly facilitate the implementation of novel all-2D photoactive devices. During this talk the scalable growth of WS_2 on graphene and hexagonal boron nitride (h-BN) via a chemical vapor deposition (CVD) approach will be demonstrated. Detailed spectroscopic and microscopic analysis will be presented revealing that the synthesized films have an epitaxial relation to the substrate. In particular, angle resolved photoemission spectroscopy (ARPES) data for the heterostack WS_2/graphene will be discussed. Remarkable room temperature conservation of polarization – peaking at 74% for bilayer WS_2 films – will be reported[1]. Furthermore, a scalable bottom-up approach for the design of photoconductive and photoemitting patterns will be discussed.

[1] Rossi et al., *2D Mater*. 3, 031013 (2016)

2D Materials Nanosculpting and Bioelectronics Applications

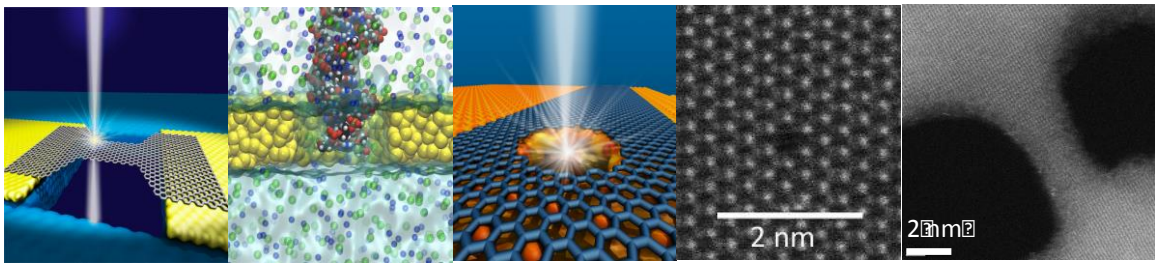
Prof. Marija Drndic
Department of Physics and Astronomy, University of Pennsylvania, United States

Short biography:

Marija Drndic is the Fay R. and Eugene L. Langberg Professor in the Department of Physics and Astronomy at the University of Pennsylvania and the faculty member of the MRSEC Center at Penn. She received her Masters from Cambridge University, PhD from Harvard University and was a Pappalardo Fellow at Massachusetts Institute of Technology, before joining Penn in 2003. Her work on nanocrystal electronics and nanofabrication has been recognized by the Presidential Young Investigator Award, the Alfred Sloan Fellowship, the DARPA Young Faculty Award, the ONR Young Investigator, and the NSF Career Award. In 2013 she was named the APS Fellow "for development of novel nanofabrication methods for graphene nanoelectronics and fast biomolecular analysis in solution". She also received several teaching awards, including the Edmund J. and Louise W. Kahn Award for Distinguished Teaching. The research in the Drndic lab focuses on the exploration of mesoscopic and nanoscale structures in the areas of experimental condensed matter physics, nanoscience and nanotechnology. The group is known for their studies of fundamental physical properties of low-dimensional and small-scale structures and the development of their device applications. Drndic lab has published a range of papers on new 2D materials including phosphorene and developed new biophysics-oriented approaches towards the detection and analysis of biomolecules using graphene and other nanopores, and *operando* transmission electron microscope experiments.

Abstract:

Graphene has been considered as one of the potential post Si-materials due to its high mobility [1].
Electron beams constitute powerful tools to shape materials with atomic resolution inside a transmission electron microscope (TEM). I will describe experiments where we push the limits of device size to atomic scale in 2D materials beyond graphene (MoS_2, WS_2, $MoTe_2$, black phosphorous) and expand their function and precision, while addressing fundamental questions about structure and properties at nanometer and atomic scales. Experiments are performed *in situ* and *ex situ TEM*. *In situ TEM* experiments include fabrication of nanoribbons and field-effect-transistors from novel two-dimensional materials down to sub-nm widths. *Ex situ TEM* experiments include the ultrafast, all-electronic detection and analysis of biomolecules by driving them through tiny holes – or nanopores – in thin membranes, including the efforts towards mapping a human genome under 10 min. As molecules are driven through nanopores in solution, they block the ion current flow resulting in current reductions from which molecule's physical and chemical properties are inferred. DNA, proteins, microRNA and other biomolecules can be analyzed. The temporal, spatial resolution and sensitivity in these experiments have been improved over the last few years thanks to advanced materials, device designs and new electronics.



From left to right: illustrations of nanoribbon sculpting with the electron beam; passage of a DNA molecule through a nanopore; illustration of nanopore drilling with an electron beam inside of the TEM; one-atom-large nanopore in a MoS_2 sheet; armchair phosphorene nanoribbon sculpted in the AC-TEM.

References:

Rodriguez-Manzo *et al*., ACS Nano 10 (4), 4004, 2016 & ACS Nano 9 (6), 6555, 2015; Qi *et al.,* ACS Nano 9(4), 3510, 2015; Balan *et al.*, Nano Letters 14 (12), 7215, 2015; Drndic, Nature Nanotechnology 9, 743, 2014; Qi *et al.*, Nano Letters 14 (8), 4238, 2014; Rosenstein *et al*., Nature Methods, 9 (5), 487, 2012.

Large Scale synthesis of TMD films and heterostructures

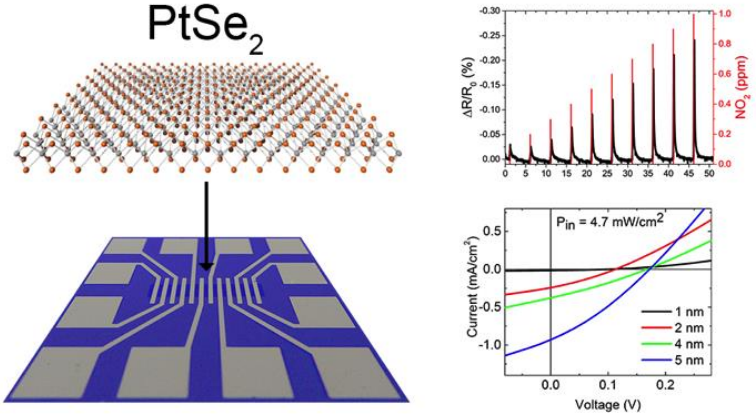
Prof. Georg Duesberg
Trinity College Dublin, Ireland

Short biography:

Prof. Georg Duesberg´s research focuses on making novel devices to exploit the unique properties of low-dimensional structures. For that functional materials are synthesized and integrated with state-of-the-art micro-processing techniques. The resulting hybrid devices aim towards the use in ICT, sensing and photonics as well as energy conversion and storage. Recently Professor Duesberg's team focuses on the synthesis and integration of novel 2D materials for electronic and photonic applications.
Prof. Georg S. Duesberg graduated in Physical Chemistry from the University of Kassel, Germany in 1996. He was researcher at the Max-Planck-Institute for Solid State Research, Stuttgart and Trinity College Dublin from 1997 – 2001 after which he received his PhD from the University of Tübingen in 2001. From 2001 – 2005 he worked at the Infineon AG, in the Corporate Research Department in Munich. From 2005 – 2007 Prof. Duesberg was in the Thin Films Department at Qimonda AG, Dresden. In 2007 Prof. Duesberg took on a position in the School of Chemistry of Trinity College Dublin and as a Principal Investigator in CRANN. He has co-authored more than 200 publications with more than 12000 citations (H-index 48) and has filed more than 25 patents.

Abstract:

Two-dimensional transition metal dichalcogenides (TMDs) have moved to the foreground of the research community owing to their unique properties, which make them of great interest for both fundamental studies and emerging applications. Thermally assisted conversion (TAC) of predeposited transition metal films and Chemical vapour deposition (CVD) show great promise for the scalable and industry-compatible synthesis of these materials [1].
In the presentation we outline the synthesis of an assortment of TMDs by TAC and CVD, and demonstrate their high-quality using an array of characterization techniques including Raman spectroscopy, X-ray photoelectron spectroscopy and transmission electron microscopy. In particular we introduce TMDs grown below 450°C allowing BEOL integration.
The potential of TMDs films for various applications in the realm of electronics will be discussed. It is possible to structure and electrically address the films yielding simple devices such as transistors, diodes and sensors. In this regards, the fabrication of high-performance gas sensors, with room temperature detection limits in the ppb range for NH_3 will be described in detail [2]. The fabrication of large-scale heterojunction diodes, formed by transferring n-type MoS_2 onto p-type Si, will be also described. [3,4]



[1] "Controlled Synthesis of Transition Metal Dichalcogenide Thin Films for Electronic Applications", Riley Gatensby, et al, Applied Surface Science, 297, 139-146, (2014)
[2] "High Performance Sensors Based on Molybdenum Disulfide Thin Films", Lee et al., Advanced Materials, 25(46), 6699-6702, (2013)
[3] "Heterojunction Hybrid Devices from Vapor Phase Grown MoS2", Yim et al., Scientific Reports, 4, 5458, (2014)

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Spin-orbit and exchange proximity effects in graphene

Prof. Jaroslav Fabian
University of Regensburg, Germany

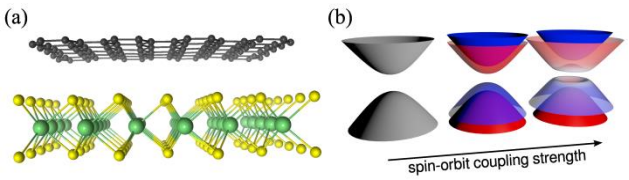
Short biography:

Jaroslav Fabian is a university professor at the University of Regensburg. JF studied mathematical physics (Master degree) at Comenius University Bratislava, and obtained his PhD in 1997 in theoretical solid state physics from the State University of New York (SUNY) in Stony Brook in 1997, under supervision of Prof. Philip Allen. JF was a postdoctoral research associate in the University of Maryland in College Park, with Prof. Sankar Das Sarma. In 2000 JF was a distinguished postdoctoral research fellow in the Max Planck Institute for Complex Systems in Dresden, and in 2001 he joined the faculty of the physics department of the Karl Franz University of Graz, as an assistant professor. In 2004 JF got his habilitation in Graz, and became associate professor. In 2004 JF accepted a call for a university professor in the University of Regensburg. Main research activities of Jaroslav Fabian are in theoretical spintronics, studying spin effects in conventional and novel materials.

Abstract:

Graphene has no orbital gap, only a small spin-orbital gap of about 20 micro eV. The energy levels of graphene are doubly degenerate, due to space inversion symmetry, demonstrating the absence of spin-orbit (Rashba) fields. Intrinsic graphene is diamagnetic, just like graphite. However, graphene is easily functionalized by adatoms, such as hydrogen, fluorine, or copper, that induce local magnetic moments, as well as giant spin-orbit couplings [1]. The induced magnetic moments yield ultrafast spin relaxation [2,3], while the giant spin-orbit couplings generate strong spin Hall signals. In addition to chemisorbed adatoms, spin and magnetic properties of graphene can be strongly influenced by substrates. Particularly interesting are substrates from two-dimensional semiconductors, such as transition-metal dichalcogenides (TMDCs), since the electronic structure of graphene/TMDC hybrids can be tuned by gating, and the direct gap of TMDCs allows optical spin orientation, and opens venues for optospintronics [4]. Furthermore, we have recently shown [5] that a zigzag graphene nanoribbon on WSe2 is a quantum spin Hall conductor (arising from the inverted Dirac band structure, see Fig. 1), with the spin-orbital gap of about 1 meV, and conducting helical edge states. This relatively large bulk gap gives hopes to observe the quantum spin Hall effect in graphene structures. In the talk I will also mention our most recent results on engineering the proximity exchange in graphene in tunnel junctions based on hBN, with ferromagnetic metals Co and Ni [6].

Fig. 1 a) Graphene on a monolayer transition-metal dichalcogenide. b) As the spin-orbit coupling increases (going from Mo to W-based TMDCs), the electronic band structure of graphene goes from normal to inverted, signalling the onset of the quantum spin Hall effect.



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4. M. Gmitra and J. Fabian, Phys. Rev. B 92, 155403 (2015)
5. M. Gmitra, D. Kochan, P. Högl, and J. Fabian, Phys. Rev. B B 93, 155104 (2016)
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Graphene in heterostructures with metals: superconductivity and magnetism

Prof. Irina Grigorieva
University of Manchester, United Kingdom

Short biography:

Irina Grigorieva is a Professor of Physics at the University of Manchester, UK, which she joined as a Lecturer (Assistant Professor) in 2001. She has received her PhD at the Institute of Solid State Physics (Chernogolovka, Russia) and then worked as a post-doctoral researcher at the Universities of Bristol (UK), Leuven (Belgium) and Nijmegen (Netherlands). Irina is an expert in mesoscopic physics and nanotechnology, having worked in several research fields, including mesoscopic superconductivity, physics, chemistry and technology of two-dimensional (atomically thin) crystals and their heterostructures and mass transport through atomically thin membranes and nanochannels. Most recent highlights of her research include demonstration of defect-induced magnetism in graphene and its control by molecular doping; understanding the factors governing formation of van der Waals heterostructures, including measurements of van der Waals pressure and understanding of its effect on confined materials; and superconductivity in two dimensions, including ultrathin superconductors, superconductivity in metal-coated graphene and in intercalated layered materials.

Abstract:

Combining graphene with other two-dimensional (2D) materials in heterostructures has opened up numerous possibilities for tailoring their properties, for example, enhancing spin-orbit interaction in graphene when in contact with a transition metal chalcogenide or opening a gap in graphene's electronic spectrum by placing it on insulating hexagonal boron nitride. In our recent experiments graphene was placed in contact with ferromagnetic films as part of a vertical structure analogous to magnetic tunnel junctions or was coated with a submonolayer of alkali/alkali-earth metal.

In the former case we found that, in contrast to theoretically predicted role of graphene as a perfect spin filter, graphene itself becomes weakly ferromagnetic due to proximity to a ferromagnet. Most interestingly and in contrast to expectations, the behaviour of a device is then determined by a combined effect of metal-induced doping and spin splitting in graphene, which in principle can be electrostatically controlled.

When coated with Ca metal graphene becomes a superconductor: In our experiments, we used so-called graphene laminates (thousands of non-interacting graphene crystallites arranged in a roughly layered structure) that were intercalated with different metals (K, Li, Cs, Ca). I will discuss the superconducting behaviour of Ca-coated graphene and its analogy with intercalated graphite.

Strains and electrons in two dimensional materials

Prof. Francisco Guinea
Imdea Nanoscience, Madrid, and University of Manchester, United Kingdom

Short biography:

Francisco Guinea is a Senior Researcher at Imdea Nanoscience, Madrid, and professor at the Department of Physics and Astronomy, University of Manchester, UK. He has worked at a number of other institutions, such as the Universidad Autónoma de Madrid, CSIC, Madrid, University of California, Santa Barbara, University of California, San Diego, University of Michigan, Boston University, and others.
Francisco Guinea is a theoretical condensed matter physicist. He has worked in topic such as superconductivity, strongly correlated systems, macroscopic quantum systems, statistical physics, mesoscopic devices, and others. In recent times he has focused on research in two dimensional materials, a field in which he has been active since its beginnings. He has developed theoretical models for the understanding many of the unique properties of graphene and other materials.

Abstract:

Graphene and other two dimensional materials are extremely thin membranes. As such, they display an extreme anharmonicity, and their elastic properties are influenced by temperature, and other external factors. The way in which these effects are manifested in different setups will be reviewed [1,2].
Strains also modify the electronic structure. In semiconducting two dimensional materials, strains modify the ga, and can lead to the confinement of charge carriers and excitons, and to a local modification of the spin-orbit coupling [3-5].

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[2] E. Khestanova, F. Guinea, L. Fumagalli, A. K. Geim, I. V. Grigorieva, Graphene bubbles on a substrate: universal shape and van der Waals pressure, Nature Comm. 7, 12587 (2016).
[3] A. Castellanos-Gómez, R. Roldán, E. Cappelluti, M. Buscema, F. Guinea, H. S. J. van der Zant, G. A. Steele, ***Local strain engineering in atomically thin MoS_2***, Nano Letters **13**, 5361 (2013).
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Electronic, electro-kinetic, and optoelectronic applications of 2D material heterostructures

Prof. Donhee Ham
Harvard University, United States

Short biography:

Donhee Ham is Gordon McKay Professor of Applied Physics and EE at Harvard University, where he has been since 2002. He earned a B.S. degree in physics from Seoul National University in 1996. Following a 1.5-year military service in the Korea Army, he went to Caltech for graduate training in physics. There he worked in LIGO under Professor Barry Barish while in physics, and later obtained a Ph.D. in EE in 2002 winning the Charles Wilts Prize awarded for the best thesis in EE for his work on the statistical physics of electrical circuits. In 2008 he was recognized by MIT Technology Review as among the world's top 35 young innovators (TR35) for his work on nuclear magnetic resonance with semiconductor chips. He was a Harvard Yearbook Favorite Professor 4 years (2011-2014) and served as an IEEE Distinguished Lecturer for the Solid-State Circuits Society (2012-2013). He served in several IEEE conference technical program committees and is an associate editor for IEEE Transactions on Biomedical Circuits and Systems.
For the full bio, see: http://ham.seas.harvard.edu/drupal/?q=donhee_ham

Abstract:

Monolayer transition metal dichalcogenides (TMDCs) are emerging as promising new semiconductor materials for electronic and optoelectronic applications. Importantly, it is feasible to stack multiple atomically thin TMDC crystals of different chemical compositions to produce a wealth of electronic, electro-kinetic (plasmonic), and optoelectronic behaviours. Such heterogeneously layered 2D material systems can open up new exciting opportunities difficult with the standard work based on bulk semiconductors. Their combination with graphene can further broaden the functional diversities. Representing a number of faculty of the Harvard NSF 2DARE research team researching on 2D materials science and technology, I will discuss our recent results as well as on-going efforts on TMDC, graphene, and their heterostructures. They will include junction optoelectronic sensors and emitters, tunnelling devices, injection based active devices, and plasmonic devices that utilize ultra-subwavelength confinement and hydrodynamic behaviours.

Advanced printing and applications of 2d material-based inks

Dr. Stephen Hodge
Cambridge Graphene Centre, University of Cambridge, United Kingdom

Short biography:

Dr Stephen Hodge is a Research Associate in the Cambridge Graphene Centre at the University of Cambridge. He has particular interests in the chemistry and physics of nanomaterials including fullerenes, carbon nanotubes, graphene and the many other two-dimensional analogues. His PhD at Imperial College London focussed on the electrochemical processing of these materials; within the University of Cambridge, the current focus is on the scalable production of these enabling materials for mechanical, optical and electronic applications. Stephen currently holds a fellowship position at Murray Edwards College and is a Teaching Fellow for the EPSRC Centre for Doctoral Training in Graphene Technology**.**

Abstract:

Functional inks and pastes is a large market sector with a huge growth potential for the next decade [1]. Conductive inks, for example, are currently dominated by silver materials due to its high conductivity [2], however, for mass produced flexible electronic devices, silver inks are not an ideal choice since they impart high device cost [3] and can have negative environmental impact if not disposed properly [4]. Graphene and related material (GRM) based inks are a promising solution to these issues; providing multiple functions including mixed electronic (conducting, insulating, semi-conducting), mechanical and thermal properties.
Specific applications requiring highly tuned properties including print resolution, film thickness, conductivity and mechanical performance, for example, have led us to develop an array of GRM inks (graphene, hBN and MoS2) produced using a high shear turbulent flow microfluidic processor and formulated using various polymeric rheology modifiers. Ink viscosity is tuned over the range of 1 – 1800 cP, so that printing methods from inkjet printing and spray coating to roll-to-roll flexographic and screen printing can be achieved.
Printing is typically performed on cheap, flexible paper or plastic (PET, PEN) substrates, paving the way for a huge range of commercial applications. In the current context, I will discuss realistic pathways to commercialization of GRM inks and demonstrate prototypes such as electrodes, strain sensors, gas sensors, photodetectors, biofilms or catalyst supports in (bio)fuel cells using single GRM inks, or multiple inks as a route towards fully printed heterostructures.

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(Mo,W)Te_2 alloys: phase diagram and phase engineering

Prof. James Hone
Columbia University, United States

Short biography:

James Hone is the Wang Fong-Jen Professor of Mechanical Engineering at Columbia University, and Director of Columbia's Materials Research Science and Engineering Center (MRSEC). Prof. Hone received his PhD in experimental condensed matter physics from UC Berkeley in 1998, and did postdoctoral work at the University of Pennsylvania and Caltech, where he was a Millikan Fellow. He joined the Columbia faculty in 2003.

Abstract:

The 2D tellurides have generated recent interest due to phase transitions between semiconducting and semi-metallic phases, as well as due to the novel properties of the semimetallic phases such as potential Weyl physics. Since pure MoTe2 is stable in the semiconducting phase and WTe2 in the semi-metallic phase, alloys of the two compounds should allow tuning of the barrier to phase transition between the two by external perturbations such as strain, temperature, and electric field. However, the nature of this phase boundary is still not well characterized experimentally. This talk will review recent collaborative work to synthesize and characterize Mo1-xWxTe2 alloys, which establishes the phase diagram of this material and sets the foundation for applications. In addition to this work, a brief overview of broad efforts in 2D materials within the Columbia Materials Research Science and Engineering Center (MRSEC) will be presented.

Top-down and Bottom-up Synthesis of 2D Transition Metal Sulphides and Selenides and their Device Applications

Prof. Anupama Kaul
University of Texas, El Paso, United States

Short biography:

Professor Anupama B. Kaul is The Associate Dean for Research and Graduate Studies in the College of Engineering and an AT&T Distinguished Professor in the Department of Electrical and Computer Engineering at the University of Texas, El Paso (UTEP). Shortly upon her arrival to UTEP in the Fall of 2014, she founded and now serves as Director of the Nanomaterials and Devices Laboratory (NDL) (http://utep.edu/kaulgroup), which is composed of three sub-labs: 1) Electronics and Opto-electronics Materials and Device Characterization Lab; 2) Materials Synthesis and Characterization Lab; and 3) Composites and Bio-materials Processing Lab. In 2015, Prof. Kaul obtained close to $2 Million in research funding as a PI and/or Co-PI from externally sponsored grants. Prior to UTEP, Prof. Kaul served as a Program Director at the National Science Foundation (NSF) in the Engineering Directorate from 2011-2014, where she was on rotation as an IPA from the Jet Propulsion Laboratory (JPL), California Institute of Technology (Caltech) where she spent a total of 12 years. Dr. Kaul obtained her M.S. and Ph.D. degrees from the University of California, Berkeley in Materials Science and Engineering with minors in Electrical Engineering and Physics, while her B.S. degrees (with Honors) were in Physics and Engineering Physics. Dr. Kaul is the recipient of the National Science Foundation's Director's Award for Program Management Excellence, one of only two received by the Engineering Directorate in 2013. At JPL-Caltech, Dr. Kaul received the NASA Service Award, a NASA Team Accomplishment Award, multiple NASA Patent Awards and numerous NASA Technology Brief Awards for her research. Dr. Kaul was selected to be a participant at the US National Academy of Engineering (NAE) 2012 Frontiers of Engineering (FOE) Symposium and in 2014 she was invited to participate in the bi-lateral Indo-US FOE. She has given more than 60 invited and keynote talks at major international conferences and meetings sponsored by professional societies such as the IEEE, SPIE, MRS, TMS, and NSTI, among others. She is currently the Associate Editor of the *IEEE Sensors Journal*, International Advisory Panel Member of the *Materials Xpress Journal* for the Institute of Physics, American Editor of *Nanoscience and Nanotechnology Letters*, Associate Editor of *Reviews in Advanced Sciences and Engineering* and serves on the Editorial Board of several other journals. Dr. Kaul is also the Editor of *Microelectronics to Nanoelectronics: Materials, Devices and Manufacturability*, that was published by CRC Press.

Abstract:

Two-dimensional (2D) layered nanomaterials such as graphene and transition-metal dichalcogenides (TMDCs) have attracted tremendous attention over recent years due to their unique properties and potential for numerous applications. Here we present our work on both bottom-up and top-down synthesis of TMDCs for device applications. For bottom-up synthesis we describe our efforts on solution-based chemical exfoliation of graphene, molybdenum disulphide (MoS_2) and tungsten disulphide (WS2) and explore some of their heterostructures that have been formed using ink-jet printing. Solution-based approaches were also used for the realization of composite structures formed with hybrid organic-inorganic materials for strain-based sensing devices. For bottom-up synthesis, we will discuss our efforts in the CVD synthesis of MoS_2 and WSe_2. To characterize our materials we have adopted Raman, photoluminescence, AFM, SEM, along with several other techniques. In the device characterization work, we present results on the photo-response obtained with some of these TMDC materials using a broad-band white light source over a range of temperatures.

Update on TMD Growth in the Graphene Flagship

Prof. Andreas Kis
Ecole Polytechnique Federale de Lausanne (EPFL), Switzerland

Short biography:

Academic Positions

Associate Professor, Institute of Electrical Engineering, EPFL, 2015-
Tenure Track Assistant Professor, Institute of Electrical Engineering, EPFL, 2008-2015
Postdoctoral Research Associate, Zettl Research Group, University of California, Berkeley, 2004-2007
PhD Student, Forro Research Group, EPFL, 2000-2003

Education

PhD, Physics, EPFL, 2003
MS, Physics, University of Zagreb, Croatia, 1999
Baccalaureate, MIOC High School, Zagreb, Croatia 1994

Awards/Achievements

ERC Consolidator Grant (2 Mill. Eur), 2016
ERC Starting Grant (1.8 Mill. Eur), 2009
Latsis Foundation University Prize (25000 CHF), 2004
Fellowship of the Swiss National Science Foundation, 2003
Scholarship of the University of Zagreb, 1997
Rector's award for the best student work in the academic year 1996/97 for the best student paper "Application of hierarchical models on the thermal relaxation in SDW systems", 1997
Participation on the 25th International Physics Olympiad in Beijing, 1994

Abstract:

The first part of this presentation will give an overview of lab-scale efforts in the growth of TMDC materials throughout the WP3 enabling materials, including recent results on the direct growth of MoS2 and WS2 on graphene substrates, synthesis of PtSe2 and MBE growth of MoSe2. In the second part, I will present new optoelectronic devices based on the valley degree of freedom in semiconducting monolayer TMDCs which demonstrate spin injection and transport inside a TMDC monolayer.

Dynamics of photons, plasmons and electrons in 2d materials

Dr. Frank Koppens
The Institute of Photonic Sciences (ICFO), Spain

Short biography:

Prof. Frank Koppens obtained his PhD in experimental physics at Delft University, at the Kavli Institute of Nanoscience, The Netherlands. After a postdoctoral fellowship at Harvard University, since August 2010, Koppens is a group leader at the Institute of Photonic Sciences (ICFO). He has received the Christiaan Hugyensprijs 2012, the Premis Nacional de Reserca, the IUPAP young scientist prize in optics, the ERC award as well as two ERC proof-of-concept awards. Prof. Koppens is leader of the optoelectronics workpackage of the graphene flagship (1B€ project for 10 years).

The quantum nano-optoelectronics group of Prof. Koppens focuses on both science and technology of novel two-dimensional materials. Extraordinary interactions between light and matter are being investigated, and probed at ultra-fast timescales and nano-scale length scales. The group also develops devices with applications for wearables, sensing, photodetection, infrared imaging, power conversion and nano-scale light processing and switching.

In total, Koppens has published more than 40 refereed papers (H-index 31), amongst which Nature (2x), Science (3x), Nature Physics (5x), Nature Photonics, Nature Materials, Nature Nanotech. (5x), Phys.Rev.Lett. (8x) and NanoLetters (6x). Total number of citations >8800.

Weblink: Graphene.icfo.eu

Abstract:

The optoelectronic response of two-dimensional (2D) crystals, such as graphene and transition metal dichalcogenides (TMDs), is currently subject to intensive investigations. Owing to its gapless character, extraordinary nano-photonic properties and ultrafast carrier dynamics, graphene is a promising material for quantum nano-optoelectronics. Vertically assembling graphene with TMDs in so-called van der Waals heterostructures allows the creation of novel and versatile quantum and nano-optoelectronic devices that combine the complementary properties of their constituent materials.

Here we present a various new device capabilities, varying from quantum nano-photonic devices to ultra-fast and broadband electrical detectors. We applied femtosecond time-resolved photocurrent measurements on 2d material heterostructures, which reveals the charge dynamics across TMD and graphene layers directly in the time domain [2,3]. In addition, we apply for the first time infrared photocurrent nanoscopy to high-quality graphene devices [4]. Using this technique, we image the plasmon-voltage conversion in real space, where a single graphene sheet serves simultaneously as the plasmonic medium and detector [5,6]. In addition, nano-structured sandwiches of graphene with boron nitride have resulted in high quality plasmonic systems for infrared light [7,8].

Finally, we present nanoscale electro-mechanical control of optical emitters using suspended graphene drums [9].

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[2] Picosecond photoresponse in van der Waals heterostructures, M. Massicotte et al., Nature Nanotechnology 11 (2016)

[3] Photo-thermionic effect in vertical graphene heterostructures, Mathieu Massicotte, Peter Schmidt, FabienVialla, Kenji Watanabe, Takashi Taniguchi, Klaas-Jan Tielrooij, Frank H.L. Koppens. Nature Communications (2016)

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Chemical and Functional Imaging of 2D Materials and Mixed Dimensional Heterojunctions

Prof. Lincoln Lauhon
Department of Material Science and Engineering, Northwestern University, United States

Short biography:

Lincoln J. Lauhon is Professor and Associate Chair in the Department of Materials Science and Engineering at Northwestern University. He received a Ph.D. in Physics from Cornell with Wilson Ho (2000) and a B.S. in Physics from the University of Michigan (1993). Prior to joining Northwestern in 2003, he was a postdoctoral researcher in the Department of Chemistry and Chemical Biology at Harvard University with Charles Lieber. At Harvard, Dr. Lauhon developed new methods for synthesizing novel semiconductor nanowire heterostructures and built unique nanoscale devices enabled by advances in synthesis. At Northwestern, the Lauhon group has pioneered the application of atom probe tomography to map the composition of semiconductor nanostructures in three dimensions with single atom sensitivity and sub-nm resolution. The group also develops new methods for investigating the electronic properties of materials on the nanoscale by combining electronic transport measurements with scanned probe microscopy and device simulations. Both the chemical and functional imaging methods have recently been extended to 2-D materials. By developing new approaches to the integrated analysis of nanostructure composition and properties, the Lauhon group aims to provide a basis for engineering new materials with extraordinary electronic, optical, and magnetic properties.

Abstract:

Low-dimensional materials enable the creation of new classes of devices with novel functionality arising from their geometries (e.g. 1-D nanowire core-shell heterostructures) and unique materials combinations (e.g. 2-D van de Waals heterostructures). However, there remain significant gaps in understanding of the the origins of device behaviors. While 2-D materials beyond graphene are becoming “clean” enough to explore mesoscopic transport phenomena, the influence of dopants and defects on the intrinsic properties of 2-D materials is just beginning to be explored. In nanoscale heterojunction devices, extrinsic influences are very strong due to the extreme thinness. We will describe correlated characterization of nanoscale structure and properties to understand intrinsic and extrinsic influences on the properties of heterojunctions in the low dimensional limit. A change in thickness of only a monolayer, for example, has a profound influence on the behavior of 2-D heterojunctions, presenting the significant challenge of connecting atomic scale electronic structure to microscale device behavior. We also find that point defects have sometimes counterintuitive influences on electronic properties, and that combinations of point and line defects can be exploited to produce a new class of device that might be used for neuromorphic computing. Finally, the extreme thinness enables access to new regimes of coupling between different degrees of freedom. Beyond isolated 2-D materials, the concept of van der Waals heterojunctions encompasses not just 2-D/2-D interfaces, but also junctions between 2-D materials and other electronic materials such as organic semiconductors and carbon nanotubes. The physical and electronic structure of these novel junctions provides manifold opportunities to realize qualitatively distinct device behaviors, such as anti-ambipolarity, but the complex interplay of quantum and electrostatic effects presents challenges to understanding. A collaboration between Northwestern University and Purdue University supported by the NSF EFRI program is investigating the electronic and photoelectronic properties of these van der Waals heterojunctions through a combination of scanning probe measurements, large-scale device fabrication and characterization, and modeling bridging atomic and microscopic length scales. We will describe recent results on lateral and vertical heterojunctions formed from MoS2, black phosphorous, pentacene, and semiconducting carbon nanotubes.

Surface and interface transport in devices based on semiconducting transition dichalcogenides

Prof. Alberto Morpurgo
University of Geneva, Switzerland

Short biography:

Prof. Morpurgo is an expert on nano-electronics of new materials. He received his PhD from the University of Groningen in 1998. After a two-year postdoc at Stanford working mainly on carbon nanotubes he moved to Delft University in the Netherlands where he became associate professor and stayed until 2008. There he worked on organic semiconductors, spin-orbit interaction in 2 dimensional electron gases, mesoscopic superconductivity, carbon nanotubes, and graphene. Since September 2008, Alberto Morpurgo is full professor at the University of Geneva, where he has broadened the scope of materials and electronic systems of interest further, to include topological insulators and a variety of new 2D materials.

Abstract:

I will discuss transport experiments at gated surfaces of transition metal dichalcogenides (TMDs) and at interfaces between these materials and graphene. In view of the limited time I will focus on two topics. The first is the use of ambipolar ionic liquid gated devices to measure the band-gap gap of semiconducting TMDs, which we have seen to give precise quantitative values in all cases in all materials investigated. The second is the investigation of spin orbit interaction induced in graphene on TMD substrates. Our most recent results allow to identify both the strength and the type of induced spin-orbit interaction. We found that the spin-orbit in graphene has a magnitude of approximately 10 meV (1000 time larger than the intrinsic spin orbit interaction) and is of the Rashba type. This extremely large increase in spin-orbit strength is achieved while maintaining a very high quality of the graphene properties, with electron mobility values as high as 200.000 cm^2/Vs at low temperature.

Heterostructures for tunnelling and optoelectronic applications

Prof. Sir. Konstantin Novoselov
University of Manchester, United Kingdom

Short biography:

Prof Sir Konstantin 'Kostya' Novoselov FRS was born in Russia in August 1974. He has both British and Russian citizenship. He is best known for isolating graphene at The University of Manchester in 2004, and is an expert in condensed matter physics, mesoscopic physics and nanotechnology. He was awarded the Nobel Prize for Physics in 2010 for his achievements with graphene. Kostya holds positions of Langworthy Professor of Physics and the Royal Society Research Professor at The University of Manchester.

He graduated from the Moscow Institute of Physics and Technology, and undertook his PhD studies at the University of Nijmegen in the Netherlands before moving to The University of Manchester in 2001. Professor Novoselov has published more than 250 peer-reviewed research papers. He was awarded with numerous prizes, including Nicholas Kurti Prize (2007), International Union of Pure and Applied Science Prize (2008), MIT Technology Review young innovator (2008), Europhysics Prize (2008), Bragg Lecture Prize from the Union of Crystallography (2011), the Kohn Award Lecture (2012), Leverhulme Medal from the Royal Society (2013), Onsager medal (2014), Carbon medal (2016) among many others. He was knighted in the 2012 New Year Honours.

Abstract:

The advent of graphene and related 2D materials has recently led to a new technology: heterostructures based on these atomically thin crystals. The paradigm proved itself extremely versatile and led to rapid demonstration of tunnelling diodes with negative differential resistance, tunnelling transistors, photovoltaic devices, etc. By taking the complexity and functionality of such van der Waals heterostructures to the next level we introduce quantum wells engineered with one atomic plane precision. Light emission from such quantum wells, quantum dots and polaritonic effects will be discussed.

Indium Selenide: From nanosheets to van der Waals heterostructures

Prof. Amalia Patanè
The University of Nottingham, School of Physics and Astronomy, United Kingdom

Short biography:

Prof. Amalia Patanè studied at the University of Rome "La Sapienza" where she graduated with first-class honours in Physics in 1994 and obtained a PhD in 1998. She has worked as an EPSRC Research Associate (1998-2002) in the School of Physics and Astronomy of the University of Nottingham, where she conducted the first imaging study by magneto-tunnelling of electrons confined in a nanocrystal (*Science* 2000). As a lecturer at Nottingham (2002-06), she has developed further her research on quantum systems by exploring novel carrier dynamics at high magnetic fields (*Nature* 2004). She was promoted Reader in 2006 and Professor of Physics in 2011. Since 1995, she has published over 200 research articles. Her most recent research focuses on quantum systems (*Nano Letters* 2016), including van der Waals crystals and heterostructures (*2D Materials* 2016, *Adv. Materials* 2015, *Nature Physics* 2015). Currently, she leads an EPSRC-funded project on "Two dimensional III-VI semiconductors and graphene-hybrid heterostructures" (2014-18) and the involvement of Nottingham in EU projects, including the EU Graphene Flagship (http://graphene-flagship.eu/) and the Initial Training Network PROMIS (http://www.physics.lancs.ac.uk/promis/). She also coordinates the UK Membership of the European Magnetic Field Laboratory (EMFL, http://www.emfl.eu/home.html), a mid-range facility funded by the EPSRC for research on technologically and fundamentally important materials (https://www.epsrc.ac.uk/research/facilities/access/currentmidrangefacilities/). Her research has been recognised through the Sir Charles Vernon Boys Institute of Physics Medal and Prize in 2007, an EPSRC Advanced Research Fellowship (2004-09), and her roles as Chair of the EMFL User Committee (2013-16), and Member of the EMFL Council (2015-to date) and of The International Union of Pure and Applied Physics Commission (IUPAP, C8: Semiconductor Commission, 2014-to date).

Abstract:

Van der Waals (vdW) two-dimensional (2D) crystals and heterostructures have electronic and optical properties that vary with the composition, thickness, and stacking of the component crystalline layers. To date, a wide variety of vdW crystals have been investigated, including transition metal dichalcogenides (TMDCs), black phosphorus (bP), and hexagonal boron nitride (hBN), and exploited as single crystals or in combination with graphene to create new functional devices.

This talk will present recent research at Nottingham on a new class of exfoliable and stable 2D layered compounds based on indium selenide vdW crystals, *e.g.* InSe and In_2Se_3, and their different polytype phases, *e.g.* α, β, γ, [1-5]. These crystals possess physical properties of fundamental and technological interest. Their chemical stability in air, high electron mobility (> 0.1 $m^2V^{-1}s^{-1}$ at 300K), tunability of the optical spectrum from the near-infrared (NIR) to the visible spectrum, and wide range of combinations with other vdW crystals, including graphene and hBN, have the potential for these compounds to impact several future technologies, ranging from sensitive NIR photodetectors and large-scale image sensors to high-mobility FETs. From fundamental studies of their unique electronic band structure to the growth and fabrication of prototype devices, this talk will discuss how these layers can provide a platform for scientific investigations and new routes to 2D electronics and optoelectronics.

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Transition Metal Trichalcogenides

Prof. François Peeters
Universiteit Antwerpen, Departement Fysica, Belgium

Short biography:

François M. Peeters received the PhD degree in physics from the University of Antwerp in 1982. He did postdoctoral research at Bell Laboratory (Murray Hill, NJ, USA) and Bell Communications Research (Red Bank, NJ, USA). He was appointed full professor at the University of Antwerp in 2000.
His areas of interests are computational modelling of mesoscopic and nanoscopic semiconductor and superconducting nanostructures, like phase transitions (structural and melting), artificial atoms (quantum dots and coupled quantum dots), graphene and other two dimensional atomic layered systems.
Peeters is a Fellow of the American Physical Society and the European Physical Society. He is a member of the Royal Flemish Academy of Belgium and of the Academia Europaea. The University of Szeged awarded him a Doctor Honoris Causa and in 2013 he was awarded the Francqui Chair. He is associate editor of Journal of Applied Physics, co-editor of Europhysics Letters and member of the excecutive editorial board of Solid State Communications. He published over 1000 papers with more than 25,000 citations and h-index 72.

Abstract:

Transition metal trichalcogenides (TMTCs) is a member of layered materials with strong in-plane anisotropy. For example, TiS_3 whiskers are made out of weakly interacting TiS_3 layers, where each layer is made of weakly interacting quasi-1D chains extending along the *b*-axis. The unusual vibrational properties of TiS_3 will be discussed. Unlike other 2D systems, the Raman active peaks have only out-of-plane vibrational mode character, and interestingly some of these lattice vibrations involve unique rigid 1D chain vibrations and S-S molecular oscillations. Various vibrational modes are doubly degenerate in ambient but the degeneracy is lifted at high pressures.
The optical properties of another TMTC, ZrS_3 will be discussed. We found that the optical properties of few-layers ZrS3 are highly anisotropic as evidenced by large PL intensity variation with polarization direction. Light is efficiently absorbed when E-field is polarized along the chain (*b*-axis), but the field is greatly attenuated and absorption is reduced when field is polarized vertical to the 1D-like chains as wavelength of the exciting light is much longer than the width of each 1D chain. Observed PL variation with polarization is similar to that in conventional 1D materials, i.e., nanowires, and nanotubes, except for the fact that here the 1D chains interact with each other giving rise to unique linear dichroism response that falls between 2D (planar) and 1D (chain) limit.

Electrons, Phonons, and Unconventional Applications of 2D Materials

Prof. Eric Pop
Stanford University, Electrical Engineering, United States

Short biography:

Eric Pop (epop@stanford.edu) is an Associate Professor of Electrical Engineering (EE) and Materials Science & Engineering (MSE) at Stanford University, where he leads the SystemX Heterogeneous Integration Focus Area. He was previously on the faculty of the University of Illinois Urbana-Champaign (2007-13) and also worked at Intel (2005-07). His research interests are at the intersection of electronics, nanomaterials, and energy. He received his PhD in EE from Stanford (2005) and three degrees from MIT (MEng and BS in EE, BS in Physics). His awards include the 2010 PECASE from the White House, the highest honour given by the US government to early-career scientists and engineers. He is also a recipient of the ONR Young Investigator Award, the NSF CAREER Award, the AFOSR Young Investigator Award, the DARPA Young Faculty Award, and of several best paper/poster and teaching/advising awards. He is an IEEE Senior member, he served as the General Chair of the Device Research Conference (DRC), and on program committees of the VLSI, IRPS, MRS, IEDM, and APS conferences. In a past life, he was a DJ at KZSU 90.1 FM from 2001-04. Additional information about the Pop Lab is available online at http://poplab.stanford.edu.

Abstract:

2D materials have unusual and anisotropic electrical and thermal properties. This talk will present recent highlights from our research on graphene, BN, and transition metal dichalcogenides (TMDs).
We have studied graphene from basic transport measurements and simulations, to the recent wafer-scale demonstration of analog dot product nanofunctions for neural networks [1]. We are also growing and evaluating the electrical and thermal properties of TMDs including MoS_2, $HfSe_2$, and WTe_2 [2,3]. Recent results include low-field resistivity and contact resistance [4], and high-field transport including velocity saturation. We have also examined the anisotropic thermal conductivity of these materials, for unconventional applications to thermal switches and thermal routing. If time permits, I will discuss “bottom up” thermal management starting at dimensions comparable to the electron and phonon mean free paths (~100 nm), where quasi-ballistic heat flow effects dominate [5,6].
Our studies reveal fundamental limits and new applications that could be achieved through the co-design and heterogeneous integration of 2D nanomaterials.

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Optical properties of semiconducting transition metal dichalcogenides: Observations and puzzles

Prof. Marek Potemski
Laboratoire National des Champs Magnétiques Intenses, CNRS-UGA-UPS-INSA-EMFL, France

Short biography:

Marek Potemski is a research director at the French Centre National de la Recherche Scientifique (CNRS), and a leader of the "semiconductors and nanophysics" group at the Grenoble site of the French National High Magnetic Field Laboratory (LNCMI). Potemski received a BS degree from the University in Warsaw, a PhD degree in physics from the Polish Academy of Sciences (PAS), and a habilitation diploma from the Joseph Fourier University of Grenoble.
Subsequently at the Institute of Physics of PAS, Hochfeld-Magnetlabor of the Max Planck Institut für Festkörperforschung, and the CNRS-LNCMI, Potemski has been also a visiting researcher/professor while on sabbaticals at the National Research Council of Canada in Ottawa, the Autonomous University of Madrid and the Faculty of Physics of the University of Warsaw.
He is a member of the Academia Europaea, a co-editor of the Europhysics Letters, has received the NRC-Canada Herzberg prize and holds now the ERC Advanced Research Grant.
Investigations of electronic properties of two-dimensional and nano-structured systems, including the conventional semiconductor, sp2-bonded carbon and new 2D material structures, are the most representative axis of his research activity, particularly in the context of optical studies and applications of high magnetic fields.

Abstract:

Atomically-thin layers of semiconducting transitions metal dichalcogenides (S-TMDs) represent a new class of two-dimensional systems which are interesting from the viewpoint of their fundamental electronic properties (unusual band structure, unconventional excitons, valley selective circular polarization of optical transitions) and possible optoelectronic applications (light emitting- and photo-diodes).
The summary of our recent works [1-6] on mono- and multi-layers of WSe_2-, $MoSe_2$-, and WS_2-compounds will be presented. Optical response of these two-dimensional systems will be discussed in dependence of a number of layers, as a function of temperature and in presence of applied magnetic fields. Considerable emphases will be focused on striking effects and unresolved problems which we met in our studies of S-TMD layers, and which will be discussed in the context of the apparent experimental data and related theoretical concepts.

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Epitaxial growth of 2D chalcogenides

Prof. Joan Redwing
Penn State University, United States

Short biography:

Joan M. Redwing received her Ph.D. in Chemical Engineering from the University of Wisconsin-Madison and joined the faculty of the Department of Materials Science and Engineering at Penn State University in 1999. She holds joint appointments in Electrical Engineering and Chemical Engineering. Her research focuses on understanding fundamental mechanisms of crystal growth and epitaxy of electronic materials, with a particular emphasis on thin film and nanomaterial synthesis by chemical vapor deposition. Dr. Redwing currently serves as director of the 2D Crystal Consortium at Penn State which is an NSF Materials Innovation Platform. She is vice president of the American Association for Crystal Growth, an associate editor for the Journal of Crystal Growth, a fellow of the American Physical Society and a fellow of the Materials Research Society. Dr. Redwing is an author or co-author on over 270 publications and holds 8 U.S. patents.

Abstract:

The spectrum of two-dimensional (2D) materials "beyond graphene" has been continually expanding driven by the compelling properties of monolayer films compared to their bulk counterparts. Device applications, however, require the ability to deposit single crystal 2D films over large areas with controlled thickness and properties. Our studies have focused on the epitaxial growth of layered chalcogenide films, including WSe_2 and WS_2, by metalorganic chemical vapor deposition (MOCVD) on sapphire and oxidized silicon substrates. The choice of precursor has a significant impact on the nucleation of 2D domains on sapphire. When metalorganic chalcogen sources are used such as dimethylselenium or diethylsulfur, a thin defective carbon layer forms on the sapphire surface during growth at elevated temperature (>700oC) which impedes the nucleation and lateral growth of W(Se,S)2. This problem was eliminated through the use of hydride sources such as H2Se and H2S thereby enabling epitaxial growth of single crystal monolayer and few layer films on sapphire.

Our synthesis research is part of the 2D Crystal Consortium (2DCC) at Penn State, a National Science Foundation-supported Materials Innovation Platform user facility that is focused on the development of 2D chalcogenides for applications in next generation electronics. The 2DCC is developing advanced synthesis tools including metalorganic chemical vapor deposition and hybrid molecular beam epitaxy systems equipped with real-time, in-situ characterization to probe the growth, electronic structure, and materials properties of atomically thin films. The experimental work is supported by theoretical techniques including molecular dynamics simulations and reactive force-field modeling to address the complex kinetic issues surrounding materials synthesis. Additional facilities are under development for bulk growth of layered chalcogenides to provide high quality crystals grown under near-equilibrium conditions. The 2DCC operates as a no-cost user facility for U.S. academic and government laboratory researchers who are interested in conducting research on the synthesis, characterization and theory/simulation of 2D films and crystals and gaining access to these materials for their studies. Further details on the 2DCC facility and user program will be provided.

Controlling Spin Dynamics in Graphene

Prof. Stephan Roche
ICREA and Catalan Institute of Nanoscience and Nanotechnology-ICN2, Spain

Short biography:

Stephan Roche studied Theoretical Physics at the Université Joseph-Fourier (UJF) and the École Normale Supérieure (ENS) in France, and then received a PhD in Physics in 1996, at the French National Centre for Scientific Research (CNRS). After several postdoctoral stays in Japan and Spain (under the support of the European Commission and JSPS), he was appointed Assistant a Professor at UJF, in 2000, and then as a researcher at the Commissariat à l'Energie Atomique (CEA), in 2004. During his stay at the Institute of Nanosciences and Cryogenics (INAC) at CEA, he coordinated the Quantum Simulation Platform of the programme CHEMTRONICS and was actively involved in the NANOSIMULATION program of CEA.
In 2009, he was awarded the Friedrich Wilhelm Bessel prize by the Alexander Von-Humboldt Foundation (Germany) and worked 1 year at the Technische Universitat Dresden. He has published more than 100 papers in journals such as Review of Modern Physics, Nature Physics, Nano Lett. and Phys. Rev. Lett. (40 papers) and he is the co-author of the tutorial book on "Introduction to Graphene-Based Nanomaterials: From Electronic Structure to Quantum Transport" (Cambridge University Press 2014).
Stephan Roche is ICREA Research Professor at the Catalan Institute of Nanoscience and nanotechnology ICN2 in Barcelona (Spain), head of the Theoretical and Computational Nanoscience Group (with about 10 members). His research focuses on the theoretical understanding of quantum transport phenomena and spin dynamics in materials such as graphene, topological insulators and organic matter. Since 2011, he has been actively involved in the Graphene Flagship project, currently as a co-leader of the Graphene Spintronics workpackage.
http://www.icrea.cat/Web/ScientificStaff/Stephan-Roche-523

Abstract:

Graphene has been heralded as the ideal material to achieve long spin propagation and further control the spin degree of freedom. However, despite ultralow intrinsic and Rashba spin-orbit couplings (SOC) in clean graphene (μeV range), the upper limit of measured spin lifetimes seems to reach 10 nanoseconds. This is orders of magnitude shorter than initially predicted, but anyway enough to develop room-temperature spintronic applications [1]. Besides, the physics of graphene "can be enriched and manipulated" by harvesting the large amount of possibilities of proximity effects with magnetic insulators, strong SOC materials, topological insulators, etc. Claims have been made that very large spin Hall angles (figure of merit for spin Hall effect-SHE) could be generated by using chemical functionalization with hydrogen or Au/Cu ad-atoms, or interfacing graphene with WS2 substrate [2]. Those results are however fiercely questioned [3].
I will first discuss the role of spin-pseudospin coupling in driving spin dephasing and relaxation in the ultraclean limit in relation with substrate effects (electron-hole) [4]. Second, the spin Hall conductivity, spin Hall angle, as well as the nonlocal resistance will be presented in realistic models of gold-decorated disordered graphene. Multiple background contributions to the nonlocal resistance, some of which are unrelated to SHE or any other spin-dependent origin, as well as a strong suppression of SHE at room temperature will be shown.

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High-mobility graphene from chemical vapor deposition on reusable copper

Prof. Christoph Stampfer
RWTH Aachen University, Germany

Short biography:

Christoph Stampfer is currently Professor of Experimental Solid State Physics at the RWTH Aachen University and researcher at the Forschungszentrum Jülich. He is primary interests include graphene and 2D materials research, mesoscopic transport, and micro electromechanical systems. He holds a Dipl.-Ing. degree in Technical Physics from the TU Vienna and a Ph.D. in Mechanical Engineering from the ETH Zurich. He was a staff member at the Institute for Micro and Nano Systems of the ETH Zurich from 2003 to 2007 and staff member of the Institute for Solid State Physics (ETH Zurich) from 2007 to 2009. From 2009 till 2013 he was JARA-FIT Junior Professor at the RWTH Aachen and the Forschungszentrum Jülich. He has been awarded with an ERC Starting Grant to work on "Graphene Quantum Electromechanical Systems" in 2011 and is member of the Young Scientist community of the World Economic Forum since 2014.

Abstract:

Over the past years many promising applications of graphene have been demonstrated on individual devices. In order to advance from basic research towards scalable industrial applications, large area high quality graphene is needed. One promising approach to achieve this is chemical vapor deposition (CVD) of graphene on copper. However, so far the charge carrier mobility of CVD grown graphene has been significantly lower than what has been observed in devices fabricated from exfoliated graphene. I will show that the electronic quality of CVD graphene depends critically on the transfer method and we present a novel dry transfer technique for CVD-grown graphene crystals that yields devices encapsulated in hexagonal boron nitride (hBN) with carrier mobilities up to 350,000 cm2/Vs [1]. In addition to the diffusive transport in such samples, we demonstrate an elastic mean free path exceeding one micrometer at temperatures of up to 200 K using Hall cross devices. By investigating large samples we furthermore conclude that the mean free path can exceed 25 micrometer at 2 K [2]. Thus, in summary we show that the electronic properties of CVD-grown ”synthetic” graphene can in principle match those of ultrahigh-mobility exfoliated ”natural” graphene.

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Superconductivity in 2D materials and heterostructures

Dr. Gary Steele
Kavli Institute of Nanoscience Delft, Delft University of Technology, The Netherlands

Short biography:

Gary obtained his PhD in 2006 studying the quantum Hall effect with a scanning capacitance microscope in the group of Prof. Ray Ashoori at MIT. After his PhD, Gary moved to Delft to work as a postdoctoral researcher with Prof. Leo Kouwenhoven, where he studied charge sensing of nanotubes with SETs and developed a new recipe for making ultra-clean carbon nanotube quantum dot devices. Exploring the ultra-clean carbon nanotube devices he developed, Gary observed Klein tunnelling in nanotube double quantum dots, discovered ultra-high quality factor carbon nanotube mechanical resonators, and observed the strong coupling of nanomechanical motion of the nanotubes to quantized charges in nanotube quantum dots.
In 2010, Gary started a new group in Delft studying nanomechanics and 2D materials as a tenure-track Assistant professor. Here, he developed superconducting circuits for detecting the motion of suspended graphene drums, and explored transport and optoelectronics of a wide range of two-dimensional materials, including MoS2, black phosphorous, and TaS2. Since 2015, Gary is an Associate Professor in Delft with a group focused using superconducting microwave devices to detect the motion of mechanical resonators, the topic of his recently granted ERC consolidator proposal, and the development of superconducting quantum devices based on Josephson junctions made from encapsulated graphene and other 2D materials.

Abstract:

In this talk, I will present recent results from Delft exploring superconductivity in 2D materials and heterostructures. In the first part of the talk, I will present recent work in which we observe superconductivity in atomically-thin layers of TaS_2 [1], a metallic transition metal dichalcogenide which is known to be superconducting in its bulk from. In contrast to recent work with exfoliated $NbSe_2$, we observe an enhancement of the superconducting transition temperature from 0.5 K in the bulk up to 2.2 K for few-layer devices, which we speculate to arise from either a suppression of possible charge-density wave states at small thickness, or an enhancement of superconductivity due to a suppression of the Coulomb interaction in thin layers. In the second part of the talk, I will present results from recent experiments using atomically thin MoS_2 as tunnel barrier in vertical Josephson junctions [2]. Reducing the thickness of the barrier, we observe a dramatic change of the transport in the junctions from a regime of strong multiple-Andreev reflections to a tunneling regime with a suppressed proximity-induced gap. I will conclude with a discussion of ideas to use these new 2D superconducting devices for quantum applications.

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Spintronics in the EU Graphene Flagship

Prof. Bart van Wees
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Short biography:

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Thesis title:	"Quantum ballistic and adiabatic transport, studied with quantum point contacts."
Promotor:	Prof. dr. ir. J.E. Mooij
Honours:	"cum laude"
Current position	
2010-present	Full Professor ("Hoogleraar 1")
	Physics of Nanodevices Group,
	Zernike Institute for Advanced Materials,
	University of Groningen

Abstract:

I will give an overview of the current experimental status of graphene spintronics in the spintronics Work Package in the EU Graphene Flagship. After a brief introduction I will discuss two recent experiments which exploit the quality of graphene as an ideal transporter of electronic spins, with the potential to be combined with other (2D) materials, using Van der Waals stacking. The first experiments demonstrate how, by using electronic carrier drift, electron spins can be transported over a much longer length, compared to diffusion only. Also, in contrast with the diffusive regime, carrier drift can be used to control the direction of the spin transport [1]. I will show that these can be used to design and realize new classes of spin logic devices.
The second experiment employs the sensitivity of the electron spins in graphene to the electronic (spin) states in the substrate. We demonstrated that spin transport, exfoliated on the magnetic insulator Yttrium Iron Garnet (YIG), can be used to sensitively measure the exchange interaction between the graphene spins and the localized spins in the YIG. In this we have in fact made the graphene magnetic, by a proximity induced exchange interaction [2].
I conclude by describing the three routes we are following in the Core 1 phase of the EU Graphene Flagship to bring graphene spintronics closer to applications:

1). Engineering large area graphene spintronic devices. Here we will make the transition from devices based on exfoliated graphene to those based on CVD grown graphene (in combination with CVD based boron nitride (BN) support or encapsulation.
2). Study and implementing Spin Hall effect and spin torque for nano oscillators technology.
3). Study of hybrid devices of graphene and other 2D materials. Here we will supplement the low spin relaxation, long distance spin transport offered by graphene with specific spin and light related functionalities of other (2D) Van der Waals materials, such as the transition metal dichalcogenides (TMDCs)

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Black Phosphorus Optoelectronics and Electronics

Prof. Fengnian Xia
Yale University, United States

Short biography:

Fengnian Xia received the B.E. degree with highest honour in electronics engineering from Tsinghua University, Beijing, China and Ph.D. degrees in electrical engineering from Princeton University, Princeton, NJ, USA. He joined IBM Thomas J. Watson research centre in Yorktown Heights, NY, USA as a postdoc in 2005, and was a Research Staff Member before he started at Yale University in September 2013. Currently he is the Barton L. Weller associate professor in engineering and science at Department of Electrical Engineering.
Professor Xia's honours include the National Science Foundation CAREER award (2016), the Office of Naval Research Young Investigator Award (2015), the IBM Pat Goldberg Memorial Best Paper Award (2014), the TR35 Award, MIT Technology Review's Top Young Innovators under 35 (2011), the IBM Corporate Award, that corporation's highest technical honour (2012), and the designation of the Weller Junior Professorship in Engineering and Science by Yale President in October 2015.

Abstract:

Black phosphorus recently emerged as a promising new 2D material due to its widely tuneable and direct bandgap, high carrier mobility and remarkable in-plane anisotropic electrical, optical and phonon properties. It serendipitously bridges the zero-gap graphene and the relatively large-bandgap transition metal dichalcogenides such as molybdenum disulphide (MoS_2). In this talk, I will first cover the basic properties of few-layer and thin-film black phosphorus, followed by a discussion of recent observation of highly anisotropic robust excitons in monolayer black phosphorus. Finally I will present a few potential applications of black phosphorus such as radio-frequency transistors and wideband photodetectors.

Heterojunctions of 2D materials and their potential applications

Prof. Huili Grace Xing
Cornell University, United States

Short biography:

Huili Grace Xing is currently a Richard Lunquist Sesquicentennial Professor of Electrical and Computer Engineering, Materials Science and Engineering at Cornell University. She was with the University of Notre Dame from 2004 to 2014. She obtained B.S. in physics from Peking University (1996), M.S. in Material Science from Lehigh University (1998) and Ph.D. in Electrical Engineering from University of California, Santa Barbara (2003), respectively. Her research focuses on development of III-V nitride and 2-D crystal semiconductor growth, electronic and optoelectronic devices, especially the interplay between material properties and device developments as well as high performance devices. More recent research interests include tunnel field effect transistors, THz applications and power electronics. She is a recipient of AFOSR Young Investigator Award, NSF CAREER Award and ISCS Young Scientist Award.

Abstract:

Similar to 3D materials, various heterojunctions can be formed in 2D material systems by vertical stacking or lateral epitaxial growth, which include Schottky junctions, p-n junctions, metal or superconductor-insulator-metal or superconductor junctions, metal-insulator-semiconductor junctions. I will discuss our pursuit of p-n heterojunctions, which have led to Esaki diodes and functional oscillators as well as tunnel field effect transistors with steep slope lower than 60 mV/dec at room temperature.

Exchange Field Effects in Van der Waals Ferromagnetic Semiconductor Heterostructures

Dr. Xiaodong Xu
Department of Physics, Department of Materials Science and Engineering, University of Washington, United States

Short biography:

Xiaodong Xu is a Boeing Distinguished Associate Professor in the Department of Physics and the Department of Materials Science and Engineering at the University of Washington. He received his PhD (Physics, 2008) from the University of Michigan and then performed postdoctoral research (2009-2010) at the Center for Nanoscale Systems at Cornell University. His nanoscale optoelectronics group at University of Washington focuses on creation, control, and understanding of novel device physics based on two-dimensional quantum materials. Selected awards include DAPRA YFA, NSF Early Career Award, DoE Early Career Award, Cottrell Scholar Award, University of Washington Innovation Award, and IUPAP Young Scientist Prize in Semiconductor Physics.

Abstract:

We present magneto-optical study of a van der Waals heterostructure formed between a monolayer semiconductor and an ultra-thin layered ferromagnetic semiconductor. We observe a large valley Zeeman splitting in the monolayer without an applied magnetic field, which directly yields a magnetic exchange field of nearly 15 T. The photoluminescence intensity strongly depends on the relative alignment between photo-excited spin in monolayer semiconductor and magnetization in the layered magnet, which reflects spin-orientation-dependent charge hopping across the heterostructure. Furthermore, studying the valley pseudospin dynamics reveals rich spin interactions and intriguing domain structures in the layered magnet, thus providing a new approach to investigate magnets by engineering van der Waals heterostructures.

From Black Phosphorus to Phosphorene

Dr. Peide Ye
Purdue University, United States

Short biography:

Dr. Peide Ye is Richard J. and Mary Jo Schwartz Professor of Electrical and Computer Engineering at Purdue University in USA. He received Ph.D. from Max-Planck-Institute of Solid State Research, Stuttgart, Germany, in 1996. Before joining Purdue faculty in 2005, he worked for NTT, NHMFL/Princeton University, and Bell Labs/Lucent Technologies/Agere Systems. His current research is focused on ALD high-k integration on novel channel materials including III-V, Ge, complex oxides, graphene and other 2D crystals. He authored and co-authored more than 150 peer reviewed articles and 300 conference presentations. He is a Fellow of IEEE.

Abstract:

Phosphorus is one of the most abundant elements preserved in earth, constructing with a fraction of 0.1% of the earth crust. In general, phosphorus has several allotropes including white, red, and black phosphorus. Black phosphorus, though rarely mentioned, is a layered semiconductor and have great potentials in optical and electronic applications. Remarkably, this layered material can be reduced to one single atomic layer in the vertical direction owing to the van der Waals structure, dubbed phosphorene, where the physical properties can be tremendously different from its bulk counterpart and needed to be further explored. In this talk, we trace back to the 100 years research history on black phosphorus from the synthesis to material properties, and extend the topic from black phosphorus to phosphorene. Their electrical, optical, thermal and mechanical anisotropic properties are thoroughly studied and will be presented and reviewed.

Moire superlattice modulation of optical and topological properties in heterobilayers of transition metal dichalcogenides

Dr. Wang Yao
The University of Hong Kong, Hong Kong

Short biography:

Wang Yao is currently Associate Professor at University of Hong Kong. He received his BSc degree from Peking University in 2001, and his PhD from the University of California, San Diego in 2006. After two years undertaking postdoctoral work at University of Texas at Austin, he joined the University of Hong Kong as Assistant Professor in 2008. The central theme of his research is to explore novel quantum phenomena associated with internal degrees of freedom of electrons such as spin and valley pseudospin for new concept quantum devices, and the current focus is exploring such phenomena in atomically thin two-dimensional materials and their van der Waals heterostructures.

Abstract:

In van der Waals heterobilayers, small twisting and/or lattice mismatch leads to the formation of long-period Moiré pattern where the atomic registry locally approximates commensurate bilayers but has local-to-local variation over long range. Such Moiré pattern forms a lateral superlattice modulation of the electronic properties because the form and strength of interlayer coupling is controlled by atomic registry. In transition metal dichalcogendes (TMD) heterobilayers of the normal type-II band alignment, we find that the local-to-local variation in the interlayer atomic registry in the Moiré superlattice leads to spatially modulated light coupling of interlayer excitons. Both the optical transition dipole strength and the valley optical selection rules vary with the position of exciton wavepacket in the Moiré supercell. When the type-II band alignment is tuned into the inverted regime, e.g. by an interlayer bias, the TMD heterobilayers can undergo a topological phase transition depending on the interlayer atomic registry. The Moire superlattice then leads to periodic modulation of local topological order, resulting in mosaic pattern of topological insulator (TI) regions and normal insulator regions in Moiré superlattices. This points to a new means of realizing programmable and electrically switchable topological superstructures from 2D arrays of TI nano-dots to 1D arrays of TI nano-stripes.

Posters

Two-dimensional gallium nitride realized *via* graphene encapsulation

Mr. Zakaria Al Balushi
The Pennsylvania State University, United States

Abstract:

The spectrum of 2D and layered materials "beyond graphene" has been continually expanding. The realization of wide bandgap (E_g) 2D materials "beyond hexagonal boron nitride (hBN)", however, has been limited. Along similar lines to initial theoretical discovery and subsequent experimental synthesis of "beyond graphene" 2D materials (i.e. silicene and borophene), theoretical studies have suggested that indium nitride (InN), gallium nitride (GaN), and aluminum nitride (AlN) take on a 2D graphitic structure with a thickness tunable energy E_g (~0.7-7.0 eV) due to quantum confinement. Despite the extensive computational discovery of 2D materials, the experimental synthesis of wide E_g 2D nitrides "beyond hBN" on technologically relevant substrates still remains elusive. We have developed a novel growth scheme, known as Migration Enhanced Encapsulated Growth (MEEG)[1], which utilizes the mechanism of intercalation *via* defects in graphene to stabilize wide E_g 2D materials that are not layered in bulk crystals. We demonstrate for the first time that 2D GaN not only can be stabilized, but also exhibits unique structural, optical and electrical properties from that of bulk material.

Here we elucidate the mechanism of 2D nitride formation and discuss the ability of the interface of quasi-free standing epitaxial graphene (QFEG) in providing sufficient thermodynamic stabilization of the (direct E_g ~5 eV) 2D buckled structure of GaN (R3m space group symmetry). In the case of 2D GaN, a layer of gallium intercalates between the hydrogenated QFEG and the SiC substrate. The intercalated bilayer of gallium is converted to a quintuple monolayer of 2D GaN via nitrogen intercalation from decomposed NH_3. Our density functional theory (DFT) calculations suggest that the atomic structure in 2D nitrides considerably impacts the stability and bandstructure. We verify the atomic structure by directly resolving the nitrogen and gallium atomic columns in 2D GaN using aberration corrected scanning TEM (STEM) in annular bright field (ABF) mode with supported ABF-STEM simulations. Our DFT calculations predict an energy E_g for 2D GaN in the range of 4.79-4.89 eV which correlates well with experimental results from UV-visible reflectance, absorption coefficient and low loss EELS measurements. Vertical transport measurements suggest 2D GaN acts as a Schottky barrier between graphene and SiC. Furthermore, high resolution x-ray photoelectron spectroscopy demonstrates that 2D GaN is stable in air for at least 24 hours after removal of the graphene cap. Recognizing the impact of 2D nitrides, it can be expected that the addition of 2D GaN will enable new avenues for scientific exploration and electronic/optoelectronic device development.

[1] Al Balushi, Z.Y. et al. "Two-dimensional gallium nitride realized *via* graphene encapsulation" Nature Materials (2016) doi:10.1038/nmat4742

Tunnel field-effect transistor process on CVD WSe2

Mrs. Mina Asghari Heidarlou
University of Notre Dame, United States

Abstract:

Tungsten diselenide tunnel field-effect transistors are being developed for low voltage, energy-efficient electronic systems. Applications of this technology will require large area growth technology to enable integration. To meet the performance targets, ION = 100 uA/um, IOFF = 1 nA/um, I60 = 1 uA/um, the process must achieve few layer channel thicknesses, <500 ohm um contact resistance, p and n doping technology, subnanometer equivalent-oxide-thickness gate stacks, and, for formation of back-gates, a low EOT back-gate dielectric technology. This poster describes progress in achieving these metrics based on WSe2 grown on sapphire by chemical vapor deposition.

Density functional investigation of spontaneous band gap opening in rhombohedral stacked multilayer graphene

Dr. Baima Jacopo
Centre national de la recherche scientifique (CNRS) and Université Pierre et Marie Curie, France

Abstract:

Transport experiments show that suspended rhombohedral-stacked trilayer graphene is insulating at low temperature. Here we study the origin of such state in multilayers from 3 to 8 layers using density functional theory (DFT) with hybrid functionals. Non spin polarized DFT find the occurrence of an extremely flat surface state at the Fermi level. The flat surface band is formed by the atomic states of the two outermost layers in the multilayer. In particular only one of the atom in each outermost layer contributes to the surface state.

Inclusion of spin polarization leads to an insulating magnetic ordered state. Within each surface layer there is an antiferromagnetic coupling between atoms of the two sublattices. The atoms forming the surface bands are coupled antiferromagnetically. By using the PBE0 functional, in this configuration we obtain a gap of Eg = 38.6 meV for rhombohedral trilayer graphene, whose value is very sensitive to the amount of Hartree-Fock exchange contained in the Hamiltonian. This gap increases up to 5 layers and then saturates. We study the temperature dependence of the gap and the Curie temperature.

Hot pickup batch assembly of graphene and TMD vdW devices

Prof. Peter Bøggild
Technical University of Denmark, Department of Physics and Nanotechnology, Denmark

Abstract:

The assembly of individual two-dimensional materials into van der Waals heterostructures enables the construction of layered three-dimensional materials with desirable electronic and optical properties. A core problem in the fabrication of these structures is the formation of clean interfaces between the individual two-dimensional materials which would affect device performance. We present here a technique for the rapid batch fabrication of van der Waals heterostructures, demonstrated by the controlled production of 22 mono-, bi- and trilayer graphene stacks encapsulated in hexagonal boron nitride with close to 100% yield. For the monolayer devices, we found semiclassical mean-free paths up to 0.9 µm, with the narrowest samples showing clear indications of the transport being affected by boundary scattering. The presented method readily lends itself to fabrication of van der Waals heterostructures in both ambient and controlled atmospheres, while the ability to assemble pre-patterned layers paves the way for complex three-dimensional architectures. The method was also used to produce MoS2 devices with graphene contacts and room mobilites above 100 cm2/Vs per layer.

Far-infrared spectroscopy of graphene under uniaxial strain

Dr. Manisha Chhikara
University of Geneva, Switzerland

Abstract:

Using Fourier transform infrared spectroscopy, we systematically studied the transmission of strained (up to 2%) CVD-monolayer of graphene on a flexible PET substrate. We observed an excellent data reproducibility of graphene under uniaxial strain. The results and amount of strain were corroborated with the Raman measurements where we observed a Red shift in 2D peak of graphene. We find a strain-induced anisotropy of terahertz transmission in graphene, which is possibly due to lattice deformation of graphene and weakening of C-C bonds.

Graphene on SiC Hall effect sensor for industrial applications

Dr. Tymoteusz Ciuk
Institute of Electronic Materials Technology, Poland

Abstract:

Tymoteusz CIUK[1,2], Oleg PETRUK[3], Andrzej KOWALIK[1], Iwona JOZWIK[1], Piotr CABAN[1], Andrzej RYCHTER[4], and Wlodek STRUPINSKI[1]
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Epitaxial CVD growth of graphene on SiC [1] offers the maturity and reliability expected for large-scale fabrication of graphene-based devices. In particular, the quasi-free-standing bilayer and the quasi-free-standing monolayer on the Si-face of SiC, offer high carrier mobility (as high as 7000 [cm^2/Vs]) and electrical stability throughout the device processing cycle.
Here, we present extensive statistics of the electrical properties of QFS-bilayer [2] and QFS-monolayer [3] graphene grown on 4H(0001) and 6H(0001) semi-insulating 10 mm × 10 mm substrates, being a result of 570 individual processes. We reaffirm the adopted explanation for the origin of the as-grown doping level in epitaxial graphene. We introduce the issue of the step-edge-induced offset voltage [4], its radial dependence and confront it with the morphological analysis of the average step edge height and terrace width, all related to the place of origin of a specific sample within a 4-inch SiC wafer.
We pay special attention to the applicability of QFS graphene on SiC in magnetic field detection. A Hall effect sensor is presented [5] that is optimized with respect to carrier concentration and mobility, geometry of the active layer, 1/f noise level, magnetic resolution and an encapsulation method that assures stability of the sensor's electrical parameters over time and temperature.
The range of characterisation tools covers Hall effect measurements in van der Pauw geometry, Raman spectroscopy, SEM, AFM and SIMS.

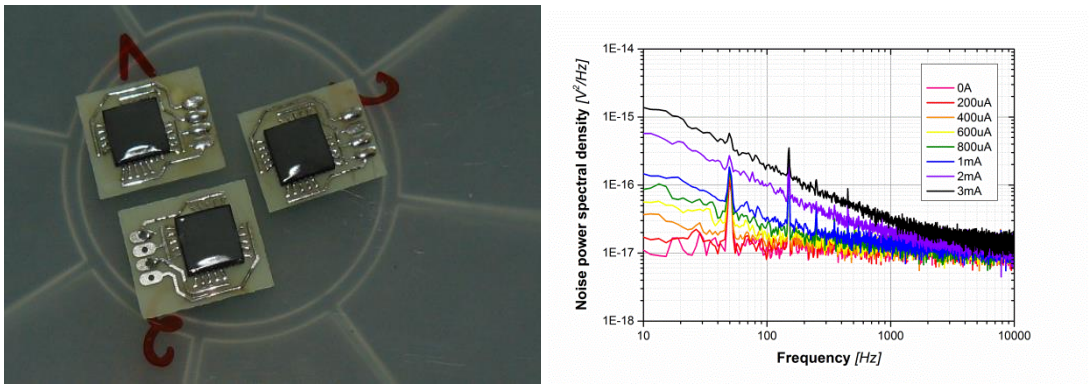

Fig.1 a) Graphene on SiC Hall effect sensor for industrial applications. b) 1/f noise characteristics.

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Two-dimensional gallium nitride realized *via* graphene encapsulation

Dr. Mike Cooke
Oxford Instruments, United Kingdom

Abstract:

MoS2 has been grown on sapphire, alumina (deposited by ALD), and SiO2, in a CVD process using MoCl5 and H2S. The layers have been characterised using Raman spectroscopy and AFM, and show good quality monolayer properties. The smoothness of the layer follows that of the substrate. We also present initial results on the atomic layer etching of MoS2 using a chlorine/argon plasma cycle.

Reversible Semiconductor-Metal Phase Transition in MoTe2 Single-Crystalline 2D Layers

Dr. Albert Davydov
National Institute of Standards and Technology, United States

Abstract:

Molybdenum ditelluride ($MoTe_2$), which can exist in a semiconducting prismatic hexagonal (2H) or a metallic distorted octahedral (1T') phases, is one of the very few materials that exhibit metal-semiconductor transition. Temperature-driven 2H --> 1T' phase transition in bulk $MoTe_2$ occurs at high temperatures (above ~900 °C) and it is usually accompanied by Te loss. The latter can exacerbate the control over reversibility of the phase transition.

Here, we study effects of high-temperature annealing on the 2H <--> 1T' phase transition in $MoTe_2$ single crystals. First, $MoTe_2$ were grown in sealed evacuated quartz ampoules from polycrystalline $MoTe_2$ powder in an iodine-assisted chemical vapor transport process at 1000 °C. The 2H and 1T' phases were stabilized by controlling the cooling rate after the growth. In particular, slow cooling at 10 °C/h rate yielded the 2H phase whereas the 1T' phase was stabilized by ice-water quenching. Next, the reversible phase transformation between 2H and 1T' was achieved by annealing $MoTe_2$ single crystals in vacuum-sealed ampoules at 1000 °C with or without additional polycrystalline $MoTe_2$ powder followed by fast or slow cooling. Similarly to the CVT growth, slow cooling and quenching consistently produced 2H and 1T' phases, respectively, regardless of the initial $MoTe_2$ crystal structure.

This poster discusses structural and optical properties of the as-grown and phase-converted $MoTe_2$ single crystals using TEM, SEM/EDS, XRD, XPS and Raman. Electrical characteristics of two-terminal devices made from metallic 1T' and bottom-gated FETs made from 2H exfoliated crystals are presented.

High Responsivity, Large-Area Graphene/MoS_2 Flexible Photodetectors

Dr. Domenico De Fazio
Cambridge Graphene Centre, University of Cambridge, United Kingdom

Abstract:

We present flexible photodetectors (PDs) for visible wavelengths fabricated by stacking centimeter-scale chemical vapor deposited (CVD) single layer graphene (SLG) and single layer CVD MoS_2, both wet transferred onto a flexible polyethylene terephthalate substrate. The operation mechanism relies on injection of photoexcited electrons from MoS_2 to the SLG channel. The external responsivity is 45.5A/W and the internal 570A/W at 642 nm. This is at least 2 orders of magnitude higher than bulk-semiconductor flexible membranes. The photoconductive gain is up to 4×10^5. The photocurrent is in the 0.1–100 μA range. The devices are semitransparent, with 8% absorptance at 642 nm, and are stable upon bending to a curvature of 1.4 cm. These capabilities and the low-voltage operation (<1 V) make them attractive for wearable applications.

Conjugated Two-Dimensional Supramolecular Polymer Single Layers for Electronics and Energy Technologies

Dr. Renhao Dong
TU Dresden, Germany

Abstract:

The discovery of graphene has triggered great interest in the design and synthesis of covalent or noncovalent organic 2D layers, because of their outstanding properties in electronics, membranes, catalysis, sensing, and energy storage and conversion. Two-dimensional supramolecular polymer (2DSP) is a promising organic 2D material, defined as a free-standing, single-monomer-thick, atomically defined nanosheet with highly ordering repeated units along two orthogonal directions via noncovalent bonds.
Here, we demonstrate the fabrication of large-area, free-standing 2DSP single-layers by metal coordination and host-guest interaction at an air/water interface by Langmuir-Blodgett (LB) method and applied these nanosheets in electronics and energy technologies.

Auxetic Black Phosphorus: A 2D Material with Negative Poisson's Ratio

Mr. Yuchen Du
Purdue University, United States

Abstract:

The Poisson's ratio of a material characterizes its response to uniaxial strain. Materials normally possess a positive Poisson's ratio - they contract laterally when stretched, and expand laterally when compressed. A negative Poisson's ratio is theoretically permissible but has not, with few exceptions of man-made bulk structures, been experimentally observed in any natural materials. Here, we show that the negative Poisson's ratio exists in the low-dimensional natural material black phosphorus and that our experimental observations are consistent with first-principles simulations. Through applying uniaxial strain along armchair direction, we have succeeded in demonstrating a cross-plane interlayer negative Poisson's ratio on black phosphorus for the first time. Meanwhile, our results support the existence of a crossplane intralayer negative Poisson's ratio in the constituent phosphorene layers under uniaxial deformation along the zigzag axis, which is in line with a previous theoretical prediction. The phenomenon originates from the puckered structure of its in-plane lattice, together with coupled hinge-like bonding configurations.

One-dimensional metallic wires at phase-engineered boundaries in two-dimensional materials

Dr. Marco Gibertini
Theory and Simulation of Materials (THEOS) and National Centre for Computational Design and Discovery of Novel Materials (MARVEL), École Polytechnique Fédérale de Lausanne, Switzerland

Abstract:

At polar discontinuities, i.e. at interfaces between systems with different electric polarization, bound and free carriers appear in order to screen the resulting polarization charges. This mechanism is believed to be the driving force for the emergence of the two-dimensional electron gas at oxide interfaces, giving rise to manifold exciting novel phenomena. Similar processes have also been posited to take place at polar discontinuities between different 2D materials [1,2]. Recently, we have suggested several realistic strategies to engineer such polar discontinuities in 2D materials [3,4], and some are starting to find confirmation in current experiments [5].

Here, we develop further the paradigm and show by first-principles simulations that some 2D polar materials can display a metastable non-polar phase, such that a boundary between the stable and metastable phases supports a polar discontinuity and the resulting 1D metallic wire [6]. We suggest several approaches to realize such phase boundaries by inducing metastable phases in a single parent crystal. Finally, we show how this approach could allow promising opportunities to manipulate and reconfigure 1D electron/hole wires or switch their conduction state.

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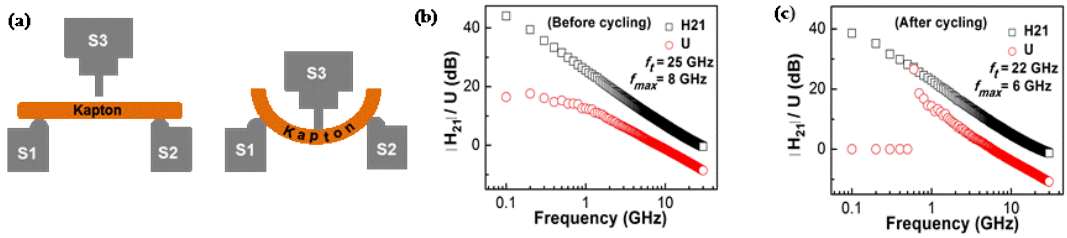
High frequency graphene transistor on flexible substrate: Impact of cycling and self-heating

Prof. Henri Happy
University Lille 1 – IEMN, France

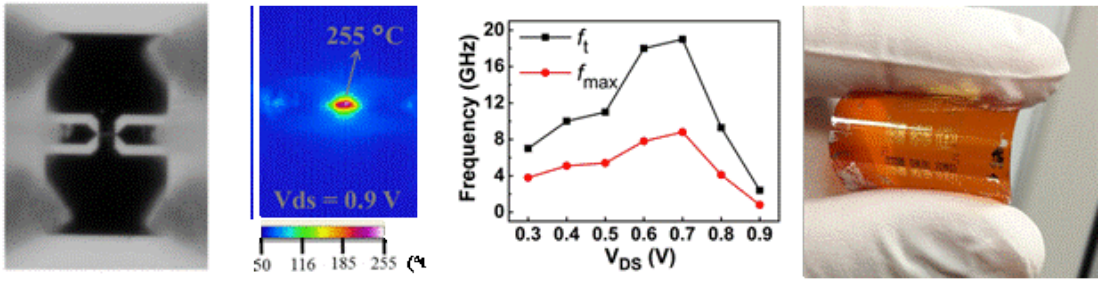
Abstract:

The possibility of large area/high quality material synthesis is essential for large scale applications. In considering graphene or 2D materials for RF applications on flexible substrates, it is important to study their transport properties and their dependence on thermal phenomena associated with heat dissipation and changes induced through substrate stress.

In our recent work we evaluated the effect of self-heating of graphene by characterizing the electrical and thermal properties of layers deposited on flexible substrates as a function of dissipated power. The obtained results showed clearly that the benefit of high thermal conductivity of graphene may be limited by low substrate thermal conductivity. Substrate stress may also affect the material and device properties as shown by our high-frequency results



Impact of cycling on RF performance of flexible GFET



Infrared and thermal mapping of graphene device on flexible substrate - Impact of self-heating on cut-off frequencies f_t and f_{max}

Microfluidic production of graphene-based conductive inks

Dr. Stephen Hodge
Cambridge Graphene Centre, University of Cambridge, United Kingdom

Abstract:

Graphene inks are a rapidly expanding research area [1-2]. However, applications are limited by current process routes (sonication [6] or high shear-mixing [7]) that yield low concentrations of few layer graphenes (<0.2 mg/mL) [2,7] following time consuming centrifugation steps to remove non-exfoliated particles [2,6,7]. Here, we exfoliate graphite in aqueous surfactant solutions (sodium deoxycholate) using a microfluidic processor. A microfluidizer is a high shear fluid processor that generates predominantly shear forces to emulsify either a liquid-liquid system or to disperse solid materials in a liquid medium. The Reynolds number (~$2.6x10^4$) indicates fully developed turbulent flow (Re >> 4000) inside the microchannel of the interaction chamber. The mean turbulent shear rate inside the microchannel is $1x10^8$ s^{-1}, which is 4 orders of magnitude higher than the minimum shear rate required to initiate graphite exfoliation [7]. Using a lab scale system with flow rate of 120 mL/min, we can obtain 1 mg/mL single/few layer graphenes (~20% single layer) with a production rate of 65 mg/h following centrifugation. However, 98 wt% of the starting graphene is sedimented; avoiding centrifugation, graphene nanoplatelets (GNPs) (mean thickness ~12 nm) can be obtained (concentration of 80 mg/mL at a rate of 7.2 g/h). Industrial scale microfluidic processors where flow rates are ~12 L/min could achieve >10 g/h and >600 g/h production rates of few layer graphenes and GNPs, respectively. Few layer graphene inks are directly deposited by vacuum filtration or inkjet printed, and conductive GNP pastes are formulated by adjusting the viscosity in the range of hundreds of mPas suitable for blade coating, flexographic and screen printing. Sodium carboxymethylcellulose (CMC) is employed as a binder, stabilizer and rheology modifier, reducing the viscosity from 600 mPas at 100 s^{-1} to 160 mPas at 1000 s^{-1} (thixotropic behaviour) thus making the pastes easier to coat or print.

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Bottom-up synthesis of graphene nanomembranes with tunable porosity and their structural characterization down to the atomic scale

Prof. Ute Kaiser
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Abstract:

The potential of 2D materials like carbon or graphene nanomembranes [1] for separation or ultrafiltration applications is based on the unique features of these novel nanomaterials having pore sizes suitable for molecular sieving and negligible thicknesses compared to the molecular mean free paths or even below. Here we present a versatile method for tuning the properties of graphene nanomembranes by conversion of carbon nanomembranes (CNM) via annealing into the percolated graphene networks (G-nanomembranes). The properties of G-nanomembranes like thickness, porosity, crystallinity and electrical conductivity can be tuned by adjusting the process parameters such as the choice of molecular precursors, conditions for electron irradiation and temperature treatment. We optimize these different production steps and characterize the resulting physical and chemical properties of CNMs and G-nanomembranes by a number of complementary techniques including X-ray photoelectron spectroscopy (XPS); Raman spectroscopy; atomic force (AFM), helium ion (HIM) and high-resolution transmission electron microscopy (HRTEM). A novel aberration-corrected low-energy HRTEM (SALVE microscope [2]) enables the microscopic characterization down to the atomic scale. Moreover, we develop protocols for a scalable synthesis for the CNMs and G-nanomembranes with a capability for their production of several 10.000 m² per year.

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Radiation reduced CNM formation from halogenated biphenylthiols

Dr. Sascha Koch
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Abstract:

The ability to produce, control and investigate homogenous 2D materials as e.g. graphene gives access to thoroughgoing physical and chemical properties for new technological applications and devices. Carbon Nano Membranes (CNM), comparable to graphene, are mechanical stable quasi 2D systems which are formed by the electron radiation induced cross linking of molecules in specific self-assembled monolayers (SAM) grown on a Au(111) substrate. This allows the tailoring of the CNMs structural and functional properties by the selection and composition of appropriate precursors for the SAM formation like for in stance phenylthiols or naphthalenes [1,2].

Here we present the study of halogenated biphenylthiols (2-Cl-BPT, 2-Br-BPT and 2-I-BPT), which allow in contrast to normal biphenylthiols a conversion of SAMs into CNMs with a highly reduced electron dosis. Additionally, this specific doping of biphenyls gives insight to the mechanisms of the formation of CNMs, helping to understand the transition of a ordered molecular layer into a nanomembrane.

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Magnetoconductance oscillations and edge states in semiconducting monolayer transition metal dichalcogenides

Dr. Andor Kormányos
University of Konstanz, Germany

Abstract:

We have developed a k.p theory framework [1] to describe the dispersion of the conduction and valence bands at their extrema (the K, Q, Γ and M points of the hexagonal Brillouin zone) in semiconducting monolayer transition metal dichalcogenides (TMDCs). We use this theory framework to study a variety of problems. Firstly, motivated by a recent experiments [2], we investigate how the spin-orbit coupling and the broken valley degeneracy of the Landau levels (LL) affect the Shubnikov-de Haas oscillations in TMDCs [3]. We find that in a wide magnetic field regime the valley degeneracy breaking of the LLs is linear in magnetic field. We use the self-consistent Born approximation and the Kubo-formalism to calculate the Shubnikov-de Haas oscillations of the longitudinal conductivity and compare the results of our theoretical calculations with recent measurements. Secondly, we derived boundary conditions for the bulk k.p Hamiltonian to describe nanoribbons of monolayer TMDCs [4]. Focusing mainly on zigzag edges, we analyze the edge states and their dispersion relation in MoS2 in particular, and find good agreement with the results of previous density functional theory calculations. Finally, we briefly discuss the extension of the k.p theory framework to bilayers of TMDCs.

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Curved Nanographenes with an Open-Shell Singlet Biradical Ground State

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Abstract:

Graphene-like molecules with an open-shell singlet biradical ground state have attracted significant interest due to their fascinating optical, electronic and magnetic properties. So far, several types of nanographenes with a singlet biradical character in the ground state have been developed, such as bisphenalenyls, zethrenes, and anthenes. To the best of our knowledge, most of these biradicaloids have the relatively planar structure and electronic configuration. In other words, the curved nanographenes with a biradical feature in the ground state was rarely reported. Here, we show an efficient synthetic method to prepare a novel saddle-shaped pentagon-embedded nanographenes, in which the conjugation of the central curved bischrysene core is extended by the annelation of the two indene units. Most interestingly, this nanographenes has a stable singlet biradical feature in the ground state, which present a new saddle-shaped open-shell singlet biradicaloids. The saddle-shaped conformation can affect the electron contribution and then stabilize the biradical species. Thus, this synthetic strategy can contribute a good understanding and design other curved open-shell nanographenes.

Valley Addressable Exciton-Polaritons in $MoSe_2$

Dr. Tom Lyons
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Abstract:

Exciton-polaritons are hybrid quasiparticles resulting from the strong coupling between excitonic and photonic states (fig 1a). Such particles inherit a strong nonlinearity from their excitonic component allowing polaritons to exhibit highly nonlinear phenomena such as Bose Einstein condensation, superfluid-like behavior and optical spin switching. This non-linearity is polarisation dependent, and for transition metal dichalocogenide (TMD) polaritons is expected to be coupled to the valley degree of freedom due to spin-valley locking. In this work, strong chiral selectivity of $MoSe_2$ polaritons under helical excitation is reported with a polarisation degree that strongly depends upon the exciton-cavity detuning (fig 1c). In contrast to the very low circular polarization degrees < 5% seen for $MoSe_2$ exciton and trion resonances, we observe a significant increase of up to 18% when in the strong coupling regime (fig 1b). A dynamical model based upon Boltzmann equations reproduces the detuning dependence through the incorporation of cavity-modified exciton relaxation, where the interplay between valley pseudospin relaxation in the exciton reservoir, and relaxation to polariton states, which are strongly dependent on the excitonic, trionic and photonic fractions, allow for an enhancement in retained polarization. We estimate that the spin relaxation time in $MoSe_2$ is an order of magnitude faster than those reported in other TMDs, indicating that the anomalously low polarization behavior of $MoSe_2$ is due to ultrafast spin relaxation of excitonic species. The valley addressable exciton-polaritons reported here offer new avenues for valley dependent nonlinear interactions where valley-polariton populations can be controlled with circularly polarized excitation.

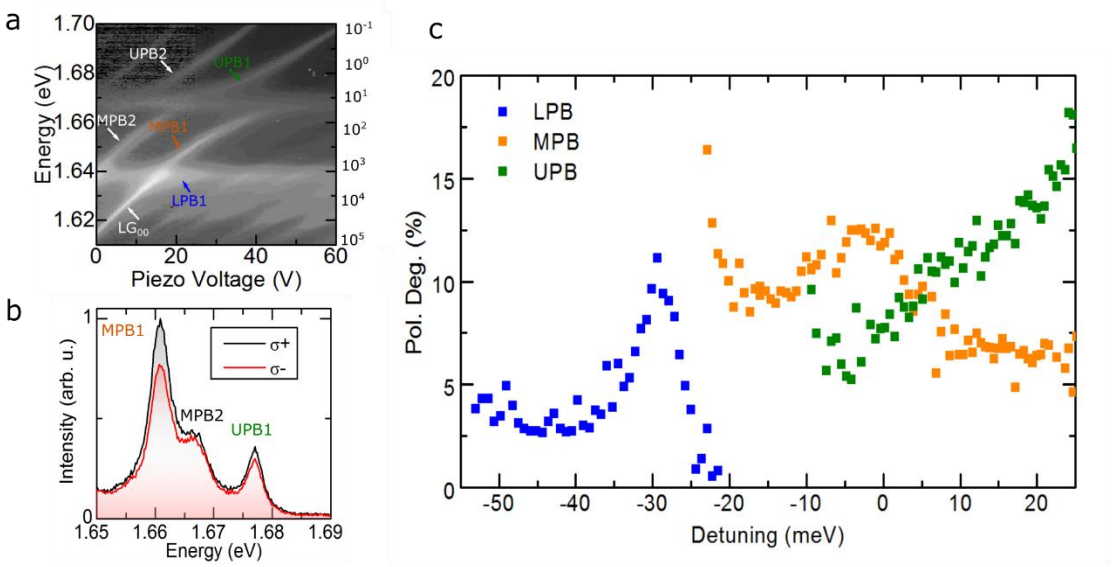

Fig. 1. **a.** Colourmap of PL spectra as a function of piezo voltage (decreasing cavity length) showing a clear anticrossing with X^0 with a Rabi splitting of 16.5meV. Upper, middle and lower polariton branches are labelled, along with the fundamental LG_{00} cavity mode. **b.** Polarisation resolved PL spectrum at zero exciton-photon detuning, showing retention of circular polarisation to various degrees in all polariton branches. **c.** Circular polarisation degree of polariton branches as a function of exciton-photon detuning.

Suppression of Inter-Valley Relaxation in hBN Encapsulated Monolayer WSe2 with Small Magnetic Fields

Dr. Tom Lyons

University of Sheffield, United Kingdom

Abstract:

In monolayers of WSe_2, bright excitonic species have been shown to exhibit strong chiral selectivity owing to the locking of light helicity to the valley degree of freedom [1,2]. The degree of valley initialisation that can be achieved is limited by inter-valley scattering of excitons due to the strong electron-hole exchange interaction which has been shown to be a significant, although inefficient, mechanism for valley pseudo-spin relaxation [3]. Here we study the magneto-PL dependence of a van der Waals (VDW) heterostructure consisting of a WSe_2 flake encapsulated with thin films of hBN, as shown in Fig.1a. PL-spectra from the sample, shown in Fig. 1b, exhibit strong excitonic features associated with the neutral (X0), charged (X-) and localised (P1) excitons along with a band of localised emitters (LEs). We demonstrate that the application of a small magnetic field in Faraday geometry (B < 500mT) leads to a large increase in X- and P1 valley polarisation of ~ 40% of its zero field value, which we attribute to suppression of intervalley relaxation (Fig. 1c). Furthermore, a clear transition to Hanlé-like depolarisation behaviour is observed in both the trion and localised emitter band as the applied external B-field is tilted from Faraday to Voigt geometry, as shown in Fig. 1d. In addition to this work, the narrow linewidths displayed by our WSe_2 samples have allowed observation of an in-plane field dependent valley splitting and associated g-factor of -1.8. This demonstration of significant suppression of pseudo-spin relaxation opens new possibilities for engineering valley relaxation channels through the use of VDW heterostructures in small magnetic fields.

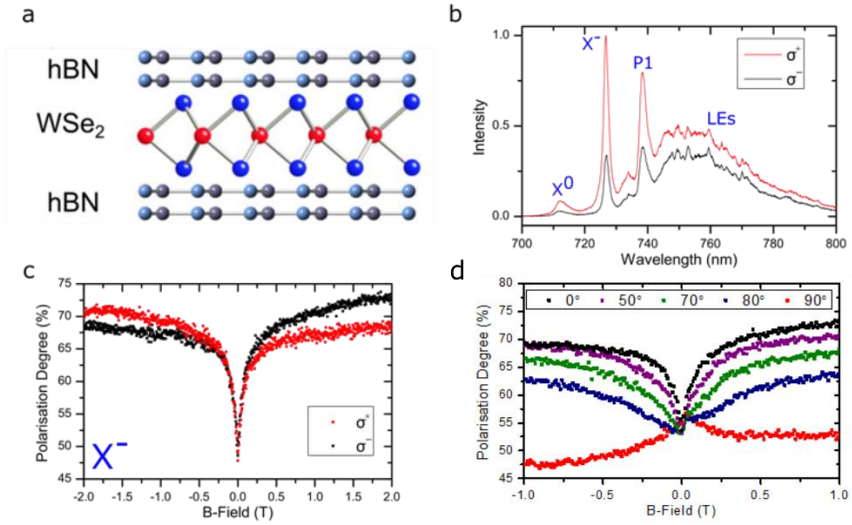

Fig.1. a Schematic of the van der Waals heterostructure. b PL spectra under σ+ polarized excitation at 637 nm with collection co- and cross-polarized. c, d Degree of polarisation for X^- as a function of magnetic field in c, Faraday geometry and d, fields applied at various angles from Faraday (0˚) to Voigt (90˚, in-plane) geometries.

Two-dimensional Silicon Nanosheets: Functionalization, Characterization and Application

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Institute for Nanoelectronics (Prof. Lugli), ATUMS Project, Technical University of Munich, Germany

Abstract:

Authors: A. Lyuleeva (1), T. Helbich (2), M. A. Narreto (3), F. Hegmann (3), B. Rieger (2), P. Lugli (1)
(1) Institute for Nanoelectronics, TUM, Theresienstraße 90, 80333 Munich, Germany
(2) Wacker-Lehrstuhl für Makromolekulare Chemie, TUM, Germany
(3) AITF Strategic Chair in Terahertz Science and Technology, UoA, Edmonton, Canada

Silicon, as a widely used material in the everyday life, attracts much interest throughout a diverse range of different research fields. The synthesis of new materials with smaller dimensions, which are faster, long living, and cheap to incorporate within electronics are just a few desired goals, which need to be reached in a near future. [1,2,3] In this context the new properties of nanostructured materials, which start to appear together with the quantum confinement effect while lowering its dimensions, are of huge importance. [4,5] Herein we present possible ways for the stabilization of highly sensitive two-dimensional silicon nanosheets (SiNSs) for the use in ambient conditions. The interesting optoelectronic properties of this nanomaterial open new possibilities for fast responsive and therefore highly sensitive electronics. Furthermore, the functionalization and synthesis of SiNSs based composites enable their application in ambient conditions and promise a facile fabrication of a long living device.

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Electron optics in ballistic graphene

Dr. Peter Makk
Department of Physics, University of Basel, Switzerland

Abstract:

Encapsulated or suspended graphene with complex gating structure [1] offers a promising platform for spintronics and electron optical devices due to the ballistic nature of electron transport. In graphene gapless p-n interfaces can be formed by electrostatic gating, showing a negative index of refraction and Klein tunnelling. We demonstrate that in graphene a ballistic p-n junction can be formed [2,3] and Fabry-Perot oscillations appear, and that confinement can also be obtained due to super-lattice effects.

We investigate current oscillations in magnetic field in the classical [4] and in the quantum regime originating from currents along the p-n interface and discuss their possible origin. Using multi-terminal devices switches can be constructed exploiting these oscillations.
These p-n junctions based devices can also be used to form guiding channels [5] similar to optical fibers, and beam-splitters [6] which rely on complex gating structure. Moreover, these high mobility samples offer a versatile platform for spintronics devices [7].

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Graphene-Enhanced Secondary Ion Mass Spectroscopy for analysis of surface, 2D materials and ultra-thin films

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Institute of Electronic Materials Technology, Poland

Abstract:

The present invention (pending European patent application no. EP 16461554.4) is related to a method of analysing a solid substrate by means of Secondary Ion Mass Spectroscopy (SIMS), comprising the steps of providing a graphene layer over the substrate surface and analysing ejected secondary anions through mass spectrometry analysis. The presence of the graphene layer significantly increases the negative ionization probability and thus the intensity of the SIMS signal can be more than two orders of magnitude higher than when compared to a similar sample without graphene. The method is particularly useful for the analysis of the surface, 2D materials and ultra-thin films. The intensity of dopants and contaminations signals can be enhanced up to 35 times, which allows reaching the detection limit of ~10^{15} atms/cm^3, otherwise unreachable in a standard static SIMS analysis.

Interface-engineered topological insulator thin films revealing quantum and finite size effects

Dr. Seongshik (Sean) Oh
Rutgers University, United States

Abstract:

Topological insulators (TIs) are a novel class of quantum materials where the bulk remains insulating, while the surface is metallic. These topological surface states (TSS) exhibit linear Dirac-like dispersion. Bi_2Se_3 is a prototypical 3D topological insulator with relatively large band gap of 0.3eV and has a single TSS with Dirac cone well separated from bulk band edges, making it an ideal material to study the novel physics of TSS. Due to its layered structure, Bi_2Se_3 thin films can be grown with ease using molecular beam epitaxy (MBE) on variety of substrates. However, all the previous Bi_2Se_3 thin films suffered from high sheet carrier density n_{sheet} (~ 10^{13}-10^{14}/cm^2) and low carrier mobility μ (~ 2000 cm^2/Vs), mostly due to defects induced by substrate. Through an interface engineering scheme, we have achieved Bi_2Se_3 thin films that are free of bulk conduction with an order magnitude lower sheet carrier density and an order of magnitude higher carrier mobility. These interface-engineered TI films have made it possible to reveal a series of previously-hidden topological properties including quantum Hall effect, quantized Faraday and Kerr rotation, and finite-size driven topological phase transition.

Highly Efficient Graphene Supports for Fuel Cells Applications

Dr. Veera Sadhu
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Abstract:

Nanomaterials based on graphene are highly important because of their unique properties for example high contact surface area, high electrical conductivity and their enormous stability. Graphene and graphene related materials have been used as promising catalyst supports in energy conversion and storage applications. However, in order to produce more efficient catalyst supports, modification of graphene oxide is our primary research focus to stick the metal nanoparticles to the graphene surface and also for solution processing of catalyst inks for better electrode fabrication. We successfully modify graphene with various active functional groups for example amine, thiophene, fluorosilane, and RGD peptide. Then, these modified graphene has been used as efficient supports for Platinum (Pt) catalyst nanoparticles. The dispersion of Pt deposited on modified graphene has been enhanced and stable optimized dispersions were obtained in organic solvents. The cyclic voltametry (CV) results of Pt on functional graphene showed a high electrochemical surface area (ECSA) of 147 m^2/g for Pt/GO-RGD compared to Pt/carbon black (Pt/C, 80 m^2/g_{Pt}) and Pt/GO (99 m^2/g_{Pt}). Also the functionalized GO/Pt showed higher oxygen reduction reaction (ORR) activity compared to Pt/C. On the other hand, we also fabricated GO/PPy/CB (carbon black) hybrid nanocomposites as catalyst support and deposited Pt nanoparticles. The CV results showed a high ECSA of 153 m^2/g_{Pt}. Gas diffusion electrode fabrication of the graphene nanomaterials and their use in proton exchange membrane fuel cells (PEMFC) will be reviewed and their electrochemical activity will be discussed further.

Highly Sensitive Broadband Photodetector Based on Multilayer MoS_2

Dr. Gustavo Saenz
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Abstract:

Two-dimensional MoS2 is the TMDC layered material that has attract special attention in recent years including its application in novel opto-electronic devices. A key characteristic of the MoS_2 is that the bandgap changes from indirect to direct bandgap between Γ and K point, from ~1.2 in bulk to ~1.8 eV in monolayer respectively due to the reduction of van der Waals interlayer interactions. Additionally, the bandgap can be also tuned by an external electric field and the manipulation of this parameter can be used for photo-detection at different wavelengths. However, multilayer MoS_2 has not been widely studied. Its narrow band gap allows wide range of photodetection from UV to NIR and the absorption of light increases compared to the few and monolayer analogue. In this work, we report on the design, the fabrication, and optoelectronic characterization of a multilayer mechanically exfoliated MoS_2 broadband photodetector with low Schottky barrier. The performance is enhanced by the used of Mo as metal contact, a clean and all-dry transference process, and the metal contact design that allows the suspension of the MoS_2 flake. This suspension reduces the phonon and charge scattering, as well as the optical interference from the substrate.

Carbon Nanomembranes, the Other Carbon-Based 2D-Material

Dr. Albert Schnieders
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Abstract:

Carbon Nanomembranes (CNMs) are one molecular monolayer - equivalent to 1 nm - thin, Carbon-based polymeric films with properties which can be specifically adjusted for a variety of applications such as filtration or separation tasks. As a Carbon-based 2D-material, CNMs are related to graphene. However, they have many properties, which cannot easily be achieved for graphene. Their surfaces can be chemically or biologically functionalised (even differently on both sides). Perforation (e.g. for size-selective separation) can be intrinsically achieved during fabrication. The size distribution and density of pores can thereby be controlled by adjusting a few manufacturing parameters. Additionally, it is possible to convert CNMs into porous nanocrystalline graphene, which can be also used for filtration and separation. A scaling of production to any wanted size is principally possible. Recently, we manufactured in a laboratory set-up the first large-size CNMs (approx. 20 x 30 cm^2). Based on these experiments, we designed a batch-based production of CNMs with a capacity of several 10,000 m^2 per year at a price comparable to conventional asymmetrical membranes.

Contacts and junction formation in TMDs

Prof. Alan Seabaugh
University of Notre Dame, United States

Abstract:

Two-dimensional materials are being actively developed for beyond-CMOS tunnel transistors [1]. High performance devices require technologies for ohmic contacts and p-n junctions. Polymer electric-double-layer (EDL) doping technology is shown to form tunneling-limited contacts in a wide range of material systems including MoTe2 [2], MoS2 [3], and WSe2 [4] using polyethylene-oxide with cesium perchlorate. Record low contact resistance and high current densities are now demonstrated in WSe2 and MoS2 field-effect transistors (FETs). Highly ideal p-n junctions has been demonstrated paving the way for EDL tunnel FETs [5].

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Interlayer Exciton Dynamics in $MoSe_2/WSe_2$ Vertical Heterostructures

Mr. Kyle Seyler
University of Washington, United States

Abstract:

Few-layer semiconducting transition metal dichalcogenides (TMDs) are generating great scientific interest for their excitonic and spin/valley properties, and the recent developments in custom stacked 2D heterostructures create excellent opportunities for novel physics and devices. A central question for new optoelectronic systems is how its quasiparticles relax after photoexcitation. We will present our studies on the dynamics of interlayer excitons in MoSe2/WSe2 vertical heterostructures using time- and spectrally resolved photoluminescence experiments. The interlayer excitons are shown to exhibit complex photoluminescence decays that are strongly dependent on the emission energy, excitation density, and temperature. We will discuss the possible underlying mechanisms for this behaviour as well as future experiments to clarify our understanding.

Graphene FET Based Negative Impedance Converter

Mr. Jing Tian
Queen Mary, University of London, United Kingdom

Abstract:

The negative impedance converters (NICs) has been proposed for applications such as broadband impedance matching of electrically small antenna. The graphene based negative impedance converter presented in this study follows Linvill's open circuit stable (OCS) topology. Through simulation, we have shown good NIC performance up to 200 MHz and the stability study is also performed using Nyquist stability criterion.

Heterostructures of 2D carbon materials for non-destructive chemical functionalization of graphene in electronic devices

Prof. Andrey Turchanin
Friedrich Schiller University Jena, Germany

Abstract:

Heterostructures of 2D carbon materials for non-destructive chemical functionalization of graphene in electronic devices

D. Kaiser[1], A. Winter[1], F. Ahlers[2], T. Weimann[2], and A. Turchanin[1]
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Chemical functionalization of single-layer graphene (SLG) is of key importance for applications in functional electronic devices such as, e.g., field effect transistor (FET) based nanosensors. However, the electronic quality of graphene is typically destroyed after the functionalization, which significantly restricts the applications. Here, we present a route to non-destructive chemical functionalization of graphene via engineering of novel carbon nanomembrane (CNM)/SLG hybrids. We employ SLG, grown by methane CVD on Cu foils, and amino-terminated 1 nm thick CNMs [1], generated by electron-beam-induced crosslinking of aromatic self-assembled monolayers, to engineer hybrid CNM/SLG FETs on oxidized silicon wafers. Structural, chemical and electronic properties of the CNM/SLG hybrids are characterized by Raman spectroscopy, X-ray photoelectron spectroscopy and electrical transport measurements. [2] We unambiguously show that the intrinsically high electronic quality of pristine SLG is preserved in the amino-functionalized hybrids opening broad avenues for their use as electrical transducers in graphene-based FETs.
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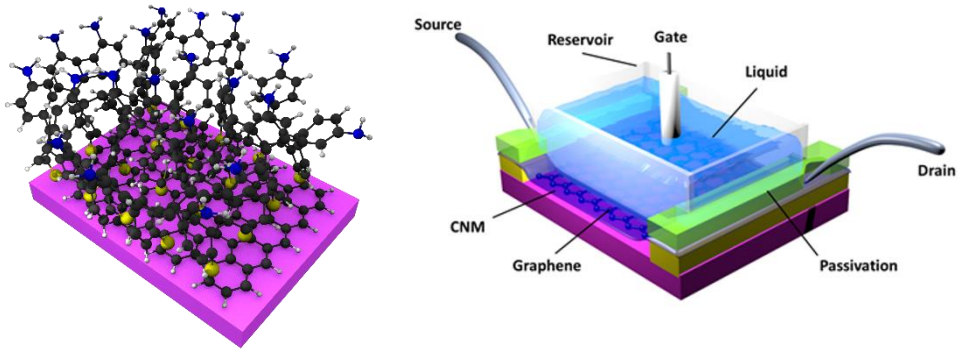

Figure: Schematic representation of a CNM/graphene heterostructures (left). Implementation of the CNM/graphene heterostructure in a FET for pH-sensing (right).

Screening and Nonlocal Manipulations of Electronic Interactions in Two-Dimensional Materials

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Abstract:

Two-dimensional (2d) materials host strong Coulomb interactions combined with ultimate sensitivity to their environment and offer unique possibilities for controlling charge carrier densities. Here, we discuss how the electronic structure and optical properties of 2d materials like graphene and MoS2 are determined by the interplay of interactions, dielectric environments and doping. First, we discuss how substrates, vertical heterostructuring as well as doping and optical excitations present means to drastically manipulate Coulomb interactions and related material properties in these systems. We show that sharp lateral heterojunctions can be created in 2d materials based on non-local manipulations of the Coulomb interaction using structured dielectric environments. We then explain how optical excitations affect the electronic properties of 2d materials similarly strong, where we find excitation induced electronic quasiparticle band gap shifts and renormalizations of exciton binding energies on the scale of several hundred meV. Upon charge doping group VI transition metal dichalcogenides undergo a series of transitions from semiconducting, to metallic and finally superconducting phases. We show how electronic screening affects these transitions.

Understanding and Exploiting Black Phosphorus Chemistry for Electronic Devices

Dr. Spencer Wells
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Abstract:

Few-layer black phosphorus is a chemically reactive 2D material that oxidizes into phosphates when exposed to ambient conditions. However, this degradation can be mitigated through a variety of techniques including physical passivation via specially engineered alumina ALD as well as chemical passivation via covalent functionalization with aryl diazonium species. While ALD encapsulation was found to reduce field effect transistor hysteresis and stabilize device performance for up to five months, aryl diazonium functionalization yielded tunable p-type doping, allowing the tuning of mobility and current modulation by several orders of magnitude. This knowledge of black phosphorus degradation mechanisms allows for the realization of solution-processed BP in both anhydrous, anoxic organic solvents as well as anoxic water with surfactants. Both solvent systems were found to produce few-layer BP, but only the aqueous solution showed spectroscopic and topographic evidence of monolayer black phosphorus. Additionally, both exfoliation techniques yield material free from oxidation, as well as field effect transistors with electrical properties similar to state-of-the-art micromechanically exfoliated devices.

GQD / Graphene based gas sensor

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Abstract:

Epitaxial Graphene has been studied as extremely sensitive gas sensor for years, which usually has good sensitivity towards nitrogen dioxide (NO_2), small response towards hydrogen (H_2) and carbon monoxide (CO), but lack of response towards ammonia (NH_3) and benzene (C_6H_6).

While graphene-based gas sensor has been exploited for years, the studies on nanostructure of graphene nanoribbon (GNB) and graphene quantum dot (GQD) gas sensors are still in preliminary stage. In this work, the surface functionalization of graphene by GQDs was studied for the first time. Moreover, GQD was modified by mixing in water solution with doping sources included hydrochloric acid (HCl), boric acid (H_3BO_3), ammonium hydroxide (NH_4OH), and potassium hydroxide (KOH). In order to acquire the desired surface functional groups.

As fabricated sensors including Cl, B, N – doped sensors were tested at room temperature (RT) with NO_2, NH_3, and C_6H_6. The sensitivity towards NO_2 for all the GQD-sensors were clearly lower than pristine epitaxial graphene. In the meantime, they also possessed distinct response towards NH_3, which usually is not the case for pristine epitaxial graphene. Moreover, Cl-doped sensor showed outstanding limit of detection and response time towards C_6H_6 ppb range. To conclude, the ionization constant of doping sources played an important role of the doping efficiency.

It is worth noticing that the recovery time was decreased effectively with the help of UV – LED exposure at RT. The study provided with a facile method to tune the gas sensing properties of graphene with GQDs, and proved the versatility of GQD/graphene – based gas sensor.

Superlattice phonon of graphene/hBN heterostructure

Dr. Duhee Yoon
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Abstract:

Two dimensional (2d) atomic crystals have attracted much attention due to the possibility to stack these materials into van der Waals heterostructures, showing unusual properties and new phenomena [1,2]. Van der Waals interactions between stacked 2d atomic crystals modify electrical and optical properties of 2d layered materials [3,4]. Graphene/hexagonal boron nitride (hBN) hetrostructures exhibit a Moiré pattern arising from a lattice mismatch between single layer graphene and boron nitride, depending on the rotation angle between both crystal lattices [5,6]. We find that the hexagonal Moiré pattern acts as superlattice in graphene, which results in a zone folded phonon structure of graphene. Here we observe zone folded phonons of graphene/hBN heterostructures by using Raman spectroscopy. Zone folded phonons give rise to multiple Raman peaks close to the G peak, whereby their peak positions strongly depend on the rotation angle. We achieved to map anomalous phonon band structure of graphene, which has kink on LO phonon branch at the Γ point of Brillouin zone due to Kohn anomaly.

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