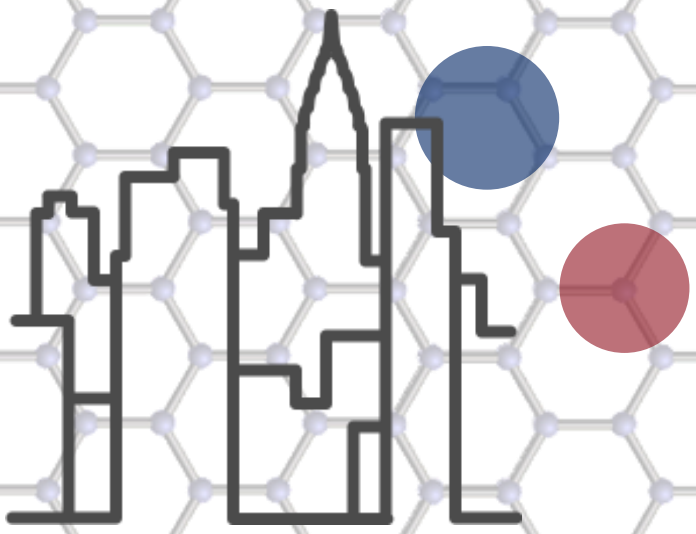
GRAPHENE FOR US

ONLINE

International Conference

★ Feb. 23-24, 2021 ★

www.grapheneforus.com



ABSTRACTS BOOK

ORGANIZERS

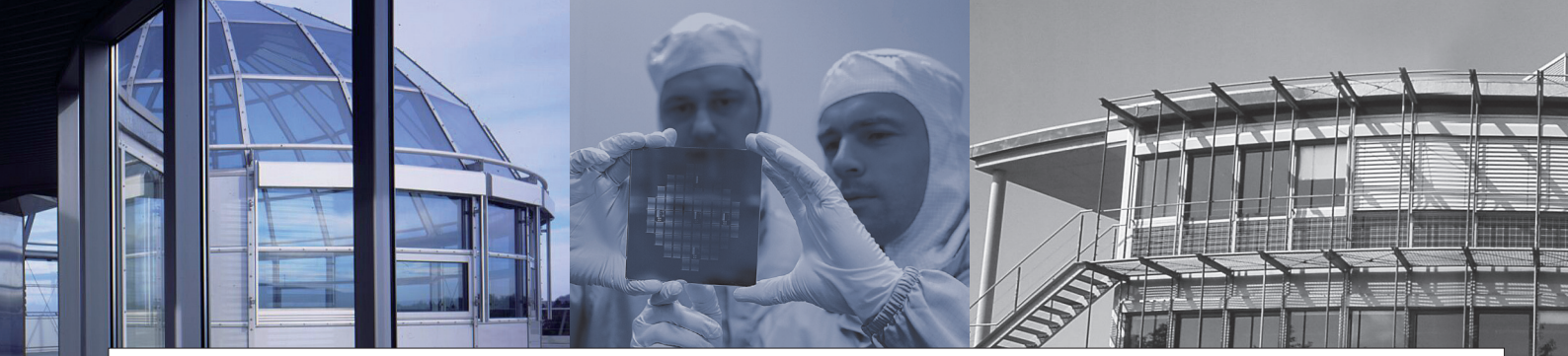
PHANTOMS foundation

PennState

UT DALLAS
The University of Texas at Dallas

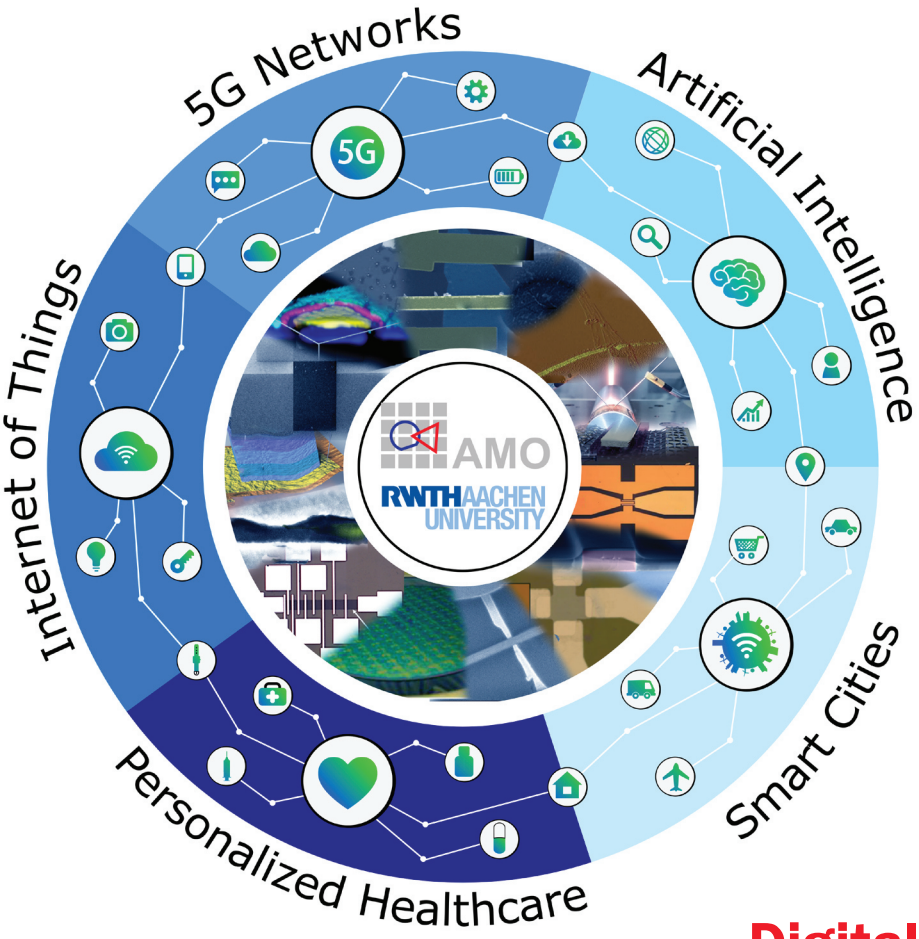
Rensselaer

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK



Aachen Graphene & 2D-Materials Center

From basic research to innovation



Digital Hardware

- Electronics for neuromorphic computing
- Sensor technology for autonomous driving and IoT
- Optoelectronics for high speed data communication
- Electronics for wearables and implantables

AMO

AMO GmbH
Otto-Blumenthal-Straße 25 ■ D-52074 Aachen ■ Germany
Phone +49 241 88 67-125 ■ Fax +49 241 88 67-571
services@amo.de ■ www.amo.de

INDEX

FOREWORD

On behalf of the Organising Committee we take great pleasure in welcoming you to the 4th edition of the **GrapheneforUS** 2021 International Conference.

GrapheneforUS 2021 online will be a 2 days event that means to gather the key players of the Graphene Community and related sectors. This event is launched again following the success of the 2018, 2019 & 2020 in-person editions. **GrapheneforUS** is now already an established event attracting global participants and sharing, exchanging, exploring new avenues of graphene-related scientific and commercial developments.
We truly hope that **GrapheneforUS** 2021 serves as an international platform for communication between science and business.

We are indebted to the following Scientific Institutions and Companies for their help and/or financial support: AMO GmbH, Heidelberg Instruments, PennState (Materials Research Institute) / Center for 2-Dimensional and Layered Materials (2DLM), Columbia University, Texas Instruments and SRC nCORE.

We also would like to thank all the exhibitors, speakers and participants that join us this year.

One thing we have for granted: very few industries, one way or another, will escape from the influence of Graphene and 2D Materials and the impact on businesses is here to stay.

Hope to see you again in the next edition of **GrapheneforUS** to be held in 2022 in New York.

ORGANIZERS

COMMITTEES

Organising Committee

Antonio Correia (Phantoms Foundation, Spain)
Luigi Colombo (University of Texas at Dallas, USA)
James Hone (Columbia University, USA)
Vincent Meunier (Rensselaer Polytechnic Institute, USA)
Mauricio Terrones (PennState University, USA)

SPONSORS

Silver Sponsors

AMO GmbH is a German high-tech company that acts as a pathfinder for new technologies and as fabrication-service provider in the field of nanotechnology since more than 20 years.
AMO operates a state-of-the-art clean room with advanced nanostructuring capabilities (UV- Nanoimprint, E-Beam lithography, Interference Lithography), offering research and fabrication services that go from proof-of-concept demonstrators to final technological solutions. Main fields of expertise are nanoelectronics, photonics, sensor technology, as well as graphene and other two-dimensional materials.

More info: https://www.amo.de/

Heidelberg Instruments and SwissLitho AG joined forces in early 2018. Together, they offer the widest range of direct write micro- and nanolithography systems in the world, from low-cost desktop solutions to high-end writers for substrates larger than 1m. Their products are used for prototyping in R&D, industrial manufacturing, and academic research. A full wafer can be patterned in a few minutes with sub-micron resolution, making mask aligners obsolete. Single-nm resolution with simultaneous pattern inspection is achieved with the unique NanoFrazor technology. Systems from both companies can be used to obtain micro- and nanostructures with high aspect ratio as well as in grayscale mode, which makes them particularly suitable to create templates for NIL applications.

More info: https://heidelberg-instruments.com/en/

Bronze Sponsor

Texas Instruments

Other Sponsors

2DLM Center for 2-Dimensional and Layered Materials

Columbia University in the City of New York

SRC Semiconductor Research Corporation

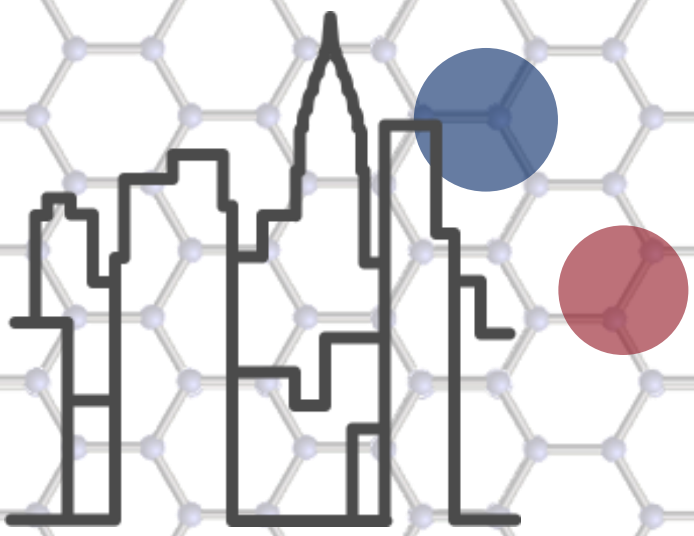
EXHIBITORS

Heidelberg Instruments

Phantoms Foundation

ABSTRACTS INDEX

Index alphabetical order



KEYNOTE SPEAKERS

Zhihong Chen
School of Electrical and Computer Engineering and Birck Nanotechnology Center Purdue University, West Lafayette, IN 47907

zhchen@purdue.edu

2D Materials for Back-end-of-line Interconnect Application

2D materials have unique properties that can be utilized in designing next generation interconnects. For example, some 2D materials have been considered as alternative barrier/liner to replace conventional TaN/Ta bilayer, since these atomically thin materials are proven to be able to efficiently block Cu diffusion and their atomically thin body thickness can maximize Cu volume in ultra-scaled interconnects to achieve lower line resistance. In this talk, I will show that the diffusion barrier and liner properties of several 2D materials are investigated by various characterization methods. We observe that the lifetime of the dielectrics surrounding Cu electrodes can be significantly extended with the presence of the tested 2D barriers, providing strong evidence for promising alternative barrier/liner solutions.

Dmitri Efetov
ICFO, Spain

Dmitri.Efetov@icfo.eu

Competing phases of correlated Chern insulators in Superconducting Twisted Bilayer Graphene

Flat-bands in magic angle twisted bilayer graphene (MATBG) have recently emerged as a rich platform to explore strong correlations, superconductivity and magnetism. Here we use magneto-transport and Hall measurements to reveal a rich sequence of wedge-like regions of quantized Hall conductance with Chern numbers C = ±1, ±2, ±3, ±4 which nucleate from integer fillings of the moiré unit cell ν = ±3, ±2, ±1, 0 correspondingly. We interpret these phases as spin and valley polarized many-body Chern insulators. The exact sequence and correspondence of Chern numbers and filling factors suggest that these states are driven directly by electronic interactions, which specifically break time-reversal symmetry in the system. In addition we observe correlated Chern insulator in zero magnetic field in hBN non-aligned MATBG, which manifests itself in an anomalous Hall effect around a filling of one electron per moiré unit cell n = +1 with a Chern number of C = 1 and has a relatively high Curie temperature of Tc ≈ 4.5 K. Slight gate tuning away from this state exposes strong superconducting phases with critical temperatures of up to Tc ≈ 3.5 K. In a perpendicular magnetic field above B > 0.5 T we observe a transition of the n = +1 Chern insulator from a Chern number C = -1 to a higher C = 3, which is characterized by a quantized Hall plateau with Ryx = h/3e2. These observations show that interaction-induced time-reversal symmetry breaking in MATBG leads to a zero-field ground state which consists of almost degenerate and closely competing Chern insulators, where the B-field always couples strongest to states with higher Chern numbers. Our study is also the first demonstration of a system which allows gate-induced transitions between magnetic and superconducting phases, and hence marks a major milestone in the creation of a new generation of quantum electronics.

Ado Jorio[1]

AC Gadelha[1], DAA Ohlberg[1], C Rabelo[1], JL Campos[1], JS Lemos[1], V Ornelas[1], D Miranda[1], R Nadas[1], FC Santana[1], LC Campos[1], G Medeiros-Ribeiro[1], LG Cançado[1], EGS Neto[2], TL Vasconcelos[3], V-H Nguyen[4], D Paszko[4], J-C Charlier[4], B van Troeye[5], M Lamparski[5], V Meunier[5]

[1]Physics Department, UFMG, Belo Horizonte, Brazil; [2]Physics Institute, UFBA, Salvador, Brazil; [3]Divisão de Metrologia de Materiais, Inmetro, Duque de Caxias, Brazil; [4]Institute of Condensed Matter and Nanosciences (IMCN), University of Louvain (UCLouvain), Louvain-la-Neuve, Belgium; [5]Physics, Applied Physics, and Astronomy, Jonsson Rowland Science Center, NY, USA.

adojorio@fisica.ufmg.br

Phonon localization in low-angle twisted bilayer graphene

Superconductivity has been found in bilayer graphene at the magic angle [1]. Below the magic angle, the bilayer graphene exhibits reconstruction, entering the strain soliton regime [2]. Direct optical images of the crystal superlattice in reconstructed twisted bilayer graphene are reported here [3], generated by nano-Raman spectroscopy (see figure) [4-9]. The observation of the crystallographic structure with visible light is made possible due to lattice dynamics localization, the images resembling spectral variations caused by the presence of strain solitons and topological points. The results are rationalized by a nearly-free-phonon model and electronic calculations that highlight the relevance of solitons and topological points, particularly pronounced for structures with small twist angles.

References

[1] Y. Cao *et al.* Nature, 556(7699) (2018) 43–50.
[2] S. Jonathan *et al.* Proc. Nat. Acad. Sci. USA 110 (2013) 11256–11260.
[3] A.C. Gadelha *et al.*Nature (2021) https://www.nature.com/articles/s41586-021-03252-5
[4] T.L. Vasconcelos *et al.* Adv. Opt. Materials 6.20 (2018) 1800528.
[5] C. Rabelo *et al.* In 4th Int. Symp. Instrumentation Systems, Circuits and Transducers (INSCIT) 1–6 (IEEE, 2019).
[6] C. Rabelo *et al.* Phys. Rev. Applied 14 (2020) 024056
[7] H. Miranda *et al.* Phys. Rev. Res. 2 (2020) 023408.
[8] H. Miranda *et al.* Phys. Status Solidi Rapid Research 14 (2020) 2000212.
[9] A.C. Gadelha *et al.* ACS Appl. Nano Matter (2021) https://dx.doi.org/10.1021/acsanm.0c03230

Figures

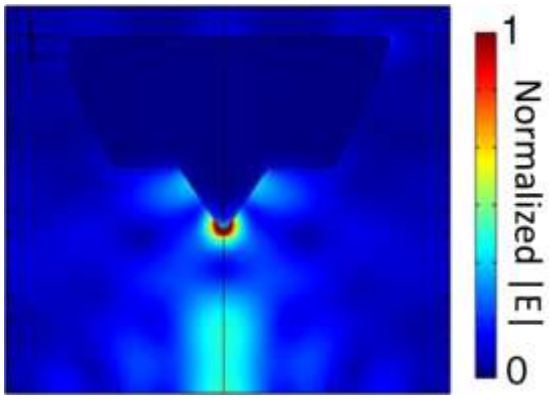


Figure 1: Nano-Raman field distribution generated in the tip-enhanced Raman spectroscopy (TERS) configuration [8].

Richard B. Kaner
Chenxiang Wang, Mit Muni, Xueying Chang, Ailun Huang, Sheng Qu, Samantha Que Anh Vi-Tang
Department of Chemistry and Biochemistry and California NanoSystems Institute, UCLA, Los Angeles, United States
kaner@chem.ucla.edu

Graphene Synthesis and Applications in Supercapacitors

Graphene is the ultimate two-dimensional material consisting of a single layer of sp^2 hybridized carbon.[1] A facile, inexpensive, solid-state method for generating, patterning and electronic tuning of laser converted graphene will be discussed (Figure 1).[2] Briefly, graphite can be converted into graphene oxide (GO) sheets, which readily disperse in water, and can then be reduced by various methods.[3] Due to its unique ability to be solution processed and patterned, GO can be laser reduced to graphene directly onto various substrates without masks, templates, post processing, or transfer techniques.[4,5] This work paves the way for the fabrication of inexpensive electrochemical energy storage devices that combine the energy density of batteries and the power density of capacitors.[6]

References

[1] D. Li, M.B. Muller, S. Gilje, R.B. Kaner and G.G. Wallace, *Nature Nanotechnology*, **3** (2008) 101-105.
[2] M.F. El-Kady, V. Strong, S. Dubin and R.B. Kaner, *Science*, **335** (2012) 1326-1330.
[3] J. Wassei, R.B. Kaner, *Acc. Chem. Res.*, **46** (2013) 2244-2251.
[4] M.F. El-Kady, M. Ihns, M. Li, J.Y. Hwang, M.F. Mousavi, L. Chaney, A.T. Lech and R.B. Kaner, *Proc. Nat. Acad. Sci.*, **112** (2015) 4233-4238.
[5] M.F. El-Kady, Y. Shao, R.B. Kaner, *Nature Review Materials*, **1** (2016) 16033-16046.
[6] Y. Shao, M.F. El-Kady, J. Sun, Y. Li, Q. Zhang, M. Zhu, H. Wang, B. Dunn and R.B. Kaner, *Chem. Rev.*, **118** (2018) 9233-9280.

Figures

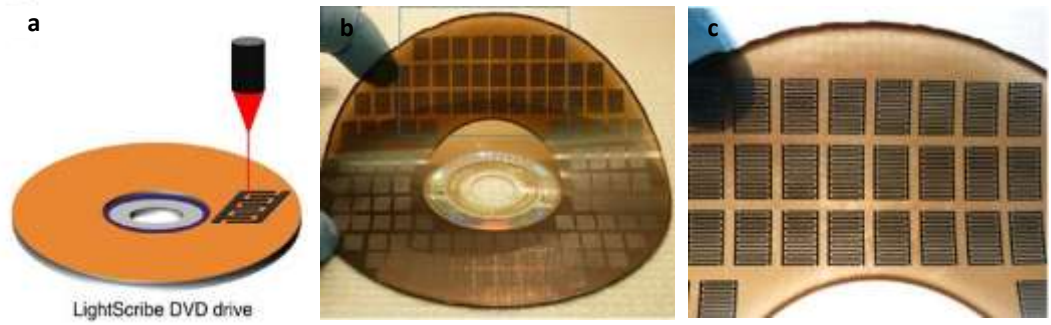


Figure 1: (a) Schematic showing the fabrication process of a graphene micro-supercapacitor using a Light Scribe DVD drive. **(b,c)** This technique can create more than 100 micro-devices in a single run on virtually any substrate.

Jun Lou
Department of Materials Science and NanoEngineering
Rice University, Houston, TX 77005, USA

jlou@rice.edu

Electrochemical Behaviors of Two-Dimensional Materials for Energy and Environmental Applications

In this talk, several aspects of the electrochemical behaviors of two-dimensional (2D) materials for energy and environmental applications will be discussed. We developed a local probe electrochemical measurement method and successfully applied it to the electro-catalytic activity measurement of various kinds of transition metal dichalcogenides. The catalytic activity and turnover frequencies of the 2H-MoS2 basal plane versus edge as well as the 1T'-MoS2 basal plane are identified by this measurement. At the same time, the basal plane activity and turnover frequencies of transition metal dichalcogenides from different element groups has been systematically studied. We have shown that the general trend of the transition metal dichalcogenides in the form of volcano plot follows the trend of metals. VB-VIA dichalcogenides have been identified as the preferred selection for non noble metal hydrogen evolution reaction (HER) catalysts. Finally, we will demonstrate the application of 2D h-BN as high-performance anti-corrosion coatings for electrothermal membrane distillation of hypersaline waters.

Stephan Roche
Catalan Institute of Nanoscience and Nanotechnology (ICN2), CSIC and BIST, Campus UAB, Bellaterra, 08193 Barcelona, Spain
ICREA—Institució Catalana de Recerca i Estudis Avançats, 08010 Barcelona, Spain
stephan.roche@icn2.cat

Topological Spin Transport in Quantum Materials and Entanglement

Abstract
In this talk, I will present theoretical spin transport features in $MoTe_2$ and WTe_2-based materials which have recently been the subject of great attention within the broad context of Quantum Materials [1]. By focusing on the monolayer limit, using DFT-derived tight-binding models and using both efficient bulk and multi-terminal formalisms and techniques [2,3], I will first discuss the emergence of new forms of intrinsic spin Hall effect (SHE) that produce large and robust in-plane spin polarizations. Quantum transport calculations on realistic device geometries with disorder demonstrate large charge-to-spin interconversion efficiency with gate tunable spin Hall angle as large as $\theta_{xy}\approx80\%$, and SHE figure of merit $\lambda_s.\theta_{xy}\sim$8-10 nm, largely superior to any known SHE material [4]. Besides, I will present our theoretical prediction of an unconventional canted quantum spin Hall phase in the monolayer Td-WTe_2, which exhibits hitherto unknown features in other topological materials [5]. The low-symmetry of the structure induces a canted spin texture in the yz plane, dictating the spin polarization of topologically protected boundary states. Additionally, the spin Hall conductivity gets quantized ($2e^2/h$) with a spin quantization axis parallel to the canting direction. Our theoretical predictions for the canted QSHE findings have just been confirmed experimentally [6]. I will finally discuss the role of entanglement between intraparticle degrees of freedom in spin transport and dynamical patterns of entanglement [7].

Acknowledgment

The author acknowledges the European Union Seventh Framework Programme under Grant Agreement No. 881603 Graphene Flagship. ICN2 is supported by the Severo Ochoa program from Spanish MINECO (grant no. SEV-2017-0706) and funded by the CERCA Programme/Generalitat de Catalunya

References

[1] The 2020 Quantum Materials Roadmap, F. Giustino et al. J. Phys. Mater. 3 042006 (2020)
[2] M. Vila et al. Phys. Rev. Lett. 124, 196602 (2020)
[3] Z. Fan et al. "Linear scaling quantum transport methodologies", Physics Reports (in press)
[4] M. Vila, C.H. Hsu, J.H. Garcia, L.A. Benítez, X. Waintal, S. Valenzuela, V.Pereira, S. Roche, "Charge-to-Spin Interconversion in Low-Symmetry Topological Materials", arXiv:2007.02053 (Nature Communications, submitted)
[5] J.H. Garcia, M. Vila, C.H. Hsu, X. Waintal, V.M. Pereira, S. Roche, "Canted Persistent Spin Texture and Quantum Spin Hall Effect in WTe_2 "Phys. Rev. Lett. 125 (25), 256603 (2020)
[6] W. Zhao et al. arXiv:2010.09986
[7] BG de Moraes, AW Cummings, S Roche, "Emergence of intraparticle entanglement and time-varying violation of Bell's inequality in Dirac matter", Physical Review B 102 (4), 041403 (2020)

Rodney S. RUOFF
IBS Center for Multidimensional Carbon Materials (IBS CMCM) and UNIST, Bldg. 101 on UNIST campus, 50 UNIST-gil, Ulsan, Republic of Korea
ruofflab@gmail.com; rsruoff@ibs.re.kr; ruoff@unist.ac.kr

F-diamane from AB-stacked graphene

Abstract

I describe our conversion of AB-stacked bilayer graphene [1,2] to the fluorinated diamane product, F-diamane [3], that can be thought of as an ultrathin ("2-atom thick") layer of diamond that has "every other" C atom on each of the top and bottom surfaces functionalized by F: C_2F stoichiometry.

Time permitting, I will also describe some other research of probable interest. *Support from the Institute for Basic Science (IBS-R019-D1) is appreciated.*

References

[1] Ming Huang, Pavel V. Bakharev, Zhu-Jun Wang, Mandakini Biswal, Zheng Yang, Sunghwan Jin, Bin Wang, Hyo Ju Park, Yunqing Li, Deshun Qu, Youngwoo Kwon, Xianjue Chen, Sun Hwa Lee, Marc-Georg Willinger, Won Jong Yoo, Zonghoon Lee, Rodney S. Ruoff, *Nature Nanotechnology*, (2020) 15(4), 289-295**, Large Area Single Crystal AB-Bilayer and ABA-Trilayer Graphene Grown on a Cu/Ni(111) Foil.**

[2] Ming Huang, Rodney S. Ruoff, *Accounts of Chemical Research*, (2020) 53(4), 800-811, **Growth of single-layer and multilayer graphene on Cu/Ni alloy substrates.**

[3] Pavel V. Bakharev, Ming Huang, Manav Saxena, Suk Woo Lee, Se Hun Joo, Sung O Park, Jichen Dong, Dulce C. Camacho-Mojica, Sunghwan Jin, Youngwoo Kwon, Mandakini Biswal, Feng Ding, Sang Kyu Kwak, Zonghoon Lee, Rodney S. Ruoff, *Nature Nanotechnology*, (2020) 15(1), 1-8, **Chemically Induced Transformation of Chemical Vapour Deposition Grown Bilayer Graphene into Fluorinated Single-Layer Diamond.**

Figures

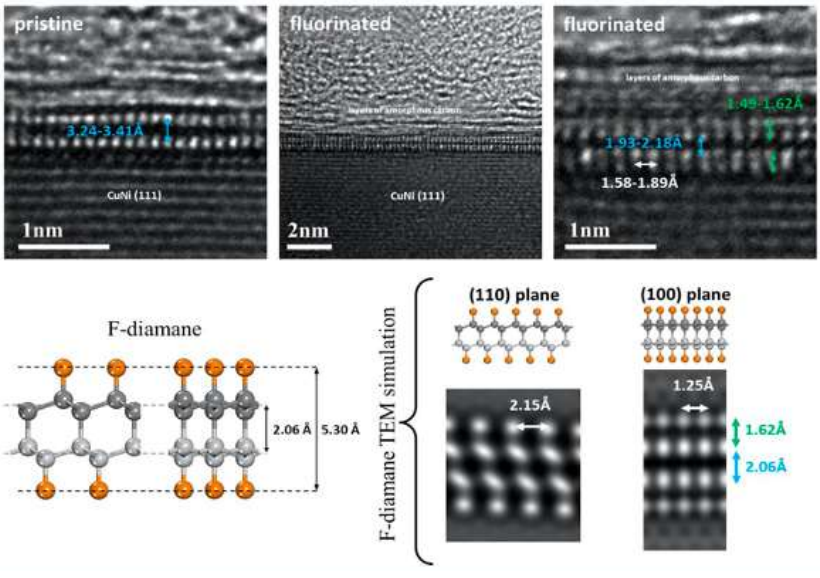


Figure 1: HRTEM cross section images of AB-stacked bilayer graphene (top left) and after its fluorination: F-diamane.

Arend M. van der Zande
Department of Mechanical Science and Engineering
University of Illinois Urbana-Champaign

arendv@illinois.edu

Electromechanical systems enabled by interfacial slip in 2D material heterostructures

Understanding the mechanical deformability of nanomaterials is critical to realizing a host of next generation technologies like stretchable electronics, reconfigurable quantum states, three dimensional multifunctional surfaces, and nanoscale machines. Due to their unparalleled mechanical strength and stability, two-dimensional (2D) materials like graphene and MoS2 represent the ultimate limit in size of both mechanical atomic membranes and molecular electronics. Moreover, many of the most interesting properties of 2D materials and new functionality arise from the van der Waals interfaces between layers and in engineering multilayer heterostructures. Open questions include how the interface affects the mechanical properties of 2D heterostructures and how to integrate the outstanding mechanical properties and electronic functionality of 2D materials together. In this presentation, we will examine the impact of the van der Waals interface on the mechanics of bending and crumpling of 2D atomic membranes, slip in nanoelectromechanical drumhead resonators, and optoelectronic devices from crumpled 2D heterostructures. Taken together, these experiments show that interfacial slip strongly affects the mechanics of 2D materials and heterostructures and leads to membranes which are orders of magnitude more deformable than conventional 3D materials

Robert M. Wallace
Xinglu Wang, Seong Yeoul Kim
The University of Texas at Dallas, Dept. of Materials Science and Engineering, Richardson, TX USA

rmwallace@utdallas.edu

An update on contact reactions with TMDs

Transition metal dichalcogenides (TMDs) are promising for applications in various electronic and photonics devices. MoS_2, as one of the most studied TMDs, demonstrates impressive subthreshold slope, I_{on}/I_{off} ratio and mobilities. However, the contact resistance of the highest-performance metal contacts to MoS_2 based devices is orders of magnitude higher than that required for state-of-the-art logic circuits. Recent studies have noted that the contact resistance can be impacted by the deposition ambient of the metal contacts.[1] Various metal contact (Au, Ti, Ir, Cr, and Sc) on MoS_2 have been studied to understand their interface chemistry and the origin of Fermi level pinning under different deposition ambients. But the interface chemistry of now popular Ni and Ag contacts on MoS_2 has not been systematically reported. CVD MoS_2 films tend to have more intensive defects than the MoS_2 bulk crystal. This difference in defect density could potentially impact the interface chemistry of the metal contacts on MoS_2 and thus probably lead to different device performance. We will present an update of our prior study of deposition ambient effects [2,3] incorporating recent results with Ag and Ni contacts.[4] This work was supported in part by NEWLIMITS, a center in nCORE, a Semiconductor Research Corporation (SRC) program sponsored by NIST through award number 70NANB17H041.

References

[1] C. English et al., Nano Lett. 2016, 16 (6), 3824-3830.
[2] C. Smyth et al., J. Phys Chem. C. 2016, 120, 14719-14729.
[3] R.M. Wallace, GrapheneforUS Conference (2019)
[4] X. Wang, at al., Submitted (2020)

Figures

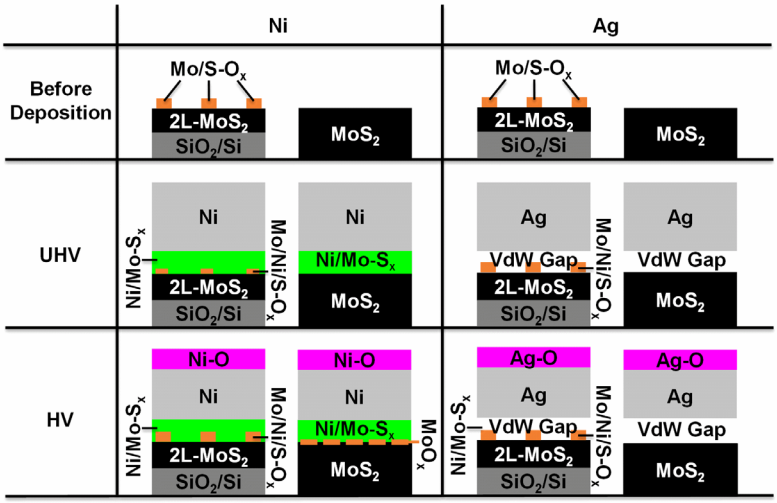
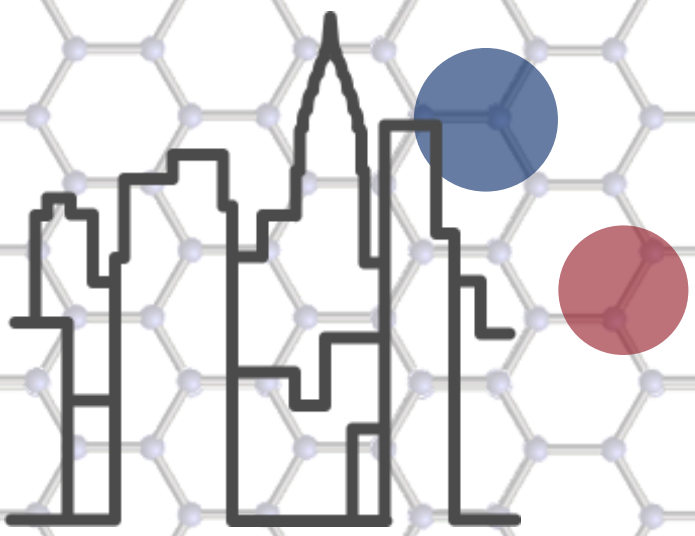


Figure 1: Schematic representations of the interface chemistry formed between contact metals (Ni, and Ag) and MoS_2 substrates (MoS_2 bulk, and 2L-MoS_2 film).



INVITED SPEAKERS

An Chen
Semiconductor Research Corporation, Durham, North Carolina, USA

an.chen@src.org

Nanoelectronics Research for Computing beyond CMOS

As a leading research consortium in the semiconductor industry, the Semiconductor Research Corporation (SRC) has funded academic research for over 35 years, helped to invent some of the most important semiconductor technologies, and educated generations of experts and technology leaders for the industry. Through a collaborative research platform provided by SRC, major semiconductor companies partner with US government funding agencies (e.g., DARPA, NSF, NIST) to sponsor cutting-edge research at the universities to advance semiconductor technologies. The "Nanoelectronics Research Initiative (NRI)" was co-funded by SRC, NSF, and NIST in 2005 with an ambitious goal – to explore nanoelectronic switches fundamentally different from CMOS transistors to achieve orders of magnitude lower switching energy. NRI has made significant contributions to the fundamental research of novel materials and devices; however, no new switch has been identified to be capable of replacing CMOS. Important lessons learned from the NRI program have helped to define the strategies of new nanoelectronics research programs: (1) unique characteristics of nanoelectronic materials and devices may be utilized for novel computing paradigms beyond Boolean logic and von Neumann architectures; (2) basic material and device research play critical roles to enable novel computing solutions; (3) beyond-CMOS research requires a holistic approach with device-architecture cooptimization supported by innovations in characterization, fabrication, and modeling. A joint NSF-SRC program, "Energy-Efficient Computing from Devices to Architectures (E2CDA)", was launched in 2017 to address the cooptimization of emerging devices and architectures to achieve over 100x improvement in system-level energy efficiency. Based on the learning from NRI, a follow-on "nanoelectronic Computing Research (nCORE)" program was launched in 2018 by SRC, NIST, and NSF to explore emerging material, device, and interconnect solutions to enable novel computing and storage paradigms based on a holistic approach. The nCORE program has funded research in 2D materials, spintronic materials and devices, analog/neuromorphic computing devices, new interconnect materials, as well as novel computing architectures including in-memory computing, probabilistic computing, etc. This talk will present these nanoelectronics research programs at SRC, review the lessons learned, and discuss potential future directions.

Sonia Conesa-Boj

Department of Quantum Nanoscience, Kavli Institute of Nanoscience, Delft University of Technology, 2600 GA Delft, The Netherlands

s.conesaboj@tudelft.nl

From crafting to visualization: low-dimensional TMD nanostructures under the electron microscope lamppost

One of the driving forces of the ongoing nanotechnology revolution is the ever-improving ability to understand and control the properties of quantum matter down to the atomic scale. Key drivers in this revolution are quantum materials, such as the two-dimensional (2D) materials of the transition metal dichalcogenide (TMD) family. The realization of novel TMD-based devices relies heavily on understanding the relation between structural and electrical properties at the nanoscale. The ultimate goal is that of crafting TMD nanostructures in a way that makes possible the tailored control of their properties. In this talk, recent studies illustrating novel fabrication approaches of TMD nanostructures based on combining top-down and bottom-up methods will be presented. These allow to control the resulting geometries and material combinations, making possible the realization of novel functionalities such as metallic edge states arising in MoS_2 nanowalls [1] and nanowires, enhanced nonlinear response in vertically-oriented MoS_2 nanostructures [2], and surface and edge plasmons in WS_2 nanoflowers [3]. I will emphasize the crucial role that cutting-edge transmission electron microscopy techniques play in these studies, together with that of machine learning techniques [4] which make possible extract a wealth of novel information which would be lost otherwise.

References

[1] M. T. Rivas, L. Maduro and S. Conesa-Boj, Scientific Reports, 9 (2019) 15602.
[2] M. Bolhuis, J. Hernández-Rueda, S. E. van Heijst, M. Tinoco Rivas, L. Kuipers and S. Conesa-Boj, Nanoscale, 12 (2020) 10491.
[3] Sabrya E. van Heijst, Masaki Mukai, Eiji Okunishi, Hiroki Hashiguchi, Laurien I. Roest, Louis Maduro, Juan Rojo, and Sonia Conesa-Boj, Ann. Phys. 2000499 (2021).
[4] Laurien I. Roest, Sabrya E. van Heijst, Louis Maduro, Juan Rojo, and Sonia Conesa-Boj, Ultramicroscopy, 222 (2021) 113202.

Figures

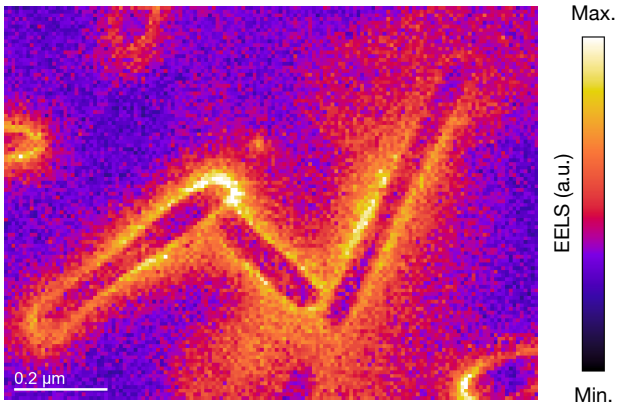


Figure 1: Experimental study of low-loss EELS acquired in MoS_2 nanotubes. Intensity map of the EELS signals integrated for a energy-loss window between 1-2 eV.

Bruno DLUBAK[1]

V. Zatko[1], S. M.-M. Dubois[1,2], M. Galbiati[1], M. Piquemal-Banci[1], R. Galceran[1], J. Peiro[1], F. Godel[1], R. S. Weatherup[3], F. Petroff[1], A. Fert[1], J. Robertson[1], S. Hofmann[1], J.-C. Charlier[2], M.-B. Martin[1], P. Seneor[1]

1 Unité Mixte de Physique, CNRS, Thales, Université Paris-Saclay, 91767 Palaiseau, France.
2 Institute of Condensed Matter and Nanosciences (IMCN), Université Catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium.
3 Department of Engineering, University of Cambridge, Cambridge CB21PZ, UK.

bruno.dlubak@cnrs-thales.fr

Spin filtering in graphene based magnetic tunnel junctions

The discovery of graphene has opened novel exciting opportunities in terms of functionalities and performances for spintronics devices. To date, it is mainly graphene properties for efficient in-plane spin transport which have been put forward. We will present here experimental results concerning integration of graphene in vertical Magnetic Tunnel Junctions. We will show that a thin graphene passivation layer, directly integrated by low temperature catalyzed chemical vapor deposition (CVD) [1][2], allows to preserve a highly surface sensitive spin current polarizer/analyzer behavior and adds new enhanced spin filtering property. The graphene layer prevents the oxidation of the ferromagnet enabling the use of novel processes for spintronics devices.[3][4] We will illustrate this property by demonstrating the use of ozone based ALD processes to fabricate efficient spin valves protected with graphene. Characterizations of complete spin valves making use of graphene grown by CVD will then be presented. We will discuss the measured experimental spin signals in light of bulk band structure spin filtering effect as usually observed with MgO [1][3][4], but also highlight the role of interfacial hybridization for spin selection (a.k.a spinterface) with ab-initio calculations in support.[5] We will further discuss these observed spin filtering effects by analyzing results with other 2D materials (such as h-BN and WS_2) integrated in MTJ devices. The different presented experiments unveil promising uses of 2D materials for spintronics.

References

[1] Dlubak et al., ACS Nano, 6 (2012), 10930
[2] Naganuma et al., APL, 116 (2020), 173101
[3] Martin et al., ACS Nano, 8 (2014), 7890
[4] REVIEW: Piquemal-Banci et al., J. Phys. D : Appl. Phys., 50 (2017), 203002
[5] Piquemal-Banci et al., Nature Comm., 11 (2020), 5670

Aida Ebrahimi
Department of Electrical Engineering, Department of Biomedical Engineering,
Center for Atomically Thin Multifunctional Coating (ATOMIC), Materials Research Institute (MRI)
Pennsylvania State University, University Park, PA 16802, USA

sue66@psu.edu

All-Ink Dopamine Sensors with Ultralow Detection Limit Enabled by One-Step Annealing of Graphene Ink

Existing analytical tools for detection of dopamine (an important neurotransmitter involved in motor function, neurological diseases, and blood pressure regulation) are expensive, bulky, or require highly-skilled personnel, making them challenging to scale to point-of-care (POC) settings.(1) Among various biosensing technologies, electrochemical devices are the leading technology in POC diagnostics owing to their simple operation, real-time readout, low cost, high sensitivity, and portability.(2-3) Being atomically thin and having high specific surface area, 2D materials are ideal for developing highly sensitive electrochemical sensors. Beyond enabling high sensitivity, analyte-specific biosensors can be developed by modifying physical, (opto)electronic, and electrochemical properties of the 2D layer via various physical and chemical modification approaches. In particular, graphene is an attractive sensing layer for dopamine detection due to their π-π interaction and favorable electrostatic interactions at physiological pH. However, the lowest reported detection limit solely based on graphene is limited to 1 nM. In this talk, I will present our recent work on developing an all-ink sensor on polyimide for electrochemical quantification of dopamine down to 5 pM, even in serum.(4) The record-low limit of detection is achieved through a one-step, low-temperature post-deposition annealing process to favorably tune the surface chemistry and surface interactions between the graphene ink layer and the dopamine molecule. Using X-ray photoelectron spectroscopy (XPS), Raman spectroscopy, Scanning Electrochemical Microscopy (SECM), and electrochemical analysis with specific control molecules, we studied the role of functional groups, defects, and anisotropy (edge vs. basal plane) on the sensor response.

References

[1] Y. Lei, D. Butler, M. Lucking, F. Zhang, T. Xia, K. Fujisawa, T. Granzier-Nakajima, R. Cruz-Silva, M. Endo, H. Terrones, M. Terrones, and A. Ebrahimi, Single-atom doping of MoS2 with manganese enables ultrasensitive detection of dopamine: Experimental and computational approach. Sci. Adv. 6, eabc4250 (2020).
[2] A. Bolotsky, D. Butler, C. Dong, K. Gerace, N. Glavin, C. Muratore, J. Robinson, and A. Ebrahimi, Two-Dimensional Materials in Biosensing and Healthcare: From In Vitro Diagnostics to Optogenetics and Beyond. ACS Nano 13 (2019) 9781-9810
[3] A. Ebrahimi, K. Zhang, C. Dong, S. Subramanian, D. Butler, A. Bolotsky, L. Goodnight, Y. Cheng, and J. Robinson, FeSx-graphene heterostructures: Nanofabrication-compatible catalysts for ultra-sensitive electrochemical detection of hydrogen peroxide. Sensors Actuators, B Chem. 285 (2019) 631-638
[4] D. Butler, D. Moore, N. Glavin, J. Robinson, and A. Ebrahimi, Facile Post-Deposition Annealing of Graphene Ink Enables Ultrasensitive Electrochemical Detection of Dopamine, ACS Applied Materials & Interfaces (2021) http://dx.doi.org/10.1021/acsami.0c21302

Avik W Ghosh
Dept. of Electrical and Computer Engineering, Univ of Virginia, Charlottesville 22904
Dept, of Physics, Univ of Virginia, Charlottesville 22904
ag7rq@virginia.edu

Unconventional switching using topological properties of electrons in graphene based heterostructures

Arguably the biggest challenge with graphene-based electronic switching is the lack of a band-gap. Unfortunately, forcing a band-gap through differential doping or vertical fields increases the effective mass and kills mobility. In contrast, the topology of spins/pseudospins in Dirac cone materials offers truly novel opportunities in electron dynamics, but has traditionally been touted for their impact on the on current, even while the off current remains the main challenge. We argue that the transmission of electrons across PN junctions can actually be gate-modulated significantly[1-4] due to added constraints imposed by their winding (Chern) number – for pseudospins in bulk monolayer/bilayer graphene, spins in topological insulators and Weyl semi-metals, magnetization in skyrmionic materials. Experiments show the control of Dirac fermion optics through negative index (Veselago) behavior, conductance modulation (Klein tunneling), magnetoconductance minima in Corbino discs (anti-Klein tunneling), current saturation and angle-dependent transmission (Malus' law) across bulk graphene PN junctions. Based on these data, we explain the opportunities for graphene based electronics and the material challenges along the way.

References

[1] "Spin control with a topological semi-metal", AW Ghosh, Physics 13, 28 (2020)
[2] "Graphene Transistor Based on Tunable Dirac-Fermion-Optics", PNAS 116, 6575 (2019)
[3] "Electron optics with p-n junctions in ballistic graphene", Science 353, 1522 (2016)
[4] "Manipulating Chiral transmission by Gate Geometry: Switching in Graphene with transmission gaps", ACS Nano, vol. 7 :11 , pp. 9808-9813, 2013

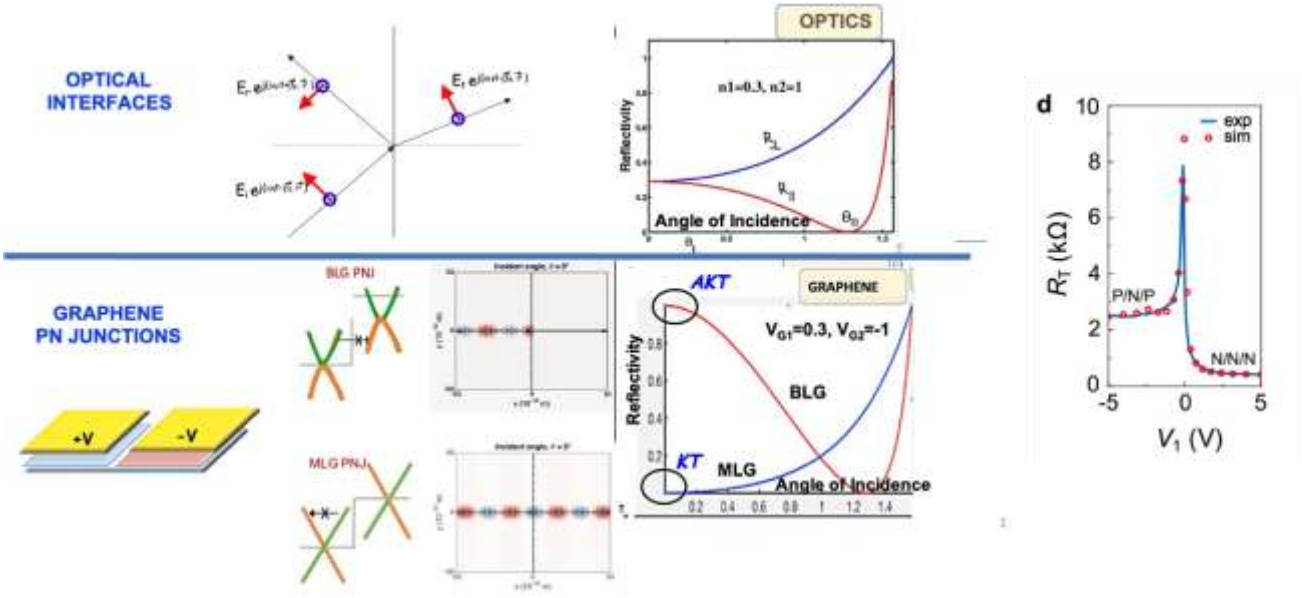


Figure 1: (Top Left) Optical Reflectivity at material interfaces at normal incidence depends on refractive index ratio at the interface. (Bottom Left) Electron reflectivity at graphene PN junctions depends only on topology of pseudospins around the Fermi circle, and is zero (Klein tunneling) for odd layer and unity (Anti-Klein tunneling) for even layers. The pinned value at normal incidence allows us to collimate electrons with a split gate and realize a *Klein tunnel transistor* with bulk graphene, based on gate-geometry alone. (Right) Experiments showing conductance modulation by gating from NNN to PNP doping in bulk graphene [2].

Mario Lanza[1]

Shaochuan Chen[2-3], Mohammad Reza Mahmoodi[3], Yuanyuan Shi[4], Chandreswar Mahata[2], Bin Yuan[2], Xianhu Liang[2], Chao Wen[2], Fei Hui[5], Deji Akinwande[6], Dmitri B. Strukov[3]

[1] Physical Sciences and Engineering Division, King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Saudi Arabia. [2] Institute of Functional Nano and Soft Materials (FUNSOM), Collaborative Innovation Center of Suzhou Nanoscience & Technology, Soochow University, 215123 Suzhou, China. [3] Electrical and Computer Engineering Department, University of California at Santa Barbara, Santa Barbara, CA 93106–9560, USA. [4] IMEC, Kapeldreef 75, B-3001 Heverlee (Leuven), Belgium. [5] Materials Science and Engineering Department, Technion – Israel Institute of Technology, Haifa 32000, Israel. [6] Microelectronics Research Center, Department of Electrical and Computer Engineering, The University of Texas at Austin, Austin, TX, USA

Mario.lanza@kaust.edu.sa

Wafer-scale integration of two-dimensional materials in high-density memristive crossbar arrays for artificial neural networks

Memristors have attracted enormous interest due to their excellent capability to store digital information, and they are being considered to be a key element to build future artificial neural networks for bio-inspired neuromorphic computing systems [1-5]. Recent works have shown that memristors made of layered two-dimensional (2D) materials can exhibit performances that traditional memristors (made of transition metal oxides) do not show, such as excellent transparency and flexibility, high-temperature stability, and unique controllability of the conductance potentiation, depression and relaxation [6-10]. However, most studies on 2D materials based memristors focused on single devices, and system level performances like yield and device-to-device variability have never been analyzed in depth, despite the great interest that they have raised [11-14]. In this talk, I will present the first wafer-scale statistical analysis of high-density memristive crossbar arrays made of 2D layered materials, their nanoscale electronic characterization with conductive atomic force microscopy [15-16], and their application to neuromorphic computing.

References

[1] Mario Lanza et al. Advanced Electronic Materials, 1800143 (2018).
[2] Na Xiao et al. Advanced Functional Materials, 27, 1700384 (2017).
[3] Kaichen Zhu et al. ACS Applied Materials and Interfaces, 11, 37999-38005, 2019.
[4] Xu Jing et al. 2D Materials, 6(3), 035021, 2019.
[5] Yuanyuan Shi et al. Nature Electronics 1, 458–465 (2018).
[6] Fei Hui et al. 2D Materials, 5, 031011 (2018).
[7] Fei Hui et al. ACS Applied Materials & Interfaces 9 (46), 39895-39900 (2017).
[8] Lanlan Jiang et al. ACS Applied Materials & Interfaces 9 (45), 39758-39770 (2017).
[9] Chengbin Pan et al. 2D Materials, 4, 025099 (2017).
[10] Shaochuan Chen et al. Nature Electronics 3 (10), 638-645
[11] Mario Lanza et al. Nature Communications, 11, 5689, 2020.
[12] Yury Illarionov et al. Nature Communications, 11, 3385, 2020.
[13] Bin Yuan et al. Advanced Electronic Materials, 6 (12), 1900115, 2019.
[14] Fei Hui et al. Nature Electronics, 2, 221-229, 2019.
[15] Fei Hui et al. Advanced Functional Materials, 30 (18), 1902776, 2019
[16] Mario Lanza, "Conductive Atomic Force Microscopy: Applications in Nanomaterials", Publisher: Wiley-VCH, Book, ISBN: 978-3-527-34091-0, August 2017.

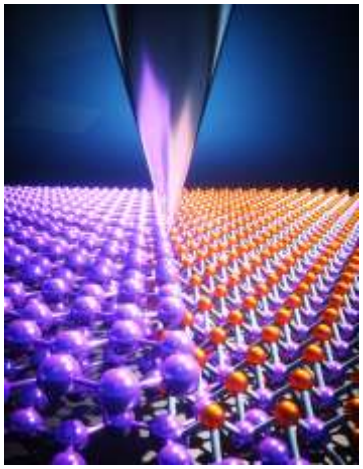
Visualizing 2D materials at the atomic scale

Adina Luican-Mayer
Department of Physics, University of Ottawa, 150 Louis-Pasteur Pvt, Ottawa, Canada
luican-mayer@uottawa.ca

Understanding and controlling the properties of 2D materials to our advantage can be contemplated with the development of experimental tools to probe and manipulate electrons and their interactions at the atomic scale. In this talk, I will present scanning tunnelling microscopy and spectroscopy experiments aimed at: elucidating the nature of atomic-scale defects in 2D materials [1], visualizing moiré patterns between crystals with different symmetries [2] and imaging surface and edge states in a magnetic topological system. Moreover, I will discuss how we leverage our expertise in probing and engineering electronic states at surfaces of 2D materials to further the development of graphene-based gas sensors [3] and gated quantum dot circuits based on 2D semiconductors [4].

REFERENCES

[1] Plumadore et al., PRB, (2020)
[2] Plumadore et al., Journal of Applied Physics, (2020)
[3] Rautela et al., ACS Applied Materials & Interfaces (2020)
[4] Boddison-Chouinard, Appl. Phys. Lett., (2019)



Gordon Rinke
AMO GmbH, Otto-Blumenthal-Str. 25, 52074 Aachen, Germany

rinke@amo.de

Wafer Scale Integration of Graphene for the 2D Experimental Pilot Line at AMO

Graphene has great potentials for applications in different fields such as electronics, optoelectronics, sensors, etc.[1] Forecasts of the markets of GRM based applications integrated with silicon technology show a massive economic impact.[2] To realize these appllications, a path to integrate graphene to state-of-the-art silicon technology process line platform needs to be developed. A fundamental roadblock facing the wafer-scale processing of graphene devices is addressed recently by the EU funded 2D-EPL Project which is part of the Graphene Flagship. In this presentation, AMO within the 2D-EPL Project is introduced and the current progress and examples of wafer scale integration of graphene is shown.

References

[1] D. Neumaier, S. Pindl, M. C. Lemme, Nature Materials, 18 (2019) 525.
[2] D. Akinwande, et al., Nature 573, (2019) 507

Figures

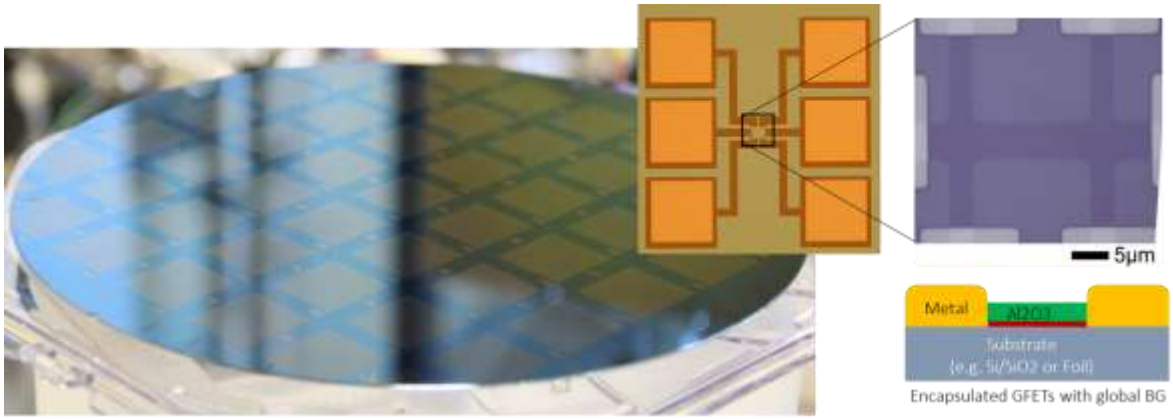


Figure 1: Graphene devices processed on 200 mm wafer at AMO

Dr. Elías Torres Alonso
Graphenea Semiconductor S.L.U., Paseo Mikeletegi 83 20009 San Sebastián (Spain)

e.torres@graphenea.com

Graphenea Foundry: a platform for the manufacture of graphene-based devices

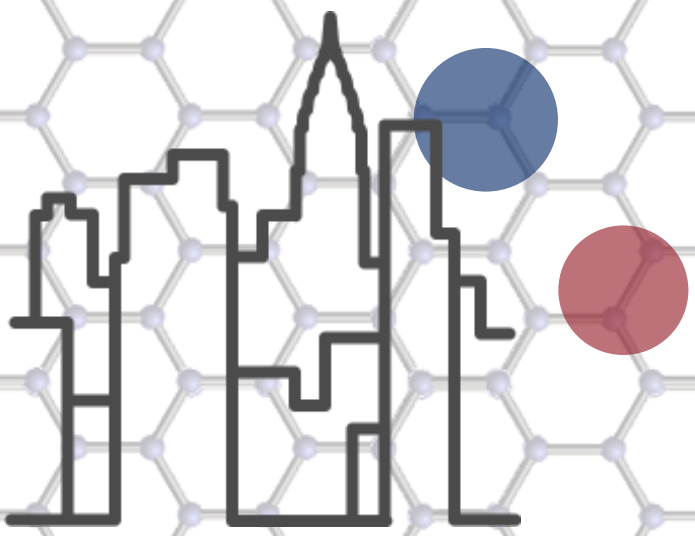
Graphene has been the subject of intense research during the past decade. A myriad of findings with potential applications in many fields have been discovered, yet no commercial products that take advantage of its fantastic and exotic properties. The reasons for this will be discussed in this talk.
In an attempt to accelerate the development and the introduction of graphene technologies into the market, the Graphenea Foundry will be introduced in this talk. Following a pure-play model, our customers seize the different process flows to manufacture a wide range of device applications, tailored to their specs, especially suited for biosensing and photonic/optoelectronic applications.

References

[1] D. Akinwande *et al.* Nature (2019), 573-579
[2] M. Lanza *et al.* Nature Communications (2020), 11 (2019)

Figures

Figure 1: The GFETs S20 (left) and S22 (right), dedicated graphene biosensors.



ORAL CONTRIBUTIONS

Fida Ali
Faisal Ahmed, Muhammad Taqi, Sekhar Babu Mitta, Tien Dat Ngo and Won Jong Yoo*
Sungkyunkwan University Suwon South Korea.
fida1418@skku.edu

Density of Interface States in Layered-WSe_2 Semiconductor

Unlike conventional bulk materials, the physical characteristics of two-dimensional (2D) materials are tailored by thickness variation and the quality of interface formed with the immediate environments. [1,2] Here, we investigate the thickness dependent intrinsic and interfacial characteristics of WSe_2 with special focus on hBN/WSe_2 interface by performing capacitance-voltage (C-V) measurements. Our results show that the interface sate density (D_{it}) at the edge of WSe_2 band gap is drastically reduced from ~10^{13} to 10^{11} cm^{-2} eV^{-1} with the increase of WSe_2 thickness from few to multilayers. The high D_{it} in thin flake-based device demonstrate that the thin flake is more sensitive to the interface to induced strain from the substrate surface roughness, device processing defects, and intrinsic defect density at the WSe_2 surface. Therefore, our findings emphasize the need of low intrinsic defect density and interfacial defect density to fabricate the reliable and high-quality 2D devices. These results can be used to understand the intrinsic and interfacial properties of 2D materials and provide guidelines to design future reliable and doping-free 2D solid-state devices.

Acknowledgement
This work was supported by the Global Research Laboratory (GRL) Program (2016K1A1A2912707) and the Global Frontier R&D Program (2013M3A6B1078873), both funded by the National Research Foundation of Korea (NRF).

References

[1] H. Schmidt, F. Giustiniano, G. Eda, Chemical Society reviews 2015, 44, 7715.
[2] Y. Y. Illarionov, T. Knobloch, M. Jech, M. Lanza, D. Akinwande, M. I. Vexler, T. Mueller, M. C. Lemme, G. Fiori, F. Schwierz, T. Grasser, Nature Communications 2020, 11, 3385.

Figures

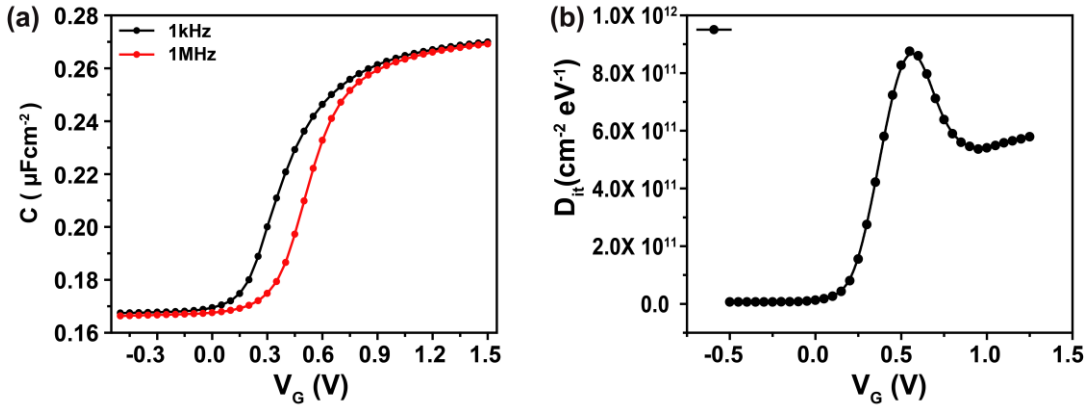


Figure 1: (a) C-V characteristics of the exfoliated n-type WSe_2 MIS capacitor at low 1 kHz and high 1 MHz frequencies.
(b) Extracted Dit as a function of applied VG of n-type WSe_2.

Mohamed BOUKHICHA‡
Joseph A. ANDRADE†, Matthew D. EISAMAN*
‡Department of Nonproliferation and National Security, Brookhaven National Laboratory, Upton, NY, USA
†Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY, USA
*Department of Electrical and Computer Engineering, Stony Brook University, Stony Brook, NY, USA

mohamed.boukhicha@stonybrook.edu

Large-scale Lithium-intercalated Multilayer Graphene Production

For more than 70 years, Graphite Intercalated Compounds (GICs) have been extensively studied, wherein LiC6 was discovered as a lead material for high-capacity electrical energy storage. With the recent surge of compact electronic devices in commercial production, we present a novel fabrication technique for ultra-thin LiC6 devices. Here we present a new transfer method, termed “bifacial float transfer”, which enables large-scale multilayer graphene transfer from both sides of a nickel growth catalyst [1]. Bifacial float transfer has the potential to reduce graphene production costs by transferring chemically vapor deposited (CVD) graphene films from both sides of their native nickel substrate, with one graphene film transferred to a polymer and the other graphene film transferred to another target substrate. In traditional transfer methods, the graphene on the “non-preferred” side, that is, the bottom of the substrate, is removed with oxygen plasma before removal of the metal catalyst in etchant solution. Although this treatment prevents undesired aggregation of the graphene films, it fails to utilize both sides of CVD-grown graphene. In this talk, we compare the quality of graphene transferred from both sides onto target glass and polymer substrates. The results of optical microscopy, confocal Raman spectroscopy, atomic force microscopy, and electronic transport measurements suggest that the quality of the multilayer graphene on the “non-preferred” side does not differ significantly from that of the “preferred” side. This method will allow more efficient and cost-effective use of graphene by doubling the usable graphene per area of growth substrate, and by eliminating the need for intermediate sacrificial transfer substrates such as poly(methyl methacrylate). By modifying the air-liquid interface, we also attempt similar polymer-free transfer of progressively thinner multilayer graphene films. The fabricated samples are then lithiated using the in-situ short-circuit direct contact method [2]. The ultra-thin LiC6 exhibits metallic behavior at room temperature with low sheet resistance and improved optical transparency in the visible spectrum [3]. We present preliminary results on the fabrication and characterization of these large-scale, stable LiC6 films.

References

[1] *Andrade J. A. et al., Adv. Funct. Mater., 2005103 (2020)*
[2] *Shellikeri A. et al., J. of Elec. Soc. 164, 14 (2017)*
[3] *Bao W. et al., Nat. Communication, 5 , 4224 (2014)*

Folkert K. de Vries[1]
Elias Portoles[1], Giulia Zheng[1], Kenji Watanabe[2], Takashi Taniguchi[2], Thomas Ihn[1], Klaus Ensslin[1], Peter Rickhaus[1]
[1]Solid State Physics Laboratory, ETH Zurich, CH-8093 Zurich, Switzerland
[2]National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan
devriesf@phys.ethz.ch

Gate-Defined Josephson Junctions in Magic-Angle Twisted Bilayer Graphene

In the past two years, magic-angle twisted bilayer graphene has emerged as a uniquely versatile experimental platform that combines metallic, superconducting, magnetic and insulating phases in a single crystal [1,2]. In particular the ability to tune the superconducting state with a gate voltage opened up intriguing prospects for novel device functionality. We present the first demonstration of a device based on the interplay between two distinct phases in adjustable regions of a single magic-angle twisted bilayer graphene crystal [3]. We electrostatically define the superconducting and insulating regions of a Josephson junction and observe tunable DC and AC Josephson effects (see Figure 1). We show that superconductivity is induced in different electronic bands and describe the junction behaviour in terms of these bands, taking in consideration interface effects as well. Shapiro steps, a hallmark of the AC Josephson effect and therefore the formation of a Josephson junction, are observed. This work is an initial step towards devices where separate gate-defined correlated states are connected in single-crystal nanostructures. We envision applications in superconducting electronics and quantum information technology as well as in studies exploring the nature of the superconducting state in magic-angle twisted bilayer graphene.

References

[1] Cao, Y.et al., Nature 556 (2018) 43–50
[2] Lu, X.et al., Nature 574 (2019) 653–657
[3] de Vries F.K. et al., arXiv:2011:00011 (2020)

Figures

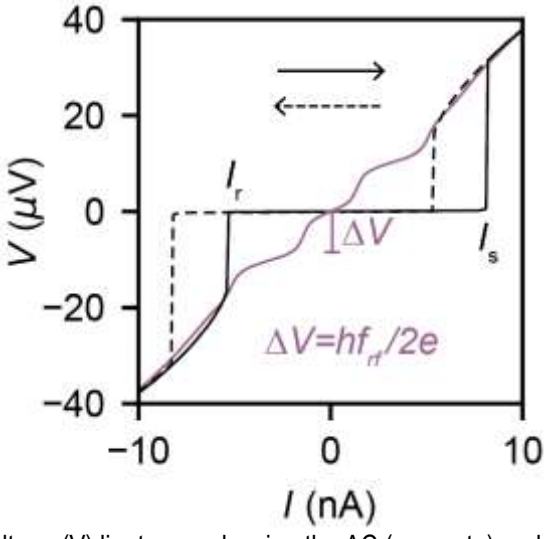


Figure 1: Current (I) versus voltage (V) linetraces showing the AC (magenta) and DC (black) Josephson effects.

Raúl Guerrero-Avilés[1]
Marta Pelc[2], Fabian Geisenhof [3], Thomas Weitz[3,4] , and Andrés Ayuela[1]
[1]Donostia International Physics Center / Material phisics Center, Donostia-San Sebastian, Spain
[2]Nicolaus Copernicus University, Toruń, Poland
[3]AG Physiscs of Nanosystems LMU, Munich, Germany
[4]Institute of Physics, Georg August University, Göttingen, Germany
rguerrero@dipc.org

Rhombohedral Phase in Trilayer-graphene

Twisted bilayer graphene systems revealed flat bands near Fermi level that exhibit interesting electronic efects, such as low-temperature superconductivity [1]. Exploring multilayer graphene in more detail is then needed, because it could still present many properties to be unravelled. Adding a third layer, trilayer-graphene (TLG) shows many new degrees of freedom in their electronic properties. The two most stable forms of TLG are Bernal and rhombohedral (see Figure 1). Despite of the fact that in these two phases the number of interlayer first-neighbors and the interactions between those are of the same kind, the phases can be seen as different by the shift of the last layer. The former contains a carbon chain in an epitaxial order, and the second one has the layers stacked in a stair shape. They show different electronic structures at low energies. Around the K-point, the Bernal phase shows symmetric parabolic and linear electronic bands, and the rhombohedral phase shows partially flat bands but non fully symmetric around that point. For that reason, the rhombohedral stacking is expected to reveal many interesting electron phenomena, including strong correlation and superconductivity [2,3].

For many years, Bernal phase has been considered as the more stable form; however, recent studies show that this question needs to be revised [3-5]. In our work, the results for TLG show that the rhombohedral stacking can be more stable than the Bernal one using a large number of functionals in calculations. We then study the role of the mechanical deformations that provoke a transition between the rhombohedral and the Bernal phase. We conclude that the symmetry breaking between the layer sublattices is crucial to induce the Bernal to rhombohedral phase transition. These findings help in answering how to either preserve or change the stackings in multilayer graphene samples.

References

[1] Y. Cao, *et. al.*, Nature, 556 (2018) 43
[2] A. Roche, *et. al.*, Phys. Rev. Materials, 1 (2017) 041001(R)
[3] F. R. Geisenhof *et. al*. ACS Applied Nano Materials, 2(9) (2019) 6067
[4] J. P. Nery, *et.al.*, Nano Lett., 20 (2020) 5017
[5] Y Shi, *et. al*., Nature, 584 (2020) 210

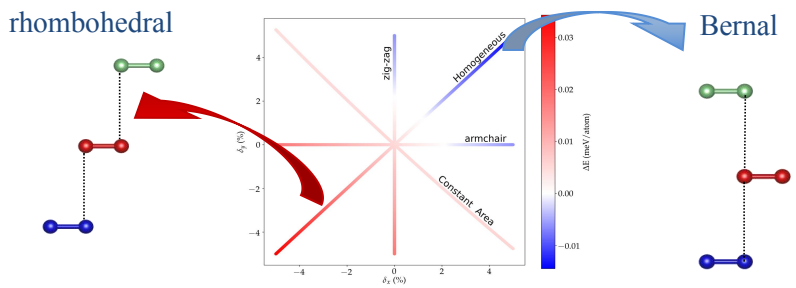


Figure 1: Energy difference between Bernal and rhombohedral stacking for in-plane deformations along different axes. Red and blue colors represent the stability of rhombohedral and Bernal stacking, respectively.

Andrey Krayev[2]
Asia Sarycheva [1], Maruda Shanmugasundaram[2], and Yury Gogotsi[1]

1. A. J. Drexel Nanomaterials Institute, and Department of Materials Science and Engineering, Drexel University, Philadelphia, USA
2. HORIBA Scientific, Novato, USA

andrey.krayev@horiba.com

Nanoscale Structural Peculiarities in Mono- to Few-Layer Crystals of $Ti_3C_2T_x$ MXene Revealed by TERS.

We report first time ever Raman imaging of mono- and few-layer crystals of 2D $Ti_3C_2T_x$ MXene, (T_x stands for surface groups such as =O, -OH and -F) deposited on gold substrate enabled by tip-enhanced Raman scattering (TERS) with 785 nm and 830 nm excitation wavelengths, matching the transversal plasmon resonance of 2D $Ti_3C_2T_x$, which is located at 780-800 nm. TERS spectra collected on the monolayers are strongly dominated by the intense peak A_{1g} (Ti, C, T_x) at 203 cm^{-1}. As the number of layers increases, relative intensity of the resonant 126 cm^{-1} and 725 cm^{-1} peaks, as compared to the intensity of the 203 cm^{-1} peak, also increases, though the absolute intensity of the peaks comes down. In addition to that, we observed peculiar TERS response from wrinkles in MXene sheets, which commonly appear in crystals of $Ti_3C_2T_x$ (and other 2D materials) deposited from colloidal suspensions. TERS spectra of the wrinkles featured a strongly enhanced absolute intensity of the 126 cm^{-1} and 725 cm^{-1} peaks, even in wrinkles that were up to 20 nm high. Using TERS for nanoscale spectroscopic characterization of $Ti_3C_2T_x$ allows collecting fast Raman maps with deep sub-diffractional resolution at the laser power density on the sample about an order of magnitude lower as compared to prior confocal Raman measurements. In addition to that, we show that the intensity of TERS response from the mono- to few-layer crystals of $Ti_3C_2T_x$ can be used to track early stages of degradation in ambient conditions, well before noticeable morphological changes start to appear in these crystals.

Tien Dat Ngo
Zheng Yang, Myeongjin Lee, Fida Ali, Inyong Moon, and Won Jong Yoo
SKKU Advanced Institute of Nano-Technology (SAINT), Sungkyunkwan University, 2066, Seobu-ro, Jangan-gu, Suwon, Gyeonggi-do, 16419, Korea.

Contact@E-mail: ngotiendat04@gmail.com

Fermi-level de-pinning at the intrinsic WSe_2-metal junction via van der Waals bottom contacts

Fermi-level pinning has been a critical challenge in the integration of 2D materials into semiconductor devices. In metal-semiconductor contact formed by physical vapor deposition, the Fermi level is pinned inside the band gap due to interface states or crystal disorder. Herein, we report a pinning-free tungsten diselenide (WSe_2) field-effect transisors (FETs) by utilizing the van der Waals bottom electrical contact. Our device structure is free of chemical disorder and crystal defects arising from metal deposition, which enables a near ideal Fermi-level de-pinning. The pinning factor of our device structure equals to 0.93, which proves our pinning free MS contact, allows us to effectively control the device polarity. With the ability to control the device polarity through metal work function variation, we prepared a complementary metal-oxide-semiconductor (CMOS) inverter with an ultrahigh gain of 198 at a bias voltage of 4.5V. Our study addresses an effective method to overcome the roadblock of further application of 2D materials to modern electronics.

Acknowledgement

This work was supported by the Global Research Laboratory (GRL) Program (2016K1A1A2912707) and the Global Frontier R&D Program (2013M3A6B1078873), both funded by the National Research Foundation of Korea (NRF).

Reference

[1] C. R. Dean, A. F. Young, I. Meric, C. Lee, L. Wang, S. Sorgenfrei, K. Watanabe, T. Taniguchi, P. Kim, K. L. Shepard, J. Hone, Nat. Nanotechnol. 2010, 5, 722.
[2] Y. Liu, Y. Huang, X. Duan, Nature 2019, 567, 323.

Figures

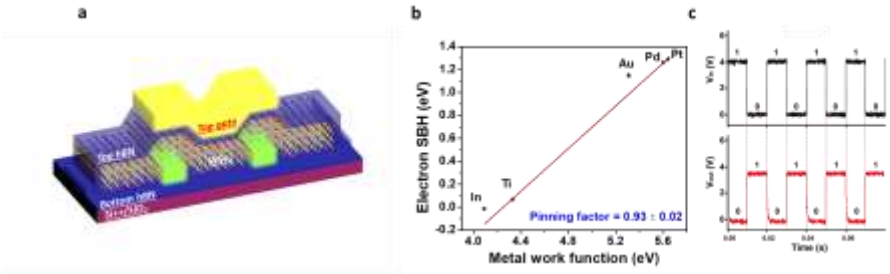


Figure 1: a) Schematic of the WSe_2 van der Waals bottom contact field-effect transistors. **b)** Pinning factor of our van der Waals bottom contact device. **c)** Dynamic output voltage response of our doping-free bottom contact CMOS inverter.

Pablo M. Perez-Piskunow[1]
Stephan Roche[1,2]
[1]Catalan Institute of Nanoscience and Nanotechnology, CSIC and BIST, Campus UAB, Barcelona, Spain
[2]ICREA–Institució Catalana de Recerca i Estudis Avançats, Barcelona, Spain
pablo.perez.piskunow@gmail.com

Hinge Spin Polarization in Magnetic Topological Insulators Revealed by Resistance Switch

We report on the possibility to detect hinge spin polarization (HSP) [1] in magnetic topological insulators (MTI) [2-4] by resistance measurements. By implementing a three-dimensional model of MTIs [5-7] into a multi-terminal device with ferromagnetic contacts near the top surface, local spin features of the chiral edge modes are unveiled. We find local spin polarization at the hinges that inverts sign between top and bottom surfaces. At the opposite edge, the topological state with inverted spin polarization propagates in the reverse direction. Large resistance switch between forward and backward propagating states is obtained, driven by the matching between the spin polarized hinges and the ferromagnetic contacts. This feature is general to the ferromagnetic (FM), antiferromagnetic (AFM) and canted-antiferromagnetic (c-AFM) phases [8-10], and enables the design of spin-sensitive devices, with the possibility of reversing the hinge spin polarization of the currents.

References

[1] P. M. Perez-Piskunow, S. Roche, arXiv:2101.05293.
[2] M. M. Otrokov et al., Nature 576, 416 (2019).
[3] C. Liu et al., Nat. Mat. 19, 522 (2020).
[4] Y. Tokura et al., Nat. Rev. Phys. 1, 126 (2019).
[5] F. Zhang et al., Phys. Rev. Lett. 110, 046404 (2013).
[6] L. Fu et al., Phys. Rev. Lett. 98, 106803 (2007).
[7] J. Wu et al., Phys. Rev. Lett. 113, 136403 (2014).
[8] K. Plekhanov et al., Phys.Rev Res. 2, 013083 (2020).
[9] R-X. Zhang et al., Phys.Rev.Lett. 124, 136407 (2020).
[10] Y. Tanaka et al., Phys. Rev. Res. 2, 043274 (2020).

Figures

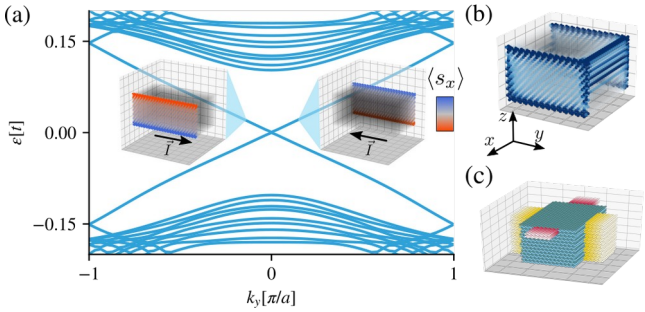


Figure 1: MTI in the FM phase. a) Dispersion relation of a slab infinite in y.The left (right) inset depicts the local spin density of states $\langle s_x \rangle$ of the edge state that covers the side wall of the slab and propagates to the right (left). b) Local density of states of a finite square slab. The edge state circulates around the sample, covers the sidesurfaces perpendicular to x, and propagates along the top or bottom hinges of the side surfaces perpendicular to y. c) Sideview of transport setup geometry: metallic leads connect to the whole walls at both ends of the slab (golden color), and ferromagnetic leads connect to the lateral walls only near top hinge (red color).

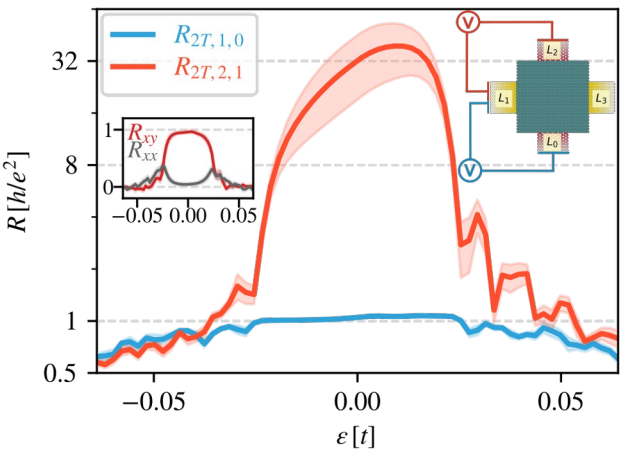


Figure 2: Transport simulations of a FM slab between metallic leads (L1 and L3) and ferromagnetic leads (L0 and L2) with spin down (s_x,↓) polarization. The FM lead L0 matches the top HSP, while L2 has the opposite spin polarization. The matching or mismatching of the spin polarizations is revealed by a large resistance switch and allows us to characterize the HSP.

Salvatore Polverino[1,2]
Antonio Esau Del Rio Castillo[2,3], Antonio Brencich[4], Renata Morbiducci[1] and Francesco Bonaccorso[2,3]
[1]*DAD, Università degli Studi di Genova, Stradone Sant'Agostino 37, 16123 Genoa, Italy*
[2]*Graphene Labs, Istituto Italiano di Tecnologia, via Morego 30, 16163, Genoa, Italy*
[3]*BeDimensional Spa., via Lungotorrente secca 3d, 16163 Genoa, Italy*
[4] *DICCA, Università degli Studi di Genova, via Montallegro 1, 16145, Genoa, Italy*

Salvatore.polverino@edu.unige.it

Few-layer graphene-based sustainable cement mortar

Building materials have a high impact on the environment during their life cycle [1]. Cement composites, the most widely used class of construction materials worldwide, is struggling in keeping the current pace of growth [2]. More than 4 billion tonnes of cement are produced every year, accounting for around 8 per cent of global CO_2 emissions. Various strategies can be adopted to reduce the impact on the environment, *e.g.*, improving the production techniques, reducing the ratio of cement to clinker, and using innovative technologies [3]. Among the technological resources for improving cement composites sustainability, a solution is the use of nano additives. Nanoparticles (*e.g.,* aluminium dioxide or titania nanoparticles) can increase the durability of cement conglomerates [4]. Graphene stands out among the wide variety of carbon-based nano additives that could revolutionise the cement composites sector. Nevertheless, the large scale production of graphene is still limited, precluding the desired high-performance cement composites commercialisation. [5,6]
A high-pressure homogeniser (HPH) method is proposed to produce multi-layer and few-layers graphene using non-toxic solvents at semi-industrial rates, *i.e.* kg per day [7]. The high production rate of graphene offered by HPHs enables us for testing innovative graphene-based cement mortar (**Fig 1**). The few-layer graphene-based composite produced shown an improvement between the 25 and 29% for both the flexural and compressive strength compared to a standard cement mortar.

References

[1] GlobalABC/IEA/UNEP, "Roadmap for Buildings and Construction," 2020, pp. 1–110.
[2] Coppola L. et al., Journal of Cleaner Production, 220 (2019), pp. 475–482.
[3] Lehne J. et al., Chatham House Rep., 2018, pp. 1–122.
[4] Reches Y., Construction and Building Materials, 175 (2018), 483–495.
[5] Bonaccorso F. et al., Materials Today, 2 (2012), 564–589.
[6] Bonaccorso F. et al., Advanced Materials 28 (2016), 6136-6166.
[7] Del Rio Castillo A. E. et al., Materials Horizons 5 (2018), 890-904

Figures

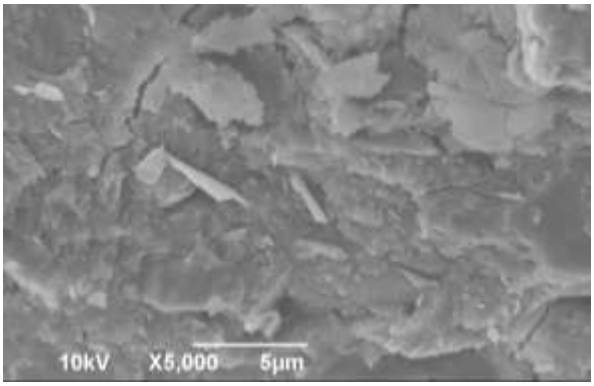


Figure 1: SEM image of the graphene-based cement mortar.

Stephen R. Power
Thomas Aktor, Jose H. Garcia, Stephan Roche and Antti-Pekka Jauho
School of Physics, Trinity College Dublin, Ireland; DTU Fysik, Denmark; ICN2, Spain.

stephen.power@tcd.ie

Manipulating valley currents in graphene nanostructures

Two-dimensional materials are promising valleytronic candidates due to the K and K' valleys at the Dirac points. All-electronic control is particularly desirable for device applications. Many proposed setups exploit strain-induced pseudomagnetic fields which act oppositely in the K and K' valleys, e.g. graphene nanobubbles can filter or split a charge current into its different valley components [1]. Experimental approaches in this direction are advancing, but promising signatures of valley-dependent phenomena have also emerged from graphene/hexagonal boron nitride heterostructures.

Large non-local resistance signals here have been interpreted in terms of a valley Hall effect (VHE) driven by a bulk Berry curvature [2], which in turn emerges from a finite, global mass term. A complete understanding of such measurements in terms of either bulk [3]- or edge-driven [4] mechanisms is very much an open question.

Here [5] we demonstrate the emergence of bulk, valley-polarized currents in graphene-based devices, driven by spatially varying regions of broken sublattice symmetry, and revealed by non-local resistance (RNL) fingerprints. Using a combination of quantum transport formalisms, the presence of a non-uniform local bandgap is shown to give rise to valley-dependent scattering and a finite Fermi surface contribution to the valley Hall conductivity, related to RNL characteristics. Our findings suggest both an alternative mechanism for the generation of valley Hall effect in graphene, and a route towards valley-dependent electron optics, by device engineering.

References

[1] M. Settnes et al, Physical review letters 117, 276801 (2016).
[2] R. Gorbachev et al., Science 346, 448 (2014).
[3] Y. D. Lensky et al, Physical Review Letters 114, 256601 (2015).
[4] J. M. Marmolejo-Tejada et al, Journal of Physics: Materials 1 (1), 015006 (2018).
[5] T. Aktor et al, accepted in PRB (2021), arxiv:1910:00489

Figures

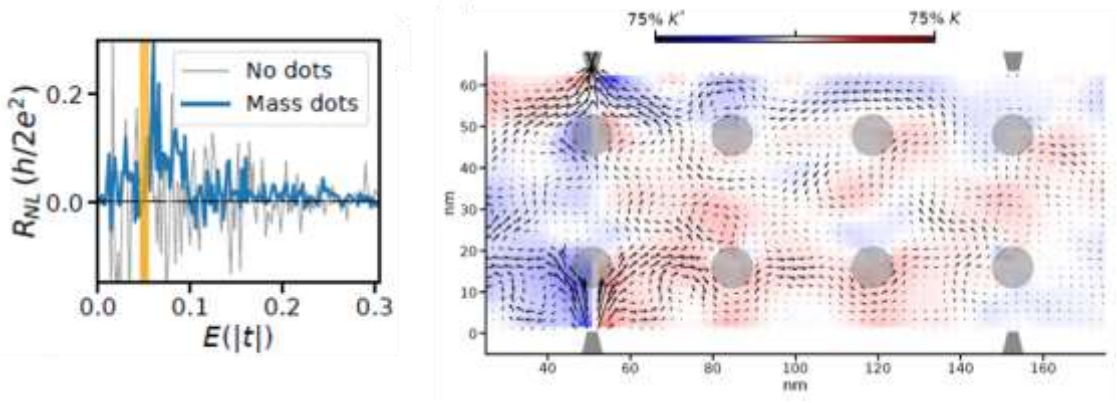


Figure 1: Nonlocal resistance and valley-dependent current flow in a graphene Hall bar with periodic mass dots [5].

Pawan Kumar Srivastava[1]
Yasir Hassan[2], Duarte. J. P. de Sousa[3], Yisehak Gebredingle[2], Minwoong Joe[1], Fida Ali[2], Yang Zheng[2], Won Jong Yoo[2], Subhasis Ghosh[4], James T. Teherani[5], Budhi Singh[1], Tony Low[3], Changgu Lee[1,2]
[1]School of Mechanical Engineering, Sungkyunkwan University, Suwon 16419, S. Korea
[2]SKKU Advanced Institute of Nanotechnology (SAINT), Sungkyunkwan University, Suwon 16419, S. Korea
[3]Department of Electrical and Computer Engineering, University of Minnesota, Minnesota 55455, USA
[4]School of Physical Sciences, Jawaharlal Nehru University, New Delhi 110067, India
[5]Department of Electrical Engineering, Columbia University, New York, NY 10027, USA.
Contact@ pksri08@skku.edu

Resonant tunneling through twisted black phosphorus homostructures

The advent of atomically thin two-dimensional materials heterostructures open new opportunities for rethinking conventional semiconductors heterostructures devices such as light-emitting diodes[1], quantum well lasers[2], tunneling field-effect transistors[3], resonant tunneling transistors, among many others. Here, we explore electronic transport in homostructures based on anisotropic material, black phosphorus and demonstrate the unprecedented degree of control that the relative staking twist angle between anisotropic layers has on the vertical transport behavior. Interlayer coupling strength between anisotropic layers depends sensitively on the twist angle and subsequently dictates the transport behavior from Ohmic to tunneling. Utilizing high quality homostructures made of orthogonally stacked anisotropic black phosphorus multilayers, we demonstrate resonant tunneling through quantum well states without the need of any physical tunneling materials[4], hence achieving the largest tunneling conductance and peak-to-valley ratio in negative differential resistance characteristics.

References

[1] F. Withers *et al.* Nat. Mater. 14 (2015) 301–306.
[2] Y. Li *et al.* Nat. Nanotechnol. 12, (2017) 987–992.
[3] X. Xiong *et al*. Nat. Electron. 3, (2020) 106–112.
[4] S. Bhattacharyya *et al.* Nat. Mater. 5, (2006) 19–22.

Figures

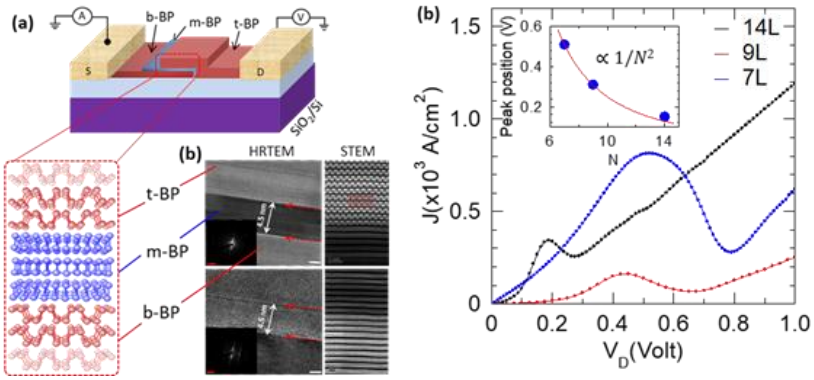


Figure 1: (a) Schematics of the BP trilayer twisted homostructure device and HRTEM/STEM images which reveal (90°) twisted middle layer. **(b)** Resonant tunneling feature as obtained from device shown in (a).

Acknowledgements This work was supported by National Research Foundation of Korea (Grant no. 2016K1A1A2912707, 2018R1D1A1B07049669, 2019R1A2B5B01070477, 2020R1A2C2014687) and Samsung Research & Incubation Funding Center of Samsung Electronics under Project Number SRFC-TB1803-04.

Megan A. Steves
Tian Zhao, Kenneth L. Knappenberger, Jr.
The Pennsylvania State University, Dept. of Chemistry, University Park, PA, USA

Mas1126@psu.edu

Correlating nonlinear optical properties with atomic-level structure in 2D-polar metals

We report on the nonlinear optical properties of 2D polar metals, an emerging group of materials synthesized through confinement heteroepitaxy (CHet) [1]. These heterostructures, consisting of two- to three- atomic layers of indium or gallium on a SiC substrate with a graphene capping layer, exhibit promising nonlinear optical properties in the technologically important NIR/Vis frequency range [2]. The large second order nonlinear susceptibility, approaching 10 nm/V, is unexpected for a centrosymmetric material. However, sub-Ångstrom changes in the lattice parameters as the bonding evolves over the thickness of the metal break the centrosymmetry and result in an out-of-plane dipole, which is confirmed by angle-resolved SHG microscopy. While the out-of-plane structure allows the second-order nonlinear response, the atomic-level in-plane structure of the 2D-metal imparts unique polarization-dependent nonlinear responses. Using polarization-resolved SHG microscopy, we identify regions which have small differences (<2Å) in the lateral displacement of successive layers of metal due to step edges in the SiC substrate. Both the in-plane and out-of-plane structure is determined by the strong interaction of the metal with the SiC substrate, suggesting the ability to tune polarization-selective nonlinear optical properties by control of the interface. Understanding of the correlation between structure and nonlinear optical responses of 2D-metals in an air-stable platform may enable future breakthroughs in nonlinear optical technology.

References

[1] N. Briggs et. al., Nat. Mat., 19 (2020) 637-643.
[2] M. A. Steves et. al. Nano Let., 11 (2020) 8312-8318.

Figures

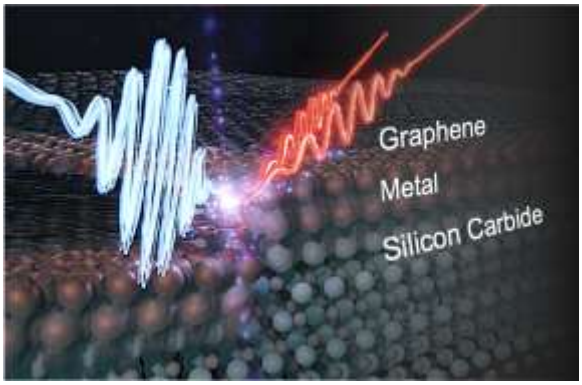


Figure 1: Second harmonic generation microscopy of 2D-polar metal heterostructure

Andrea Tomadin[1]
Matteo Carrega[2], Marco Polini[1,3,4]
[1]Dipartimento di Fisica, Università di Pisa, Largo Bruno Pontecorvo 3, I-56127 Pisa, Italy
[2]CNR-SPIN, Via Dodecaneso 33, 16146 Genova, Italy
[3]School of Physics & Astronomy, University of Manchester, Oxford Road, Manchester M13 9PL, UK
[4]Istituto Italiano di Tecnologia, Graphene Labs, Via Morego 30, I-16163 Genova, Italy

andrea.tomadin@unipi.it

Microscopic theory of plasmon-enabled resonant terahertz detection in bilayer graphene

The electron gas hosted in a two-dimensional solid-state matrix under external driving supports the propagation of plasma waves.[1] Nonlinear interactions between plasma waves generate a constant density gradient which can be detected as a dc potential signal at the boundaries of the system. This phenomenon is at the heart of a plasma-wave photodetection scheme which was first introduced by Dyakonov and Shur for electronic systems with a parabolic dispersion [2] and then extended to the massless Dirac fermions in graphene.[3] Motivated by a recent experimental breakthrough in the resonant detection of plasma waves in double-gated bilayer graphene, [4] we develop the theory of plasma-wave photodetection in such geometry, [5] where the dispersion relation depends locally and dynamically on the intensity of the plasma wave. We show that quantum capacitance effects, arising from the local fluctuations of the electronic dispersion, modify the intensity of the photodetection signal. An external electrical bias, e.g. induced by top and bottom gates, can be used to control the strength of the quantum capacitance corrections, and thus the photoresponse.

References

[1] A.N. Grigorenko, M. Polini, and K.S. Novoselov, Nature Photon. **6**, 749 (2012).
[2] M.I. Dyakonov and M.S. Shur, IEEE Trans. Electron Devices **43**, 380 (1996); *ibid.* **43**, 1640 (1996).
[3] A. Tomadin and M. Polini, Phys. Rev. B **88**, 205426 (2013).
[4] D.A. Bandurin et al., Nature Commun. **9**, 5392 (2018).
[5] A. Tomadin, M. Carrega, and M. Polini, arXiv:2012.11463.

Figures

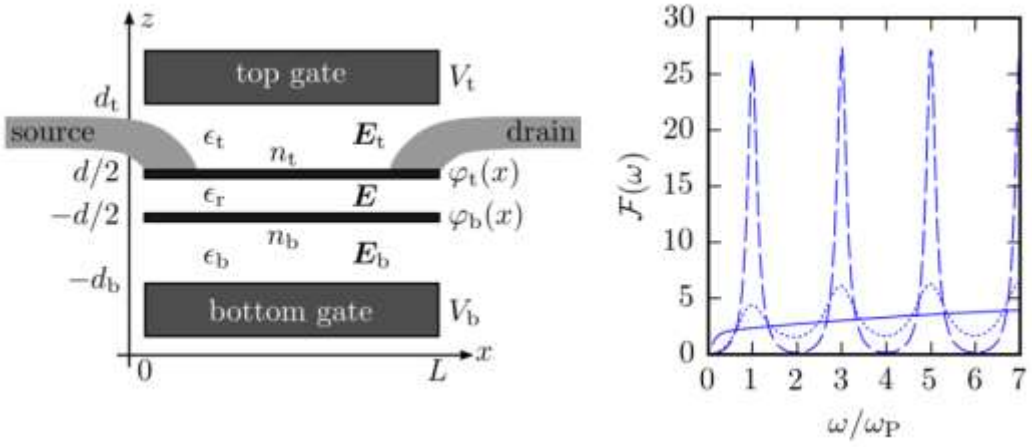


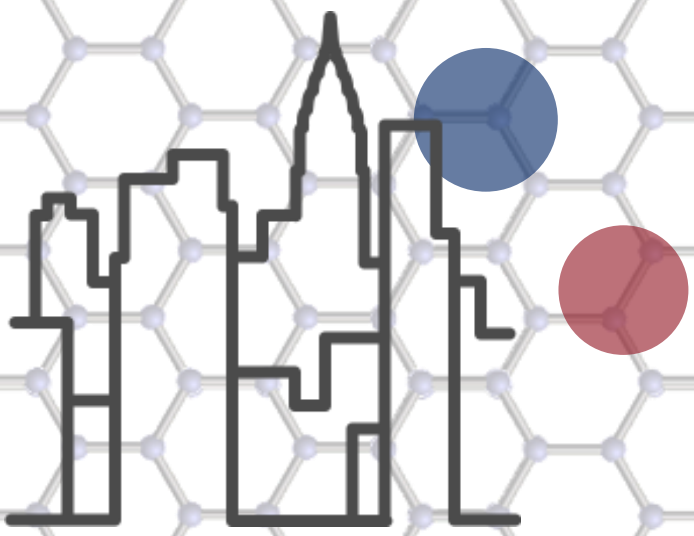
Figure 1: Schematics of the double-gated bilayer graphene setup (left) and photoresponse as a function of the driving frequency (right) for several carrier densities n = 0.1 (solid), 1.0 (dotted), and 5.0 (dashed) × 10^{12} cm^{-2}.

Niels Wijnaendts van Resandt
Heidelberg Instruments

nie@himt.us

Direct Write Lithography Tools and Applications

In this talk you will receive a brief overview of Heidelberg Instruments' direct write tools and a number of interesting applications. We will also highlight the ability do do 'in situ' lithography with our MLA150 Maskless aligner and the Nanofrazor systems.



FLASH POSTERS

Filippo Giubileo[1]
Enver Faella[1,2], Aniello Pelella[1,2], Alessandro Grillo[1,2], Maurizio Passacantando[3], Marika Schleberger[4], Niall McEvoy[5] and Antonio Di Bartolomeo[1,2]
[1]CNR-SPIN Salerno, via Giovanni Paolo II, 132, Fisciano (SA), Italy
[2]Physics Department, University of Salerno, via Giovanni Paolo II, 132, Fisciano (SA), Italy
[3]Dept of Physical and Chemical Science, University of L'Aquila, and CNR-SPIN, via Vetoio, L'Aquila, Italy
[4]Fakultät für Physik and CENIDE, Universität Duisburg-Essen, Lotharstrasse 1, Duisburg D-47057, Germany
[5]AMBER & School of Chemistry, Trinity College Dublin, Dublin 2, Ireland

filippo.giubileo@spin.cnr.it

Transition metal dichalcogenide monolayers as gate controlled field emitters

Monolayers of molybdenum disulfide (MoS_2) and tungsten diselenide (WSe_2) have been synthetized by chemical-vapour deposition on a SiO_2/Si substrate. They were initially contacted to realize back-gated field-effect transistors, both showing n-type conduction under high-vacuum conditions. The n-type conduction enables field emission (FE), i.e. the extraction of electrons by quantum tunneling under the application of a high electric field. Local field emission measurements from the edges of the monolayers have been performed inside a scanning electron microscope (SEM) by using a nanomanipulated tip-shaped anode [1,2]. We demonstrate a turn-on field of the order of 100 V μm−1 and a good time stability of the emitted current for both materials. Finally, we show that the field emission current can be modulated by the back-gate voltage, opening the way for the development of a field-emission vertical transistor.

References

[1] Aniello Pelella, Alessandro Grillo, Francesca Urban, Filippo Giubileo, Maurizio Passacantando, Erik Pollmann, Stephan Sleziona, Marika Schleberger, and Antonio Di Bartolomeo, Adv. Electron. Mater, (2020) 2000838.
[2] Antonio Di Bartolomeo, Francesca Urban, Maurizio Passacantando, Niall McEvoy, Lisanne Peters, Laura Iemmo, Giuseppe Luongo, Francesco Romeo and Filippo Giubileo, Nanoscale, 11 (2019) 1538

Figures

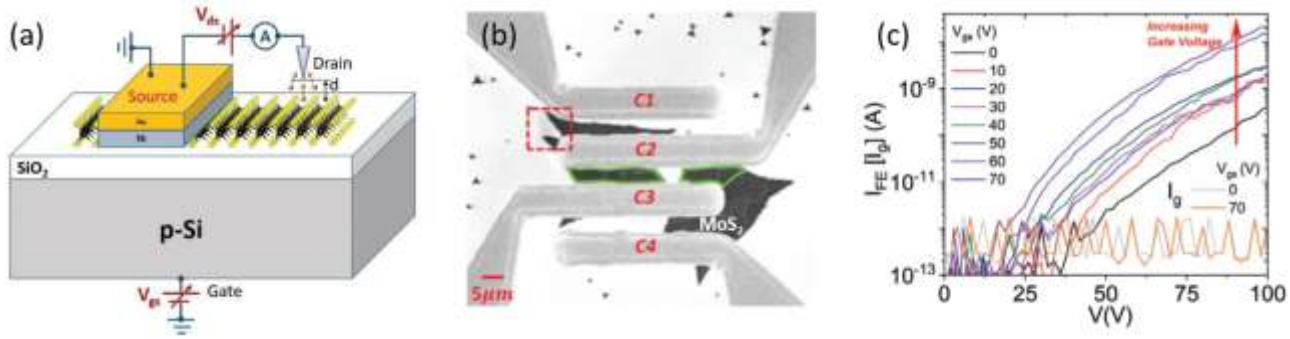
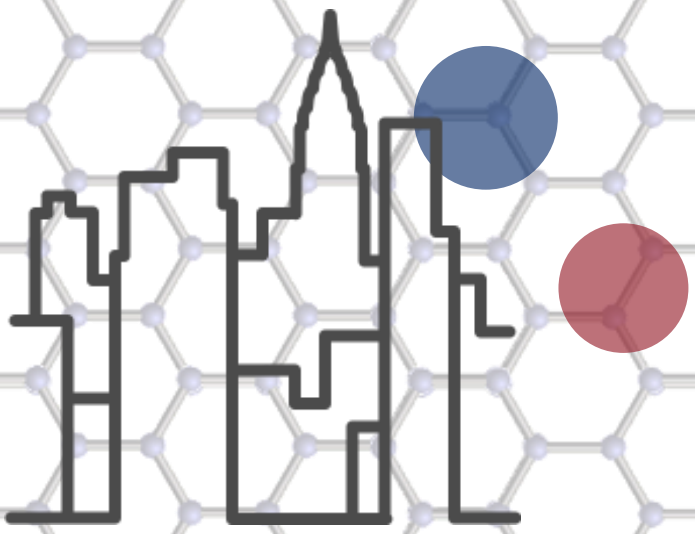


Figure 1: (a) Layout of a back-gate FE transistor with a TMD monolayer channel over a SiO_2/Si substrate. (b) SEM images of the MoS_2 device. The red dashed square highlights the part of the flake used for field emission measurements. (c) Field emission current measured at d = 200 nm for increasing gate voltage.



E-POSTERS

Abhinandan Antony[1]
Martin V. Gustafsson[2], Anjaly Rajendran[1], Guilhem Ribeill[2], Amirali Zangiabadi[3], Kenji Watanabe[4], Takashi Taniguchi[4], Thomas A. Ohki[2], Kin Chung Fong[2], James C. Hone[1]

1. Department of Mechanical Engineering, Columbia University, New York, NY, 10027
2. BBN Technologies, Raytheon, Cambridge, Massachusetts, 02138
3. Electron Microscopy Labs, Columbia University, New York, NY, 10027
4. National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0047, Japan

a.antony@columbia.edu

Ultralow-Resistance Contacts to 2D Superconductors

Two dimensional Van der Waals (VdWs) superconductors show great promise as materials for quantum information systems thanks to their crystallinity and potentially defect and dirt free interfaces. Common VdWs superconductors such as niobium diselinde (NbSe2) are highly air sensitive, and fabricating ultra-high performance contacts to these superconductors has remained a challenge[1][2]. Here we report a reliable method for making superconducting contact to many layer NbSe2 using argon ion milling to remove oxidised layers of NbSe2 before in situ aluminium deposition. To test the performance of these contacts at the levels needed for quantum applications, we measured resonators embedded with contacted NbSe2 flakes at cryogenic temperatures. We find that the contacts have losses low enough to be used in high quality quantum devices even at microwave frequencies.

References

[1] Telford, E. J., Benyamini, A., Rhodes, D., Wang, D., Jung, Y., Zangiabadi, A., … Hone, J. (2018). Nano Letters, 18(2), 1416–1420. https://doi.org/10.1021/acs.nanolett.7b05161
[2] Sinko, M. R., de la Barrera, S. C., Lanes, O., Watanabe, K., Taniguchi, T., Pekker, D., … Hunt, B. M. (2019). Physical Review Materials, 014001, 1–10. https://doi.org/10.1103/physrevmaterials.5.014001
[3] Probst, S., Song, F. B., Bushev, P. A., Ustinov, A. V., & Weides, M. (2015). Review of Scientific Instruments, 86(2), 024706. https://doi.org/10.1063/1.4907935

Yusong Bai

Yusong Bai,[1] Lin Zhou,[1,2] Jue Wang,[1] Wenjing Wu,[1] Leo J. McGilly,[3] Dorri Halbertal,[3] Chiu Fan Lo,[3] Fang Liu,[1] Jenny Ardelean,[4] Pasqual Rivera,[5] Nathan Finney,[4] Xu-Chen Yang,[6] D.N. Basov,[3] Wang Yao,[6] Xiaodong Xu,[5] James Hone,[4] Abhay Pasupathy,[3] X.-Y. Zhu[1,*]

[1]Department of Chemistry, Columbia University, New York, NY, USA. [2]College of Engineering and Applied Sciences, Nanjing University, Nanjing, China. [3]Department of Physics, Columbia University, New York, NY, USA. [4]Department of Mechanical Engineering, Columbia University, New York, NY, USA. [5]Department of Physics and Department of Materials Science and Engineering, University of Washington, Seattle, WA, USA. [6]Department of Physics, University of Hong Kong, Hong Kong, China.

Contact@yb2453@columbia.edu

Moiré Excitons in Transition Metal Dichalcogenide Heterobilayers

The possibility of confining interlayer excitons in interfacial moiré patterns has recently gained attention as a strategy to form ordered arrays of zero-dimensional quantum emitters and topological superlattices in transition metal dichalcogenide heterostructures.[1] Strain is expected to play an important role in the modulation of the moiré potential landscape, tuning the array of quantum dot-like zero-dimensional traps into parallel stripes of one-dimensional quantum wires. Here, we present real-space imaging[2] of unstrained zero-dimensional and strain-induced one-dimensional moiré patterns along with photoluminescence measurements of the corresponding excitonic emission from $WSe_2/MoSe_2$ heterobilayers.[3] Whereas excitons in zero-dimensional moiré traps display quantum emitter-like sharp photoluminescence peaks with circular polarization, the photoluminescence emission from excitons in one-dimensional moiré potentials shows linear polarization and two orders of magnitude higher intensity. These results establish strain engineering as an effective method to tailor moiré potentials and their optoelectronic response on demand.

References

[1] McGilly, L. J. et al., Nat. Nanotech., 15 (2020) 580-584
[2] Tong, Q. et al., Nat. Phys., 13 (2017) 356-362
[3] Bai, Y. et al., Nat. Mater., 19 (2020) 1068-1073

Figures

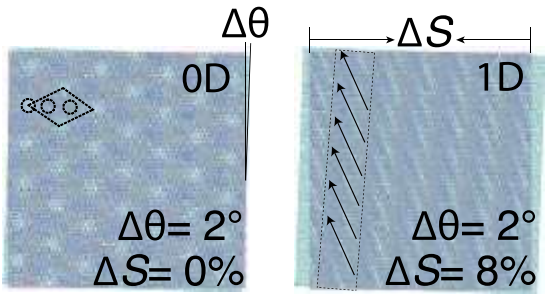


Figure 1: Schematic of hexagonal moiré superlattices (left) vs quasi-1D (strained) moiré superlattices (righrt). Δθ is the twist angle, ΔS is the uniaxial tensile strain.

Eleonora Bonaventura[1,2]
C. Grazianetti[2], C. Martella[2], A. Molle[2], S. Lupi[3]
[1]Dipartimento di Scienza dei Materiali, Universita' di Milano-Bicocca, Via Cozzi 53, Milano I-20125, Italy
[2]CNR-IMM Unit of Agrate Brianza, via C. Olivetti 2, Agrate Brianza, I-20864, Italy
[3]CNR-IOM Dipartimento di Fisica, Sapienza Università di Roma, P.le Aldo Moro 2, Roma, I-00185, Italy
eleonora.bonaventura@mdm.imm.cnr.it

Optical Properties of Silicon and Tin Nanosheets

The dimensional reduction brought by the advent of two-dimensional (2D) materials opens new routes for nanoelectronics and photonics applications. In this framework, the Xenes - artificial graphene-like monoelemental lattices - represent a new forefront due to their electronic structure that is expected to be tunable by the substrate interaction or surface chemistry [1]. The possibility of hosting Dirac electrons in their band structure makes them particularly interesting also for plasmonics [2]. Epitaxial thin films of silicon and tin could be the experimental way to access the optical properties of silicene and stanene. To this purpose, silicon and tin nanosheets on a transparent substrate like sapphire are investigated by means of optical spectroscopy in the photon range from THz to UV. Here, we report on the Dirac-like electrodynamics in silicon nanosheets deduced from the observation of a low-energy optical conductivity feature, when a 2D regime is approached [3]. Similarly, the same experimental approach is also extended to tin therein showing an unexpected optical behavior with stanene-like properties [4].

References

[1] Molle et al., Nature Materials 2017, 16, 163–169
[2] Lupi and Molle, Applied Materials Today 2020, 20, 100732
[3] Grazianetti et al., Nano Letters 2018, 18, 11, 7124–7132
[4] Grazianetti et al., ACS Applied Nano Materials, Accepted, DOI: 10.1021/acsanm.0c03221

Figures

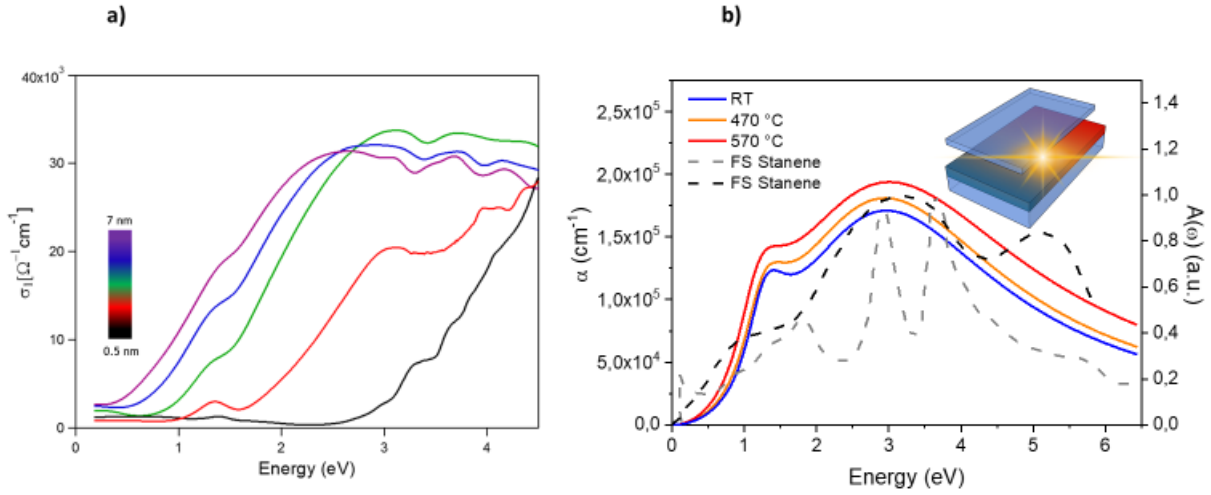


Figure: a) The real part of the optical conductivity of silicon nanosheets. **b)** Absorption coefficients α(ω) of tin films compared with the theoretical absorbance A(ω) of freestanding stanene (black and gray dashed lines).

Óscar Cebadero Domínguez[1]
Soraya Sánchez-Ballester[2]
María Jorda-Beneyto[2]
María Puerto Rodríguez[1]
Ana María Cameán Fernández[1]
Ángeles Jos Gallego[1]
[1] Universidad de Sevilla. Departamento de Nutrición, Bromatología, Toxicología y Medicina Legal. Profesor García González 2, 41012 Seville. Spain.
[2] Packaging, Transport and Logistic Research Institute. Albert Einstein 1. Paterna, 46980 Valencia. Spain.

ocebadero@us.es

Characterization and cytotoxicity of Reduced Graphene oxide on CaCo-2 cells.

Recently, reduced graphene oxide (rGO) has attracted attention for food packaging applications owing to its ability to provide enhanced mechanical and barrier properties[1]. The commercial rGO (Graphitene, Ltd), prepared by thermal reduction procedure, was assessed by structural studies and its potential toxic effects on a human colorectal adenocarcinoma cell line (CaCo-2).

The commercial rGO was characterized by Fourier-Transform Infrared Spectroscopy (FTIR), Zeta Potential (ζ potential), transmission electron microscopy (TEM), scanning electron microscopy (SEM), X-ray photoelectron spectroscopy (XPS) and X-ray diffraction (XRD). By FTIR the main functional groups still remaining onto the surface of GO after its thermal reduction process was determined. The ζ potential shows negative values in cell culture medium (-15.8 ± 2.5) and Milli-Q water (-17.4 ± 0.4). TEM and SEM images revealed wrinkled and scrolled structures in rGO samples. The atomic content, measured by XPS, showed oxygen content (13.6 At %), carbon content (86.3 At %) and traces of chlorine (0.1 At %). The diffraction peak, analyzed by XRD, was detected at 2Θ = 21.5º.

The cytotoxicity of rGO was investigated by mitochondrial activity (MTS) and protein content (PC) on CaCo-2 cells at 0-250 µg ml^{-1} after 24-48h of exposure. MTS reduction shows a significant reduction in cell viability from 62.5 µg ml^{-1} for 24 h and at 250 µg ml^{-1} after 48h of exposure. Nevertheless, Caco-2 cells exposed to rGO showed no significant changes in PC after both exposure times at any concentration assayed.

In conclusion, rGO was characterized and the toxicity observed should be further evaluated before its potential application of rGO as food contact material.

Acknowledgement: Project US-1259106 cofunded by Programa Operativo FEDER 2014-2020 and Consejería de Economía, Conocimiento, Empresas y Universidad de la Junta de Andalucía. And project P18-RT-1993 (PAIDI-2020, Junta de Andalucía). Functional characterization, microscopy, photoelectron spectroscopy, X-ray diffraction and Biology Services of CITIUS are acknowledged for technical assistance.

References

1. Barra, A. *et al.* Graphene derivatives in biopolymer-based composites for food packaging applications. *Nanomaterials* 10, 1–32 (2020).

Min Sup Choi[1,2]
Ankur Nipane[1], Abhinandan Borah[1], Younghun Jung[1], Bumho Kim[1], Mark E. Ziffer[1], Daniel Rhodes[1], Myeongjin Lee[2], Amirali Zangiabadi[1], Maya N. Nair[3], Xiaoyang Zhu[1], Won Jong Yoo[2], James Hone[1], and James T. Teherani[1]

[1]Columbia University, New York, USA
[2]Sungkyunkwan University, Suwon, Republic of Korea
[3]The City University of New York, New York, USA

mc3614@columbia.edu

High-quality p-type doping of 2D materials by UV-ozone treated WSe_2

Abstract
The use of graphene as a transparent electrode requires the development of high-quality doping methods. There have been many studies of graphene doping techniques that use electrostatic force, chemical adsorption, molecular doping, annealing, and UV/plasma treatments.[1] Many of these techniques have trade-offs such as process damage, dopant instability, and poor transparency due to thick polymer coatings. Here, we develop an atomic-layer of p-type doping for graphene using 'monolayer' tungsten oxyselenide (TOS), which is formed by the room-temperature UV-ozone oxidation of monolayer WSe_2. The conversion from WSe_2 to TOS strongly p-type dopes graphene as evidenced by G band shift in Raman spectra, missing Dirac peak in the measured range, low sheet resistance of ~100 Ω/□, and high hole density (3.2×10^{13} cm^{-2}). With additional WSe_2 interlayers between TOS and graphene, sheet resistance further reduces to 48 Ω/□ and graphene shows acoustic phonon-limited mobility, extending mobility trend of edge contacted graphene to higher density.[2] More importantly, the high doping density improves the transmittance of graphene >99% at near IR region. This work demonstrates the potential of 'monolayer' TOS as a p-type dopant for graphene for use in electronics as well as an IR transparent electrode.

References

[1] H. Lee, K. Paeng, I. S. Kim, Synthetic Metals, 244 (2018) 36-47
[2] L. Wang et al., Science, 342 (2013) 614-617

Augusto Ghiotto[1]
En-Min Shih[1], Giancarlo S. S. G. Pereira[1], Daniel A. Rhodes[2], Bumho Kim[2], Kenji Watanabe[3], Takashi Taniguchi[3], James C. Hone[2], Lei Wang[1,4], Cory R. Dean[1]*, and Abhay N. Pasupathy[1]*
[1]Department of Physics, Columbia University, New York, NY, USA [2]Department of Mechanical Engineering, Columbia University, New York, NY, USA [3]National Institute for Materials Science, Namiki 1-1, Tsukuba, Ibaraki, Japan [4]National Laboratory of Solid-State Microstructures, School of Physics, Nanjing University, Nanjing, China

augusto.ghiotto@columbia.edu

Quantum Criticality in Twisted Transition Metal Dichalcogenides

In moiré heterostructures, gate-tunable quantum phases driven by electronic correlations have been recently discovered [1]. Here, we report the properties of the metallic phases and the metal-insulator transition in twisted WSe_2 near half filling. We find that the metal-insulator transition as a function of both density and displacement field is continuous. At the metal-insulator boundary, the low temperature resistivity displays strange metal T-linear behavior down to the lowest temperature of our measurement (200mK) with dissipation comparable to the Planckian limit. Further into the metallic phase, the low temperature resistance recovers a Fermi-liquid quadratic dependence at low temperature, whose coefficient rises an order of magnitude as it approaches the quantum critical point. More surprisingly, the projected zero-temperature resistivity of the metallic regime is a qualitative predictor of the insulating gap.

References

[1] Balents, L. et al. *Nature Physics* **16**, 725–733 (2020)
[2] Wang, L. et al. *Nature Materials* **19**, 861–866 (2020)

GrapheneforUS

Saher Hamid
Tyler Dacosta, Adina Luican-Mayer
Department of Physics, University of Ottawa, Ottawa, Canada

shamid3@uottawa.ca

Multilayer Graphene as Adaptive Thermal Camouflage

In this work we explore the use of multi-layer graphene (MLG) films grown by chemical vapor deposition for adaptive thermal camouflage. Using different ionic liquids, we tune the opto-electronic properties of MLG (150 – 200 layers) and investigate changes in optical reflectivity and emissivity in the infrared region (IR). We fabricate devices having a metallic back electrode supporting a porous membrane onto which we deposit the MLG as shown in Figure 1. We use both non-stretchable polyethylene (PE), and stretchable polydimethylsiloxane (PDMS) as porous membranes. Using a thermal imaging system, we demonstrate that even when the device temperature is maintained higher than the environment, the MLG emissivity can be electrically controlled such that the device appears indistinguishable from the environment [1]. Moreover, we evaluate the performance of such devices based on flexible textiles towards developing a new material platform for defense applications.

References

[1] Omer Salihoglu, Hasan Burkay Uzlu, Ozan Yakar, Shahnaz Aas, Osman Balci, Nurbek Kakenov, Sinan Balci, Selim Olcum, Sefik Süzer, and Coskun Kocabas, Nano Letters, 18, 7, (2018), 4541

Figure

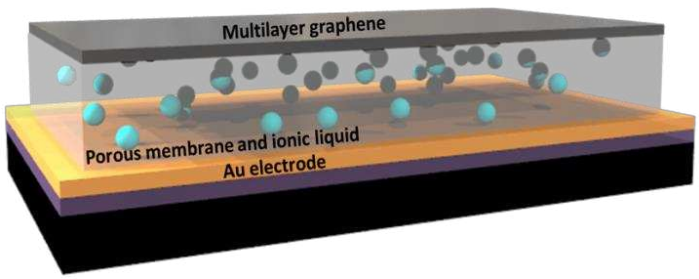


Figure 1: Schematic of the Adaptive Thermal-Camouflage Device.

Óscar Cebadero Domínguez[1]
Soraya Sánchez-Ballester[2]
María Jorda-Beneyto[2]
María Puerto Rodríguez[1]
Ana María Cameán Fernández[1]
Ángeles Jos Gallego[1]
[1] Universidad de Sevilla. Departamento de Nutrición, Bromatología, Toxicología y Medicina Legal. Profesor García González 2, 41012 Seville. Spain.
[2] Packaging, Transport and Logistic Research Institute. Albert Einstein 1. Paterna, 46980 Valencia. Spain.

angelesjos@us.es

Synthesis, characterization and cytotoxicity of graphene oxide

Graphene oxide (GO) is a derivate of graphene whose structure have a high oxygen content. This structure confers many important properties to be used in improved packaging materials[1]. But before the application of this material, it is required to know its potential toxic effects.
Graphene oxide was synthetized from graphite by using the Modified Hummers Method[2]. The product obtained was characterized by Fourier-Transform Infrared Spectroscopy (FTIR), X-ray photoelectron spectroscopy (XPS), Zeta Potential (ζ potential), X-ray diffraction (XRD), scanning electron microscopy (SEM), and transmission electron microscopy (TEM).
FTIR was used to confirm the introduction of the oxygen-containing functional groups onto the surface of graphite. The elemental composition of GO, investigated by XPS, revealed carbon content (66.3 At%), oxygen content (33.2 At%) and traces of nitrogen (0.6 At%). The C/O atomic ratio was 1.99. The ζ potential in cell culture medium was -10.9 ± 0.3 and -30.3 ± 0.6 in Milli-Q water. GO showed two diffraction peaks at 2Θ = 12.6 and 2Θ = 42.5. SEM micrographs showed that large number of layers have been stacked to each other and formed into thick and bulk sheet clusters which are opaque in nature.
The toxicological effects were evaluated on a human colorectal adenocarcinoma cell line (CaCo-2) by the MTS reduction assay and protein content assay. Caco-2 cells showed no significant changes in the endpoints considered after 24 and 48h of exposure at any concentration assayed (0-250 µg/mL). Further toxicological tests are required before the potential application of GO as food contact material.
Acknowledgement: Project US-1259106 cofunded by Programa Operativo FEDER 2014-2020 and Consejería de Economía, Conocimiento, Empresas y Universidad de la Junta de Andalucía. And project P18-RT-1993 (PAIDI-2020, Junta de Andalucía). Functional characterization, microscopy, photoelectron spectroscopy, X-ray diffraction and Biology Services of CITIUS are acknowledged for technical assistance.

References

1. Arfat, Y. A., Ahmed, J., Ejaz, M. & Mullah, M. Polylactide/graphene oxide nanosheets/clove essential oil composite films for potential food packaging applications. *Int. J. Biol. Macromol.* 107, 194–203 (2018).
2. Zaaba, N. I. *et al.* Synthesis of Graphene Oxide using Modified Hummers Method: Solvent Influence. *Procedia Eng.* 184, 469–477 (2017).

Brian S. Y. Kim[1]
Aaron Sternbach[1], Minsup Choi[1], Lin Xiong[1], Song Liu[1], Sang Hoon Chae[1], Kenji Watanabe[2], Takashi Taniguchi[2], Jamie Teherani[1], James C. Hone[1], Dmitri N. Basov[1]
[1]Columbia University, New York, NY, USA
[2]National Institute for Materials Science, Tsukuba, Japan,
bsk2137@columbia.edu

Tunable charge-transfer surface plasmon polaritons at tungsten oxyselenide/graphene interface

Surface plasmon polaritons (SPP) are of fundamental interest due to their ability to confine light at the nanoscale, providing exciting opportunities for fundamental studies and applications, including lasing, topological protection, and biosensing [1,2]. Here, we use mid-infrared near-field imaging to study SPP at tungsten oxyselenide (TOS)/graphene interface. We find clear signatures of SPP propagation at TOS/graphene interface in an ungated geometry, verifying a significant amount of charge transfer across the interface [3]. We further demonstrate that the degree of charge transfer can be systematically tuned by inserting WSe_2 layers at the TOS/graphene interface. More importantly, we find that the quality factor of SPP approaches the fundamental limit of graphene plasmons as we increase the layer number of the WSe_2 layer. Our work provides a general strategy for engineering graphene SPP on demand without external gate or chemical doping.

References

[1] Z. Fei, A. S. Rodin, G. O. Andreev, W. Bao, A. S. McLeod, M. Wagner, L. M. Zhang, Z. Zhao, M. Thiemens, G. Dominguez, M. M. Fogler, A. H. Castro Neto, C. N. Lau, F. Keilmann, and D. N. Basov, Nature, 487 (2012) 82.
[2] G. X. Ni, A. S. McLeod, Z. Sun, L. Wang, L. Xiong, K. W. Post, S. S. Sunku, B.-Y. Jiang, J. Hone, C. R. Dean, M. M. Fogler, and D. N. Basov, Nature, 557 (2018) 530.
[3] D. J. Rizzo, B. S. Jessen, Z. Sun, F. L. Ruta, J. Zhang, J.-Q. Yan, L. Xian, A. S. McLeod, M. E. Berkowitz, K. Watanabe, T. Taniguchi, S. E. Nagler, D. G. Mandrus, A. Rubio, M. M. Fogler, A. J. Millis, J. C. Hone, C. R. Dean, and D. N. Basov, Nano Lett., 20 (2020) 8438.

Baichang Li
Xiangye Liu, Xufan Li, Avetik Harutyunyan, James Hone, Daniel Esposito
Columbia University

bl2621@columbia.edu

The Critical Role of Electrolyte Gating on the Hydrogen Evolution Performance of Monolayer MoS2

According to density functional theory, monolayer (ML) MoS2 is predicted to possess electrocatalytic activity for the hydrogen evolution reaction (HER) that approaches that of platinum. However, its observed HER activity is much lower, which is widely believed to result from a large Schottky barrier between ML MoS2 and its electrical contact. In order to better understand the role of contact resistance in limiting the performance of ML MoS2 HER electrocatalysts, this study has employed well-defined test platforms that allow for the simultaneous measurement of contact resistance and electrocatalytic activity toward the HER during electrochemical testing. At open circuit potential, these measurements reveal that a 0.5 M H2SO4 electrolyte can act as a strong p-dopant that depletes free electrons in MoS2 and leads to extremely high contact resistance, even if the contact resistance of the as-made device in air is originally very low. However, under applied negative potentials this doping is mitigated by a strong electrolyte-mediated gating effect which can reduce the contact and sheet resistances of properly configured ML MoS2 electrocatalysts by more than 5 orders of magnitude. At potentials relevant to HER, the contact resistance becomes negligible and the performance of MoS2 electrodes is limited by HER kinetics. These findings have important implications for the design of low-dimensional semiconducting electrocatalysts and photocatalysts.

Song Liu[1]
Daniel Rhodes[1], Bumho Kim[1,2], Drew Edelberg[3], Jue Wang[4], Pasqual Rivera[5], Minhao He[5], Xiaodong Xu[5], Xiaoyang Zhu[4], Abhay Pasupathy[3], Katayun Barmak[2], James Hone[1]
[1]Department of Mechanical Engineering, [2]Department of Applied Physics and Applied Mathematics, [3]Department of Physics and [4]Department of Chemistry, Columbia University, New York, NY 10027, USA
[5]Department of Physics, University of Washington, Seattle, WA 98195, USA

Synthesis of Ultrapure Transition Metal Dichalcogenides

There has been explosive research on 2D transition metal dichalcogenides (TMDs) due to their novel optical and electronic properties. These properties offer great promise for energy, health, composite material, optoelectronics and nanophotonics applications. TMDs exhibit a unique combination of direct band-gap, strong spin-orbit coupling and fascinating optical and electronic properties, which are of great interest for fundamental studies and new applications. To date, a variety of methods has been developed for TMDs synthesis, including chemical vapor transport (CVT), chemical vapor deposition (CVD) and molecular beam epitaxy (MBE). However, the experimental measurements of their physical properties are still be far from the theoretical predictions. This indicates that disorder in these materials has been poorly controlled by the aforementioned growth methods, obscuring their intrinsic behaviors. Thus, improving the quality of these materials is urgently needed to advance fundamental studies and practical applications. In this work, we developed self-flux growth technique to reduce defect density by two orders of magnitude in TMDs, comparing to the commercially available crystals. A combination of scanning tunneling microscopy (STM) and scanning transmission electron microscopy (STEM) was utilized to characterize the type and density of intrinsic defects in $MoSe_2$ and WSe_2. The fundamental study of how process parameters affect the type and density of intrinsic defects enables us to control the properties in TMDs. By studying the low-temperature photoluminescence (PL) of monolayer WSe_2 and $MoSe_2$ with different defects density, we found a new series of low energy excitonic emission in WSe_2 and near unity quantum yield in $MoSe_2$.

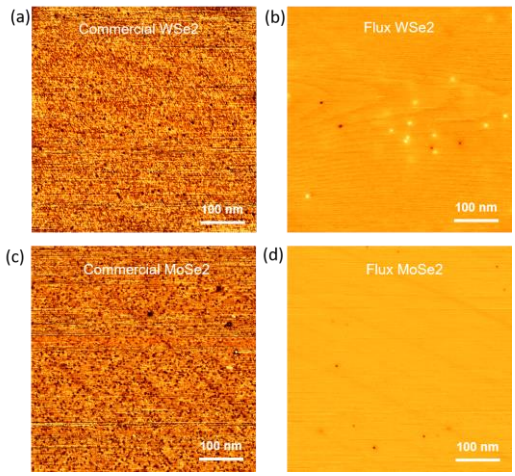


Figure 1: Scanning Tunneling Microscopy (STM) topographic images of 500×500 nm^2 area of WSe_2 grown by a, commercial companies and b, self-flux method and $MoSe_2$ grown by c, commercial companies and d, self-flux method.

Carmen Rubio Verdu
Simon Turkel, Larry Song, Lennart Klebl, Rhine Samajdar, Mathias S. Scheurer, Jörn W. F. Venderbos, Kenji Watanabe, Takashi Taniguchi, Héctor Ochoa, Lede Xian, Dante Kennes, Rafael M. Fernandes, Ángel Rubio, Abhay N. Pasupathy
Columbia University

cr3080@columbia.edu

Universal moiré nematic phase in twisted graphitic systems

Graphene moiré superlattices display electronic flat bands. At integer fillings of these flat bands, energy gaps due to strong electron-electron interactions are generally observed. However, the presence of other correlation-driven phases in twisted graphitic systems at non-integer fillings is unclear. Here, we report scanning tunneling microscopy (STM) measurements that reveal the existence of threefold rotational (C3) symmetry breaking in twisted double bilayer graphene (tDBG). Using spectroscopic imaging over large and uniform areas to characterize the direction and degree of C3 symmetry breaking, we find it to be prominent only at energies corresponding to the flat bands and nearly absent in the remote bands. We demonstrate that the C3 symmetry breaking cannot be explained by heterostrain or the displacement field, and is instead a manifestation of an interaction-driven electronic nematic phase, which emerges even away from integer fillings. Comparing our experimental data with a combination of microscopic and phenomenological modeling, we show that the nematic instability is not associated with the local scale of the graphene lattice, but is an emergent phenomenon at the scale of the moiré lattice, pointing to the universal character of this ordered state in flat band moiré materials.

Jue Wang[1]
Lin Zhou[1], Wenjing Wu[1], James Hone[2], X.-Y. Zhu[1,*]
[1] Department of Chemistry, Columbia University, New York, NY 10027, USA.
[2] Department of Mechanical Engineering, Columbia University, New York, NY 10027, USA.
* xyzhu@columbia.edu

jw3227@columbia.edu

Probing Coulomb interaction in monolayer $MoSe_2$

The Coulomb interaction in two-dimensional (2D) transition metal dichalcogenides (TMDCs) plays the fundamental role in series of quantum phenomena, ranging from strongly correlated states in equilibrium to excitonic many-body complexes under photo-excitation. The celebrated Rytova-Keldysh model [1], while successful in most situations, failed to recover the behavior of trion under dielectric screening [2]. Here we take advantage of the deep understanding of exciton and trion in monolayer $MoSe_2$ and the high sensitivity of time, space and energy resolved photoluminescence (PL) spectroscopy to probe the nature of Coulomb interaction in TMDCs. We observed a surprising disorder tolerant trion binding energy which suggests extra screening mechanism at nanometer scale, probably from the chalcogen atomic sheets in TMDCs. The phonon broadening of trion binding energy distribution indicates the involvement of phonon in trion binding processes [3]. Furthermore, the Coulomb interaction can be effectively screened by photo-doping, resulting in the disappearance of trion and exciton peaks in PL spectrum and emergence of halo effects in PL diffusion [4] across Mott transition. Our observations reveal the highly confined nature of Coulomb interaction in TMDCs while establishing trion and exciton as probes of Coulomb interaction and call for further identification of similar quantum sensors.

References

[1] Cudazzo, P. et al. *Phys. Rev. B* **84** (2011) 085406.
[2] Tuan, D. V. et al. *Phys. Rev. B* **98** (2018) 125308.
[3] Tuan, D. V. et al. *Phys. Rev. Lett.* **122** (2019) 217401.
[4] Kulig, M. et al. *Phys. Rev. Lett.* **120** (2018) 207401.

Adam K Williams[1]
Evan J Telford[1], Kenji Watanabe[2], Takashi Taniguchi[2], Cory R Dean[1]
[1]Department of Physics, Columbia University, New York, New York 10027, United States
[2]National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan

a.k.williams@columbia.edu

Towards high transparency in crystallographic superconductor-graphene interfaces

The interface of superconductors and normal materials is characterized by their transparency, or the likelihood of Andreev reflection over normal reflection of particles crossing the junction. In this study we probe the transparency of contact to the van der Waals superconductor $NbSe_2$ via tunneling spectroscopy in transport. We find that the granularity of deposited gold contact erases superconducting features whereas crystalline graphene and graphite contacts do not.

Edited by

PHANTOMS foundation

C/ Alfonso Gómez, 17 - 2ª planta - Loft 16
28037 Madrid, Spain

www.phantomsnet.net