GRAPHENE FLAGSHIP

CHINA ACADEMY OF SCIENCES

The 4th Graphene Flagship EU-China Workshop on *Graphene and related 2D materials*

Online event

05 November 2021

8:30 a.m. – 1:00 p.m. CET (Paris, Brussels time)
3:30 p.m. – 8:00 p.m. CST (Beijing time)

Overview

The 4th EU-China Workshop on Graphene and Related Materials was held online on the 5th of November 2021. The aim of this workshop was to foster exchange of experiences, practices and ideas related to the current and emerging topics associated with fundamental materials synthesis/growth, physics and devices of graphene and related 2D materials.

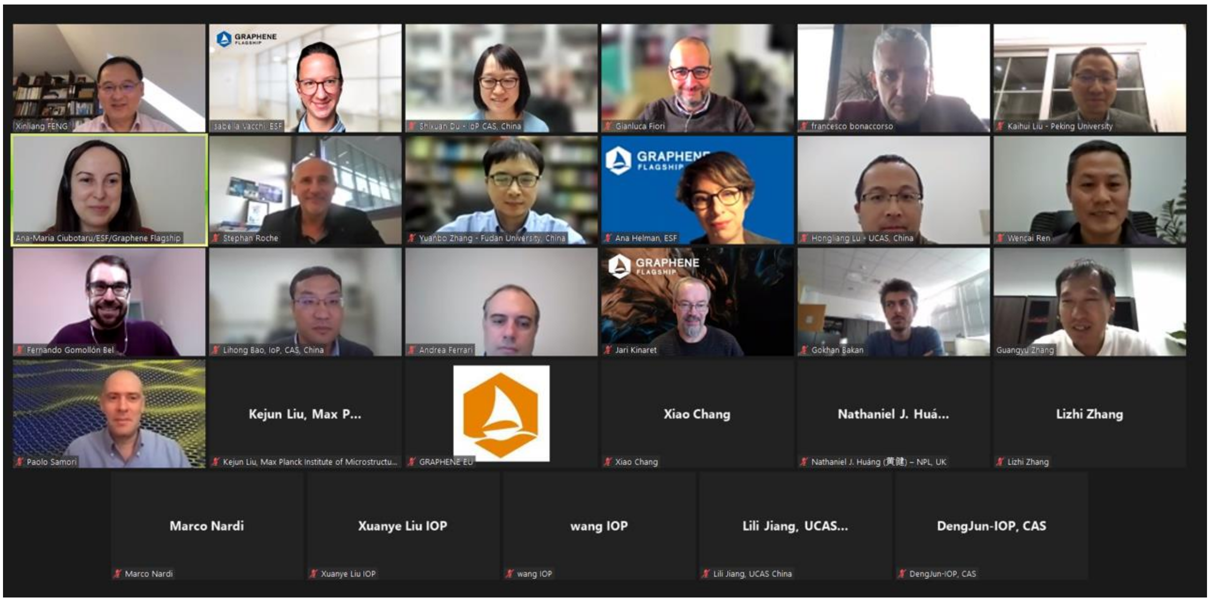
The event was a follow-up of three previous workshops, held in Beijing (China) in 2017, in Dresden (Germany) in 2018 and in Shanghai (China) 2019. The meeting was jointly organised and co-chaired by European and Chinese researchers.

Workshop chairs: Prof. Jari Kinaret (Sweden) and Prof. Hong-Jun Gao (China)

Program chairs: Prof. Xinliang Feng (Germany), Prof. Francesco Bonaccorso (Italy) and Prof. Shixuan Du (China)

The workshop was followed by over 50 participants mainly from academic institutions and research organisations. Ten invited speakers gave a talk, five from each side, showcasing the activities and topics investigated by their respective research groups. The selection of scientific speakers was done by the organizers.

The workshop was opened by Prof. Feng and Prof. Du who set the scene and introduced the overall goals of the meeting. A strong point was made on the importance of these workshops as opportunities to initiate new scientific collaborations in which the involvement of young researchers is the key. Both sides expressed the wish to continue with yearly events. After the welcome speech, Prof. Kinaret presented the status of the Graphene Flagship and the plans for the Horizon Europe phase. Prof. Du has also given a welcome introduction on behalf of China delegates.



Common challenges and opportunities for collaborations

The workshop covered topics related to fundamental research which included 2D materials production, properties and characterization, functionalization and electronic devices. A general strong desire to share scientific results was felt. Below there are some highlights from the workshop:

Production

- Growth of high-quality monolayer MoS_2 wafers and oxygen doped MoS_2 wafers with a transfer process in water for large-scale flexible devices resulting in a good mobility and on/off ratio.
- Development of a new exfoliation method for “difficult” 2D materials to obtain materials with few atomic layers. $MnBi_2Te_4$ thin flakes have been obtained, a topological insulator with intrinsic magnetic order, ferromagnetic when the sample has odd number of septuple layers, exhibiting quantum anomalous Hall effect.
- Manufacturing of meter-scale 2D single crystals through nucleation control.
- CVD growth of high-quality centimeter-scale monolayer $MoSi_2N_4$, with superconducting behaviour, high strength and excellent ambient stability.

Properties and characterization

- Probing quantum transport in $MnBi_2Te_4$ thin flakes.
- Single-photon emission in layered quantum materials for applications in biosensing and chemometric imaging.
- Valley Hall effect in bilayer graphene, without magnetic field, generated with light as of the Berry curvature.
- Optical nano-imaging of twisted graphene with near-field microscopy allowing to see the moiré structure.
- Exploration of the physical properties of amorphous graphene through computer simulations. This project started and brought to a collaboration with Samsung (Korea) after the EU-Korea workshop 2019.
- Properties modulation through functionalization of 2D materials, specifically, physisorption of molecular switches fabricating back gated devices, chemisorption of doubly-thiolated molecules to create bridges for charge transport, usage of ferroelectric P(VDF-TrFE) as gate insulator layer at the interface with the 2D material.

Applications

- MoS_2-based printed transistors and MoS_2-based OPAMP for applications in wearable circuits and systems on flexible substrates.
- High-performance heterostructured InSe FETs with high electron mobility. If placed onto SiO_2/Si substrate, it can work as floating-gated FET and can be used as flash memory cell.
- Optical devices using single-crystal materials, i.e., electro-optic modulator.

The participants see the abundant opportunities for the continuous collaborations on the preparation/growth of large-area 2D materials, their fundamental physic properties characterizations and device integrations. The meeting fosters the synergy between the developments carried out in the Graphene Flagship and the advancements made by the Chinese groups actively involved in the 2D materials area.

At the end of the meeting, a clear interest to continue the series of workshops was expressed, wishing it to be an in-person event, without, however, setting the place yet as the current pandemic situation is not allowing to foresee what will be the status in one year time.

Programme

November 5th, 2021 *Online event*			
CET (EU)	**CST (China)**		
08:30-	**15:30-**	**Welcome and Introduction** *Welcome from Prof. Xinliang Feng and Prof. Shixuan Du* *Introduction: Prof. Jari Kinaret – Graphene Flagship update* *Prof. Hong-Jun Gao – China Academy of Science update*	
Chair: Xinliang Feng			
08:50-	15:50-	*Frank Koppens*	Valley-selective hall and optoelectronics of twisted and bilayer graphene
09:10-	16:10-	*Guangyu Zhang*	Monolayer MoS_2 for large scale electronics
09:30-	16:30-	*Andrea Ferrari*	Layered Quantum Materials and Applications
09:50 -	16:50-	*Yuanbo Zhang*	Quantum anomalous Hall effect in intrinsic magnetic topological insulator $MnBi_2Te_4$
10:10 -	17:10-	*Stephan Roche*	The Universe of Disordered and Amorphous Two-dimensional Materials: Scientific Challenges & Technology Opportunities
10:30- **10:45**	**17:30-** **17:45**	**15 min. break**	
Chair: Shixuan Du			
10:45-	17:45-	*Kaihui Liu*	Designed Growth and Applications of Meter-sized 2D Single Crystals
11:05-	18:05-	*Gianluca Fiori*	Two-dimensional materials for printable and wearable applications
11:25-	18:25-	*Wencai Ren*	Discovery of layered 2D $MoSi_2N_4$ family
11:45-	18:45-	*Paolo Samorì*	Multi-responsive and high-performance 2D materials based opto-electronic devices
12:05-	19:05-	*Lihong Bao*	Atomically Sharp Interface of van der Waals Heterostructures Enabled High-performance Electronic Devices
12:25-	**19:25-**	**Final discussion**	
13:00	**20:00**	**Closing**	

List of speakers

Title	First name	Last name	Institution	Country
Ass. Prof.	Lihong	Bao	Institute of Physics, Chinese Academy of Sciences (CAS)	China
Prof.	Francesco	Bonaccorso	BeDimensional	Italy
Prof.	Shixuan	Du	Institute of Physics, Chinese Academy of Sciences	China
Prof.	Xinliang	Feng	Technical University of Dresden	Germany
Prof.	Andrea	Ferrari	University of Cambridge	United Kingdom
Ass. Prof.	Gianluca	Fiori	University of Pisa	Italy
Prof.	Hong-Jun	Gao	Institute of Physics, Chinese Academy of Sciences	China
Prof.	Jari	Kinaret	Chalmers University	Sweden
Prof.	Frank	Koppens	Institute of Photonic Sciences (ICFO)	Spain
Prof.	Kaihui	Liu	Peking University	China
Prof.	Wencai	Ren	Institute of Metal Research, Chinese Academy of Sciences (CAS)	China
Prof.	Stephan	Roche	ICREA and Catalan Institute of Nanoscience and Nanotechnology (ICN2)	Spain
Prof.	Paolo	Samorì	University of Strasbourg	France
Prof.	Guangyu	Zhang	Institute of Physics, Chinese Academy of Sciences (CAS)	China
Prof.	Yuanbo	Zhang	Fudan University	China

List of participants*

Title	Last name	First name	Institution	Country
Dr.	Gokhan	Bakan	National Physical Institute	United Kingdom
Dr.	Ana-Maria	Ciubotaru	European Science Foundation	France
Mr.	Peng	Fan	Institute of Physics, Chinese Academy of Sciences	China
Dr.	Fernando	Gomollon – Bel	University of Cambridge	United Kingdom
Dr.	Ana	Helman	European Science Foundation	France
Mrs.	Li	Huang	Institute of Physics, Chinese Academy of Sciences	China
Dr.	Nathaniel J.	Huáng	National Physical Laboratory	United Kingdom
Dr.	Guo	Hui	Institute of Physics, Chinese Academy of Sciences	China
Prof.	Lili	Jiang	University of Chinese Academy of Sciences	China
Dr.	Deng	Jun	Institute of Physics, Chinese Academy of Sciences	China
Mr.	Zhixuan	Li	University of Chinese Academy of Sciences	China
Prof.	Kaihui	Liu	Institute of Physics, Chinese Academy of Sciences	China
Dr.	Kejun	Liu	Technische Universität Dresden	Germany
Mr.	Chenjun	Ma	Nanjing University	China
Dr.	Marco	Nardi	Italian National Research Council (IMEM)	Italy
Dr.	Ruixi	Qiao	Peking University	China
Mr.	Xinwei	Shi	University of Chinese Academy of Sciences	China
Ms.	Camelia	Steinmetz	European Science Foundation	France
Dr.	Melanie	Timpel	Italian National Research Council (IMEM)	Italy
Dr.	Isabella Anna	Vacchi	European Science Foundation	France
Prof.	Haohao	Xu	University of Chinese Academy of Sciences	China

*For 22 attendees (not listed) the information on the affiliation and country was not available.

BOOK OF ABSTRACTS

Valley-selective hall and optoelectronics of twisted and bilayer graphene

Frank Koppens
Institute of Photonic Sciences (ICFO), Spain

Short biography

Prof. Frank Koppens is group leader at the Institute of Photonic Sciences (ICFO). The quantum nano-optoelectronics group of Prof. Koppens focuses on both science and technology of novel two-dimensional materials and quantum materials. Prof. Koppens is vice-chairman of the executive board of the graphene flagship program and the leader of the optoelectronics workpackage within the flagship.

Abstract

Two-dimensional (2D) materials offer extraordinary potential for control of light and light-matter interactions at the atomic scale. In particular, twisted 2D materials has recently attracted a lot of interest due to the capability to induce moiré superlattices and discovery of electronic correlated phases [1,2]. In this talk, we present nanoscale optical techniques such as near-field optical microscopy and photocurrent nanoscopy, and reveal with nanometer spatial resolution unique observations of the optical properties of twisted 2D materials. The freedom to engineer these so-called optical and electronic quantum metamaterials [1,3] is expected to expose a myriad of unexpected phenomena.

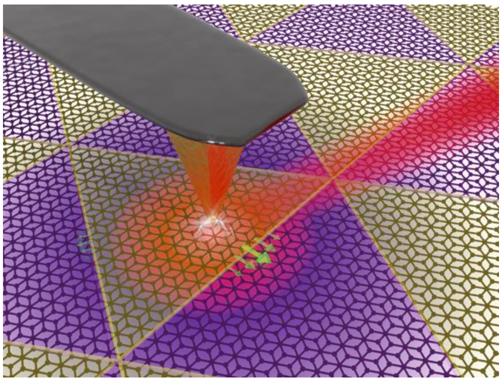


Figure 1: Photocurrent nanoscopy inside the Moiré unit cell of minimally twisted bilayer graphene

References:

[1] Song, Gabor et. al., Nature Nanotechnology (2019)
[2] Cao et al., Nature (2018)
[3] Hesp et al., Nature Physics (2021)
[4] Hesp et al., Nature Communications (2020)
[5] Epstein et al., Science (2020)
[6] Herzig Sheinfux et al., (2021)

Monolayer MoS_2 for large scale electronics

Guangyu Zhang
Institute of Physics, Chinese Academy of Sciences, China

Short biography

Guangyu Zhang, Professor of Physics, group leader in Nanoscale Physics and Devices Lab., Institute of Physics, Chinese Academy of Sciences. His main research interests include: 1) transport study of moire superlattices; 2) investigation of electronic devices; in the area of 2D materials. He has published more than 170 peer reviewed papers in prestigious scientific journals with a H-index >50.

Abstract

In the past decade, 2D semiconductors are an emergent family of new materials that are intensely investigated. Such materials are naturally thin, flexible, and transparent, offering great promise in various electronic applications. In this talk, I will introduce our recent progress on wafer-scale epitaxy of intrinsic and doped high-quality monolayer MoS2; demonstration of large-scale flexible devices based on wafer-scale monolayer MoS2; and vertical assembly of different 2D layers for 3D integration.

Layered Quantum Materials and Applications

Andrea Ferrari
University of Cambridge, United Kingdom

Short biography

Andrea Ferrari is Professor of nanotechnology at the University of Cambridge and a Fellow of Pembroke College. He founded and directs the Cambridge Graphene Centre and the Engineering and Physical Sciences Research Council Doctoral Training Centre in Graphene Technology. He chairs the management panel and is the Science and Technology Officer of the European Graphene Flagship. He is a Fellow of the American Physical Society, Fellow of the Materials Research Society, Fellow of the Institute of Physics, Fellow of the Optical Society and he has been recipient of numerous awards, such as the Royal Society Brian Mercer Award for Innovation, the Royal Society Wolfson Research Merit Award, the Marie Curie Excellence Award, the Philip Leverhulme Prize, The EU-40 Materials Prize.

Abstract

Not provided

Quantum anomalous Hall effect in intrinsic magnetic topological insulator $MnBi_2Te_4$

Yuanbo Zhang
Department of Physics, Fudan University, China

Short biography

Yuanbo Zhang received his BS from Peking University in 2000 and his PhD in Physics from Columbia University in 2006. He was a Miller Research Fellow at the University of California at Berkeley from Sept. 2006 to Jun. 2009, a postdoc research associate at IBM Almaden Research Center from Mar. 2010 to Sept. 2010, and a professor of Fudan University from 2011. His main research interests are: Electronic transport in low-dimensional systems including graphene; Scanning probe techniques and their application in studying low-dimensional nanostructures. Major honors include: IUPAP Young Scientist Prize, International Union of Pure and Applied Physics (2010); Nishina Asia Award, Nishina Memorial Foundation, Japan (2014).

Abstract

In a magnetic topological insulator, nontrivial band topology conspires with magnetic order to produce exotic states of matter that are best exemplified by quantum anomalous Hall (QAH) insulators and axion insulators. Up till now, such magnetic topological insulators are obtained by doping topological insulators with magnetic atoms. The random magnetic dopants, however, inevitably introduce disorders that hinder further exploration of topological quantum effects in the material. We resolve this dilemma by probing quantum transport in MnBi2Te4 thin flake—a topological insulator with intrinsic magnetic order. In this layered van der Waals crystal, the ferromagnetic layers couple anti-parallel to each other, so bulk $MnBi_2Te_4$ is an antiferromagnet. Atomically thin $MnBi_2Te_4$, however, becomes ferromagnetic when the sample has odd number of septuple layers (a septuple layer represents a single structural unit in the out-of-plane direction). We observe zero-field QAH effect in a five-septuple-layer specimen; an external magnetic field further enhance the QAH quantization by forcing all layers to align ferromagnetically. $MnBi_2Te_4$ therefore becomes the first intrinsic magnetic topological insulator exhibiting QAH effect. The results establish $MnBi_2Te_4$ as an ideal arena for further exploring various topological phenomena.

The Universe of Disordered and Amorphous Two-dimensional Materials: Scientific Challenges & Technology Opportunities

Stephan Roche

ICREA and Catalan Institute of Nanoscience and Nanotechnology (ICN2), CSIC and BIST, Campus de la UAB, Spain

Short biography

ICREA Prof. Stephan Roche is working at the Catalan Institute of Nanosciences and Nanotechnology-ICN2 and BIST. He leads the "Theoretical and Computational Nanoscience" group which focuses on physics of Dirac materials (graphene & topological insulators) and 2D materials-based van der Waals heterostructures. He pioneered the development of linear scaling quantum transport approaches enabling simulations of billion atoms-scale disordered models (wwwlsquant.org). He studied Theoretical Physics at ENS and got PhD (1996) at Grenoble University (France); worked in Japan, Spain & Germany; was appointed as assistant Prof. in 2000, CEA Researcher in 2004 and joined ICREA in 2009. He received the Friedrich Wilhelm Bessel prize from the Alexander von Humboldt Foundation (Germany). Since 2013, he has been very active in the Graphene Flagship, currently as leader of the workpackage SPINTRONICS and is acting as DIVISION leader.

Abstract

After fifteen years of pursuing the fabrication or single crystal growth of monolayer materials, it turns out that for plenty of practical and performances reasons, more disordered forms such as reduced graphene oxides, polycrystalline or even totally amorphous forms of monolayer membranes present superior properties for heterostructures applications and composites. Here I will discuss the importance to explore the variety of physical properties of such disordered or completely amorphous forms of two-dimensional based materials and devices in the context of industrial applications including gas sensing, composites for thermal, electronic and spintronic applications. Particular attention will be devoted to amorphous forms of sp^2 carbon and recently emerged amorphous boron-nitride, which are presently unprecedented properties of advanced microelectronics materials or neuromorphic computing.

This work is supported by the European Union’s Horizon 2020 research and innovation programme under grant agreement No 825272.

References:

[1] A. Isacsson, A.W. Cummings, L. Colombo, L. Colombo, J.M. Kinaret, S. Roche, *Scaling properties of polycrystalline graphene: a review*, **2D Materials** 4 (1), 012002 (2016);

[2] S Hong, et al. A. Antidormi, S. Roche, M. Chhowalla, H.-J. Shin, H. S. Shin, *Ultralow-dielectric-constant amorphous boron nitride*, **Nature** 582 (7813), 511-514 (2020)

[3] C Wen, X Li, T Zanotti, FM Puglisi, Y Shi, F Saiz, A Antidormi, S Roche, et al. *“Data Encryption: Advanced Data Encryption using 2D Materials”*, **Advanced Materials** 33 (27), 2170205 (2021)

[4] A Antidormi, S Roche, L Colombo, *Thermal transport in amorphous graphene with varying structural quality* **2D Materials** 8 (1), 015028 (2020)

Designed Growth and Applications of Meter-sized 2D Single Crystals

Kaihui Liu
School of Physics, Peking University, China

Short biography

Kaihui Liu is currently a professor of Physics in Peking University, China. He received his Ph.D. from the Institute of Physics, Chinese Academy of Sciences in 2009 and afterward worked as a postdoctoral research fellow at UC Berkeley until 2014. His current research interests are the manufacture, characterization and application of two-dimensional (2D) single-crystal materials. His main academic achievements include (i) designing the interfacial element feeding for the ultrafast growth of 2D materials, (ii) developing a universal method for the synthesis of meter-sized 2D single-crystals, and (iii) fabricating advanced 2D materials-optical fibre devices. Professor Liu has published more than 50 correspondence-authored papers, including Nature (2) and other Nature series (10). Currently, Prof. Liu serves as the Associate Editor of Science Bulletin and team leader of National Key R&D Program of China. Besides, he has received several honors, including The National Science Fund for Distinguished Young Scholars (2020), Beijing Municipal Natural Science Foundation for Distinguished Young Scholars (2019), Beijing Outstanding Young People (2017), Third prize of Beijing Science & Technology Award (2017), and Ten "Xin Rui" Scholar of China (2016).

Abstract

Single-crystal materials have demonstrated as one main driving force to proceed the development of high-tech industry. From the first-generation semiconductor of silicon, the second-generation of gallium arsenide to the third-generation of gallium nitride, the large-size high-quality single crystals have promoted significant improvements in the performances of the electronic and optoelectronic devices. Now we are entering a “post-Moore” era, and new single-crystal materials are highly desired to accelerate the development of technologies in the 21st century. Quantum materials, including two-dimensional (2D) materials, topological materials, superconducting materials, etc., are novel single crystals that are expected to bring innovative applications and launch the next industrial revolution. In this talk, I will introduce our recent progress on the interfacial engineering of 2D materials growth, the manufacturing of meter-scale 2D single crystals, and the applications of 2D materials embedded optical fiber devices. The developed materials and technologies are expected to be applied to electronic circuitry, acoustic devices, photoelectric catalysis, thermal management and other fields.

Two-dimensional materials for printable and wearable applications

Gianluca Fiori
Dipartimento di Ingegneria dell'Informazione, University of Pisa, Italy

Short biography

Gianluca Fiori is Professor of Electronics at University of Pisa, from which he obtained the PhD in 2005. Prof. Fiori's field of activity includes the modelling, the fabrication and electrical characterization of novel devices based on new architectures and new materials. Prof. Fiori has a renowned expertise in assessing device performance against Industry requirements, through the exploitation of purposely-devised multi-scale, multi-physics in-house atomistic simulators.

Prof. Fiori's interest also focuses on printed electronics, aiming at obtaining fully printed integrated circuits on flexible substrates as paper.

Abstract

Two-dimensional materials (2DMs) can be the game changer for a wide range of applications, due to their mechanical and electrical characteristics with unpreceded performance.
From the perspective of a device engineer, the goal is to obtain wearable circuits and systems on flexible substrates [1] with performance comparable to what obtained on rigid substrates [2,3].
In this talk, I will show recent results on this topic, while addressing the main issues and potentials this technological option is currently facing and providing performance projections through a purposely devised theoretical approach.

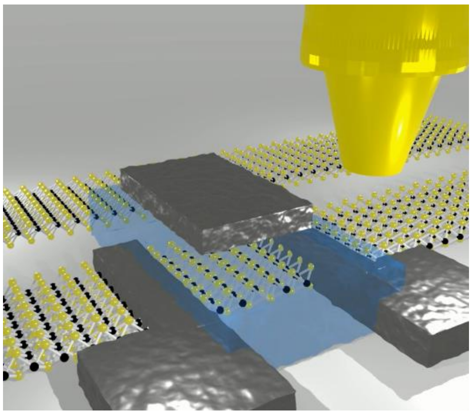


Figure 1: Sketch of an inkjet printed transistor exploiting 2DMs

References:

[1] Silvia Conti, Lorenzo Pimpolari, Gabriele Calabrese, Robyn Worsley, Subimal Majee, Dmitry K Polyushkin, Matthias Paur, Simona Pace, Dong Hoon Keum, Filippo Fabbri, Giuseppe Iannaccone, Massimo Macucci, Camilla Coletti, Thomas Mueller, Cinzia Casiraghi, Gianluca Fiori, Nature Communications, 11, 3566, 2020.
[2] Dmitry K Polyushkin, Stefan Wachter, Lukas Mennel, Matthias Paur, Maksym Paliy, Giuseppe Iannaccone, Gianluca Fiori, Daniel Neumaier, Barbara Canto, Thomas Mueller, Nature Electronics, 3, 486, 2020
[3] Yury Yu Illarionov, Theresia Knobloch, Markus Jech, Mario Lanza, Deji Akinwande, Mikhail I Vexler, Thomas Mueller, Max C Lemme, Gianluca Fiori, Frank Schwierz, Tibor Grasser, Nature Communications, 11, 3385, 2020

Discovery of layered 2D $MoSi_2N_4$ family

Wencai Ren

Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, China

Short biography

Dr. Wencai Ren is a professor in materials science at the Institte of Metal Research, Chinese Academy of Sciences. His research interests mainly focus on the synthesis of graphene and other two-dimensional materials and their applications in optoelectronics, energy storage, thermal management, and membrane technology. Prof. Ren has published over 160 papers in *Science*, *Nature Mater.*, *Nature Nanotechnol., Nature Commun.*, *PNAS*, *Adv. Mater.*, *JACS, etc.* with a total citation over 27,000 times, and filed more than 100 patents (over 60 issued). He is also a main founder of two graphene companies. He has received several awards including the Second Prize of National Natural Science Award, HO LEUNG HO LEE FOUNDATION Prize for Scientific and Technological Innovation, National Science Fund for Distinguished Young Scholars, and National Award for Youth in Science and Technology.

Abstract

Identifying 2D layered materials in the monolayer limit has led to discoveries of numerous new phenomena and unusual properties. We have developed a chemical vapor deposition (CVD) method to grow high-quality nonlayered 2D transition metal carbides/nitrides with diverse structures. However, these nonlayered materials tend to grow as islands rather than layers because of surface energy constraints. Recently, we introduced elemental silicon during CVD growth of non-layered molybdenum nitride to passivate its surface dangling bonds, which enabled the growth of centimeter-scale monolayer films of a new van der Waals layered material, MoSi2N4. This monolayer was built up by septuple atomic layers of N-Si-N-Mo-N-Si-N, which can be viewed as a MoN2 layer sandwiched between two Si-N bilayers. This material exhibited semiconducting behavior (bandgap, ~1.94 eV), high strength (~66 GPa), and excellent ambient stability. Density functional theory calculations predict a large family of such monolayer structured 2D layered materials, including semiconductors, metals, magnetic half-metals, superconductors, and topological insulators, which are expected to have promising applications in electronics, spintronics, valleytronics, optoelectronics, energy conversion and storage, and thermal management.

References:

1. C. Xu, L. B. Wang, Z. B. Liu, L. Chen, J. K. Guo, N. Kang, X. L. Ma, H. M. Cheng, W. C. Ren, Large-area high-quality 2D ultrathin Mo2C superconducting crystals, Nature Materials 14: 11, 1135-1141 (2015)
2. Y. L. Hong, Z. B. Liu, L. Wang, T. Y. Zhou, W. Ma, C. Xu, S. Feng, L. Chen, M. L. Chen, D. M. Sun, X. Q. Chen, H. M. Cheng, W. C. Ren, Chemical vapor deposition of layered two-dimensional MoSi2N4 materials, Science 369: 6504, 670-674 (2020).

Multi-responsive and high-performance 2D materials based opto-electronic devices

Paolo Samori
Institut de Science et d'Ingénierie Supramoléculaires - Université de Strasbourg & CNRS, Strasbourg, France

Short biography

Paolo Samorì is Distinguished Professor at the University of Strasbourg and Director of the *Institut de Science et d'Ingénierie Supramoléculaires* (ISIS), where he leads the Nanochemistry Laboratory. He obtained a master's degree (*Laurea*) in Industrial Chemistry from the University of Bologna, Italy in 1995 and a PhD in chemistry from the Humboldt University of Berlin, Germany in 2000. He was appointed Permanent Researcher at the National Research Council (CNR) in Bologna in 2001, Visiting Professor at ISIS in 2003 and Full Professor in 2008.
The current research activities of Paolo Samorì are focused on the chemistry of two-dimensional materials, smart supramolecular systems as well as high-performance multifunctional materials and (nano)devices in order to develop an "Internet of functions" for energy, sensing and optoeletronic applications.

Paolo Samorì was elected Junior Member of the *Institut Universitaire de France* (IUF) in 2010, Fellow of the Royal Society of Chemistry (FRSC) in 2012, Member of the Academia Europaea and of the European Academy of Sciences (EURASC) in 2014 and Foreign Member of the Royal Flemish Academy of Belgium for Science and the Arts (KVAB) in 2019. He also received numerous prestigious awards, including the Guy Ourisson Prize from the *Cercle Gutenberg* in 2010, the CNRS Silver Medal in 2012, the Spanish-French Catalán–Sabatier Prize from the Spanish Royal Society of Chemistry (RSEQ) and the German-French Wittig–Grignard Prize from the German Chemical Society (GDCh) in 2017, the RSC Surfaces and Interfaces Award, the Pierre Süe Prize from the French Chemical Society (SCF) and the Blaise Pascal Medal in Materials Science from EURASC in 2018, the ERC Advanced Grant (2019), the "Étoiles de l'Europe" Prize (2019), the ERC Proof of Concept Grant (2020), the RSC/SCF Joint Lectureship in Chemical Sciences (2020) and MRS fellow (2021).

Paolo Samorì is Associate Editor of *Nanoscale* and *Nanoscale Advances* (RSC) and Member of the Advisory Board of *Advanced Materials*, *Small*, *ChemPlusChem*, *ChemNanoMat*, *ChemPhysChem*, *ChemSystemsChem* (Wiley-VCH), *Chemical Society Reviews*, *Nanoscale Horizons*, *Journal of Materials Chemistry*, *Chemical Communications* (RSC), *ACS Nano*, *ACS Omega* (ACS) and *BMC Materials* (Springer Nature).

Abstract

Two dimensional materials exhibit exceptional physical and chemical properties which can be further enhanced and enriched via the controlled functionalization with molecules and (supra)molecular assemblies thereof yielding hybrid systems with ad hoc characteristics for applications in (opto)electronics, sensing and energy. Molecules can be designed and synthesized in order to physisorb or chemisorb onto 2D materials in a controlled fashion.
In my lecture I will review our recent findings on the functionalization of 2D materials to engineer hybrid systems *via*:
- physisorption of molecular switches onto the two surfaces of scotch tape and CVD 2D ambipolar semiconductors, following a Janus approach, as a route to confer two distinct and additional properties to WSe_2, rendering the 2D material-based transistors capable to respond to four different independent stimuli.

- chemisorption of doubly-thiolated molecules onto solution-processed semiconducting transition metal dichalcogenides as a way to simultaneously heal sulfur vacancies in metal disulfides (MS_2) and covalently bridge adjacent flakes, thereby promoting percolation pathways for the charge transport, leading to an increase by one order-of-magnitude in field-effect mobility, I_{ON} / I_{OFF} ratio, and switching times of liquid-gated transistors.

Our modular strategies relying on the combination of 2D material with molecules offer a simple route to generate multifunctional 2D materials-based coatings, foams and nanocomposites with pre-programmed properties to address key global challenges in electronics, sensing and energy applications.

Figures:

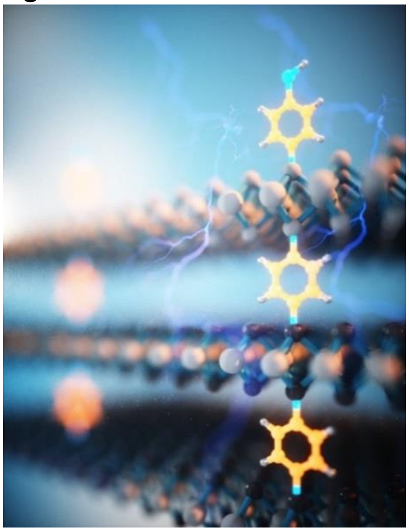


Figure 1: 1,4-benzenedithiol molecules simultaneously healing sulfur vacancies in solution-processed MoS_2 and covalently bridging adjacent flakes, to create percolation pathways for the charge transport in transistors.

Atomically Sharp Interface of van der Waals Heterostructures Enabled High-performance Electronic Devices

Lihong Bao
Institute of Physics, Chinese Academy of Sciences, China

Short biography

I received the Ph. D for condensed matter physics in Institute of Physics, CAS in 2008. After the postdoctoral research at University of South Carolina and Iowa State University, USA, I joined in Institute of Physics, CAS as an associate Professor in 2013. Currently, my research is mainly focused on construction, electronic devices, and electrical transport properties of low-dimensional systems. The other important aspect of my research is in-situ measurement of electrical transport properties of low-dimensional materials and characterization of their structure-property relationship by UHV four probe-STM. In past years, I have published more than 70 papers in high-profile journals, including Nature Nanotechnology, Nature Communications, Nano Letters, Advanced Materials, Applied Physics Letters etc., and have been cited by others for more than 2700 times.

Abstract

While the scaling of devices continues, to meet the increasing demands for high performance, silicon-based technology will soon reach a critical limit. One of the key challenges is related to the unavoidable interfacial dangling bonds in ultrathin-body silicon, which causes substantial degradation in device performance. It is thus an urgent need to seek atomically sharp interfaces and seamlessly integrate them into the device architecture. Among all candidates, emerging two-dimensional (2D) materials and their heterostructures represent ideal atomically flat in-plane surfaces potentially free from surface dangling bonds and are immune to short-channel effects that can allow effective electrostatic control and mechanical flexibility.

In this talk, I will demonstrate that by mechanical exfoliation and dry-transfer method, InSe/hBN/graphite van der Waals heterostructure with atomically sharp interface have been successfully achieved. Using this heterostructure as the unit of 2D field-effect transistor (FET), with InSe as channel material, hBN as dielectric, and graphite as gate, respectively, we obtained high-performance heterostructured InSe FETs with high electron mobility up to 1146 $cm^2V^{-1}s^{-1}$ at room temperature and on/off ratio up to 10^{10}. Digital inverters are constructed by integrating two such FETs with local gate modulation and an ultrahigh voltage gain up to 93.4 is achieved. Furthermore, the heterostructured InSe FET stacked on a flexible substrate shows little change in performance at high strain level of ~ 2%.

The InSe/hBN van der Waals heterostructure can also work as the core component of the photodetector due to the superior optoelectronic properties of InSe. We will show that using ferroelectric organic P(VDF-TrFE) thin film as the top gate dielectric, the dark current in the photodetector can be successfully suppressed to 10^{-14} A. At the same time, hexagonal boron nitride (hBN) is used as substrate to improve the interface between the dielectric layer and the InSe channel. As a result, the ferroelectric-copolymer-gated InSe photodetectors not only show a high on/off ratio of over 10^8, but also exhibit high photoresponsivity up to 14250 AW^{-1} and detectivity as high as 1.63 $\times 10^{13}$ Jones even at zero gate voltage in the polarization-up state.

When we placed the InSe/hBN/graphite van der Waals heterostructure onto SiO_2/Si substrate, this heterostructure can work as a floating-gated FET, an elementary device of flash memory, with InSe, hBN, graphite, SiO_2 and p++ Si serving as the channel, tunnel barrier, floating gate, control-gate dielectric and control gate, respectively. Due to the improved interfacial coupling and atomically sharp interface, ultrahigh-speed operation with nanoscecond write and read times that is limited by

instrumentation response, extremely high extinction ratio of 10^{10} and a retention time of 10 year have been achieved in the floating-gate memory devices based on this van der Waals heterostructure.
All the above results highlight that van der Waals heterostructures offer a unique platform for next-generation high-performance electronic devices.

References:
[1] Wu L. M. et al. InSe/hBN/graphite heterostructure for high-performance 2D electronics and flexible electronics. Nano Research, 2020, 13: 1127-1132.
[2] Liu L. et al. Ferroelectric-gated InSe photodetectors with high on/off ratios and photoresponsivity. Nano Letters, 2020, 20: 6666-6673.
[3] Wu L. M. et al. Atomically sharp interface enabled ultrahigh-speed, nonvolatile memory devices. Nature Nanotechnology (2021, published online).