GRAPHENE FLAGSHIP

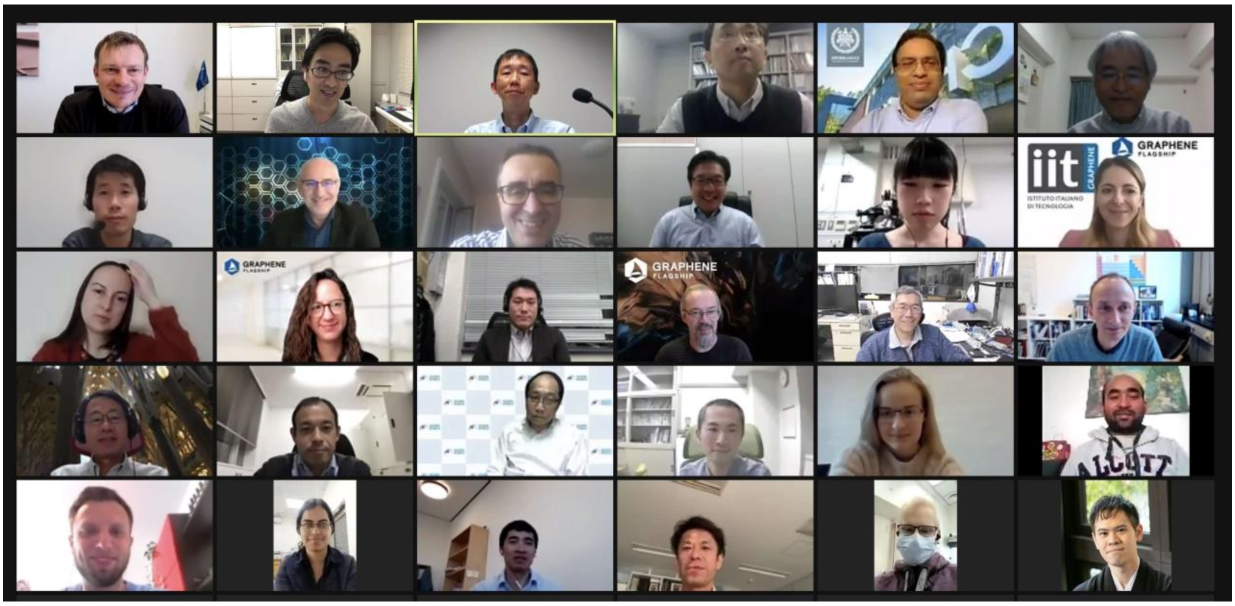
2.5D Materials

5th EU-Japan Workshop on Graphene and Related 2D Materials (2021)

25 October 2021

Held Online

Workshop Report



The 5th EU-Japan Workshop on Graphene and Related Materials was held online on 25 October 2021. The goal of this workshop was the exchange of experiences, practices, and ideas related to the current and emerging topics associated with graphene and related 2D materials in the field of electronics, spintronics, plasmonics, valleytronics, optoelectronics, and photonics. A special focus has been given to fundamental materials synthesis, physics, and devices. In addition to knowledge exchange and networking, an important aim was to explore further possibilities for collaborative research opportunities between researchers in Europe and Japan. This workshop was a follow up of a series of four workshops, the first workshop was held in Tokyo (Japan) in 2015, the second in Barcelona (Spain) in 2017, the third in Sendai (Japan) in 2018, and the fourth in Pisa (Italy) in 2019.

The meeting was co-organised by Japanese and European researchers:

Tomoki Machida (University of Tokyo, Japan)
Christoph Stampfer (RWTH Aachen University, Germany)
Mikito Koshino (Osaka University, Japan)
Camilla Coletti (Istituto Italiano di Tecnologia, Italy)
Taiichi Otsuji (Tohoku University, Japan)
Jari Kinaret (Chalmers University of Technology, Sweden)

The workshop gathered 45 participants (21 from the Japan and 24 from Europe), coming mainly from academic and research institutions.

At this workshop, 10 invited speakers (5 from Japan and 5 from Europe) presented several topics from the field of electronics, spintronics, plasmonics, valleytronics, optoelectronics, and photonics from fundamentals up to device prototypes. Many common interests came up for future closer collaborations in the field of materials, physics, devises as well as applications such as biosensing and energy harvesting by bottom-up forming collaborative partners, exchanging students.

At the European side, Graphene Flagship mobility grants are recognised as tool to further strengthen the collaborations and enable young researchers from Europe to perform research stays in laboratories in Japan. Equivalently, at the Japan side, Science of 2.5 Dimensional Materials, which has just launched this year, is serving various programs that financially support international collaborative research activities. Bilateral formation of the programs supported by funding agencies in both counter-partner countries will help stimulate further EU-Japan research collaborations.

At the end of the workshop, we had a general discussion session to exchange information on the status of Europe and Japan. The current status of Graphene Flagship was presented by Jari Kinaret (Chalmers University of Technology, Sweden), and that of Science of 2.5 Dimensional Materials was presented by Hiroki Ago (Kyushu University, Japan). Atsushi Kurobe (Japan Science and Technology Agency, Japan) commented on the current status of CREST Program, Japan Science and Technology Agency. In the final discussion, there was clear interest to continue the series of workshops by organizing the next one onsite either in Japan or Europe.

The workshop was not held last year due to the influence of COVID-19. This year, we decided to hold the workshop online to maintain the good relationship between Europe and Japan. Though the situation is still challenging and uncertain, we hope we can meet onsite in the future workshop to promote EU-JP collaborations in this field.

5^{th} EU-Japan Workshop on Graphene and Related 2D Materials

25 October, 2021 (zoom)

Workshop Chairs: Taiichi Otsuji (Tohoku University, Japan)
Jari Kinaret (Chalmers University of Technology, Sweden)

Program Chairs: Tomoki Machida (University of Tokyo, Japan)
Mikito Koshino (Osaka University, Japan)
Christoph Stampfer (RWTH Aachen University, Germany)
Camilla Coletti (Istituto Italiano di Tecnologia, Italy)

CEST (EU)	JST (JP)	Opening session Session chair: Tomoki Machida (University of Tokyo, Japan)
8:30	15:30	Opening address Taiichi Otsuji (Tohoku University, Japan) Christoph Stampfer (RWTH Aachen University, Germany)

CEST (EU)	JST (JP)	Scientific session 1 (15 min. talk + 5 min. discussion) Session chair: Mikito Koshino (Osaka University, Japan)
8:40	15:40	Nonlinear optical response of two-dimensional materials Giulio Cerullo (Dipartimento di Fisica, Politecnico di Milano, Italy)
9:00	16:00	Intrinsic photovoltaic response in symmetry-engineered van der Waals heterointerfaces Toshiya Ideue (Quantum-Phase Electronics Center (QPEC) and Department of Applied Physics, the University of Tokyo, Japan)
9:20	16:20	Spin communication on 2D material devices and circuits Saroj Prasad Dash (Chalmers University of Technology, Sweden)
9:40	16:40	Generation of orbital angular moment at van Hove singularity in rotationally aligned graphene/h-BN moiré superlattice Rai Moriya (Institute of Industrial Science, University of Tokyo, Japan)

10:00	10:20	20 minutes break

CEST (EU)	JST (JP)	Scientific session 2 (15 min. talk + 5 min. discussion) Session chair: Christoph Stampfer (RWTH Aachen University, Germany)
10:20	17:20	The universe of disordered and amorphous two-dimensional materials: scientific challenges & technology opportunities Stephan Roche (Fundacio Institut Catala de Nanociencia i Nanotecnologia, Spain)
10:40	17:40	Creation of a 2D electronic system with 1D wired materials Yasumitsu Miyata (Department of Physics, Tokyo Metropolitan University, Japan)
11:00	18:00	Direct observation of the layer-number-dependent electronic structure in few-layer WTe_2 Masato Sakano (Quantum-Phase Electronics Center and Department of Applied Physics, The University of Tokyo, Japan)
11:20	18:20	Towards super-resolution lithographic bandgap engineering of graphene PeterBøggild (Centre for Nanostructured Graphene, Technical University of Denmark, Denmark)

11:40	18:40	20 minutes break

CEST (EU)	JST (JP)	Scientific session 3 (15 min. talk + 5 min. discussion) Session chair: Rai Moriya
12:00	19:00	Phase transitions in the quantum Hall magnet of bilayer graphene Michihisa Yamamoto (RIKEN Center for Emergent Matter Science, Japan)
12:20	19:20	Synthesis and properties of quantum materials: from twisted graphene to monolayer 1T'-$MoTe_2$ Camilla Coletti (Istituto Italiano di Tecnologia, Italy)

CEST (EU)	JST (JP)	General discussion Session chair: Riichiro Saito (Tohoku University, Japan)
12:40	19:40	Current status of "Graphene Flagship" Jari Kinaret (Chalmers University of Technology, Sweden)
12:50	19:50	Launching "Science of 2.5 Dimensional Materials: Paradigm Shift of Materials Science Toward Future Social Innovation" Hiroki Ago (Kyushu University, Japan)
12:55	19:55	Current status of "CREST: Development of Atomic or Molecular Two-Dimensional Functional Films and Creation of Fundamental Technologies for Their Applications" Atsushi Kurobe (Japan Science and Technology Agency, Japan)
13:00	20:00	Discussion

CEST (EU)	JST (JP)	Closing session Session chair: Tomoki Machida (University of Tokyo, Japan)
13:30	20:30	Closing remark Toshiaki Enoki (Tokyo Institute of Technology, Japan) Camilla Coletti (Istituto Italiano di Tecnologia, Italy)

Scientific session: 15 minutes for talk and 5 minutes for discussion

Conference photo: We plan to take a conference photo via zoom at the end of the first scientific session.

Video: The presenter is asked to turn on the video during the presentation. The chair person is asked to turn on the video during the discussion time. Other participants are asked to turn off the video to lighten the load on the network.

Recording: Recording and screen shot by general attendees without permission are prohibited.

Workshop website: https://graphene-flagship.eu/events/japan-eu-workshop-2021/

List of invited speakers and organizers

Title	Last Name	First Name	Affiliation	Country
Prof.	Bøggild	Peter	Technical University of Denmark	Denmark
Prof.	Cerullo	Giulio	Polytechnic University of Milan	Italy
Prof.	Dash	Saroj	Chalmers University of Technology	Sweden
Dr.	Loiseau	Annick	National Centre for Scientific Research (CNRS)	France
Prof.	Roche	Stephan	Fundacio Institut Catala de Nanociencia i Nanotecnologia (ICN2)	Spain
Prof.	Stampfer	Christoph	RWTH Aachen University	Germany
Dr.	Coletti	Camilla	Istituto Italiano di Tecnologia (IIT)	Italy
Prof.	Kinaret	Jari	Chalmers University of Technology	Sweden
Dr.	Vacchi	Isabella	European Science Foundation	France
Dr.	Ciubotaru	Ana-Maria	European Science Foundation	France
Dr.	Ideue	Toshiya	University of Tokyo	Japan
Prof.	Miyata	Yasumitsu	Tokyo Metropolitan University	Japan
Dr.	Moriya	Rai	University of Tokyo	Japan
Dr.	Sakano	Masato	University of Tokyo	Japan
Dr.	Yamamoto	Michihisa	RIKEN	Japan
Prof.	Ago	Hiroki	Kyushu University	Japan
Emer. Prof.	Enoki	Toshiaki	Tokyo Institute of Technology	Japan
Mr.	Katsumata	Yasuhiro	Japan Science and Technology Agency	Japan
Dr.	Kurobe	Atsushi	Japan Science and Technology Agency	Japan
Prof.	Saito	Riichiro	Tohoku University	Japan
Prof.	Machida	Tomoki	University of Tokyo	Japan
Prof.	Mikito	Koshino	Osaka University	Japan
Prof.	Otsuji	Taiichi	Research Institute of Electrical Communication	Japan
Dr.	Onodera	Momoko	University of Tokyo	Japan

5th EU-Japan Workshop on Graphene and Related 2D Materials (2021)

Title of the Presentation: Nonlinear optical response of two-dimensional materials

First Name: Giulio Cerullo

Affiliation: Dipartimento di Fisica, Politecnico di Milano

Piazza Leonardo da Vinci 32, 20133 Milano, Italy

Short Biography:
Giulio Cerullo is a Full Professor with the Physics Department, POLIMI, where he leads the Ultrafast Optical Spectroscopy laboratory. His research deals with the generation of tunable ultrashort light pulses and with their application to the study of photoinduced processes in bio-molecules and nanostructures. He has published >450 papers which have received >24000 citations (H-index: 79, Scopus). He is a Fellow of the Optical Society of America and of the European Physical Society and Chair of the Quantum Electronics and Optics Division of the European Physical Society. He is the recipient of an ERC Advanced Grant (2012-2017) on two-dimensional electronic spectroscopy of biomolecules. He is on the Editorial Advisory Board of the journals Optica, Laser&Photonics Reviews, Scientific Reports, Journal of Raman spectroscopy. He has been General Chair of the conferences CLEO/Europe 2017, Ultrafast Phenomena 2018 and International Conference on Raman Spectroscopy 2020.

Abstract:

Two-dimensional materials show extraordinarily strong second- and third-order nonlinear optical response which, thanks to their unique electronic properties and despite their atomic thickness, allow a wide range of fundamental studies and technological applications. In this presentation we will discuss some of our recent results on the study of the nonlinear optical response of two-dimensional materials: gate-tunable third harmonic generation in single-layer graphene [1], optical parametric amplification in single-layer transition metal dichalcogenides [2] and all-optical switching of second-harmonic generation in MoS_2 with modulation depth close to 100% [3].

[1] Soavi, G. et al. Broadband, electrically tunable third-harmonic generation in graphene. Nat. Nanotechnol. **13**, 583–588 (2018).

[2] Trovatello, C. et al. Optical parametric amplification by monolayer transition metal dichalcogenides. Nat. Photon. **15**, 6–10 (2021).

[3] Klimmer, S. et al. All-optical polarization and amplitude modulation of second-harmonic generation in atomically thin semiconductors, Nat. Photon. online (2021).

5th EU-Japan Workshop on Graphene and Related 2D Materials (2021)

Title of the Presentation: Intrinsic photovoltaic response in symmetry-engineered van der Waals heterointerfaces

First Name: Toshiya

Last Name: Ideue

Affiliation: Quantum-Phase Electronics Center (QPEC) and Department of Applied Physics, the University of Tokyo, Tokyo, Japan.

Short Biography:
Toshiya Ideue received M.S. from the University of Tokyo in 2011 and worked at Fujifilm Corporation (2011-2012). He received Ph.D. in engineering from the University of Tokyo in 2015. He is now a research associate in the University of Tokyo.

Abstract:
At the interface of two dimensional materials, unique nanostructures, which are absent in the original two dimensional crystals, can emerge represented by moiré superlattice and dodecagonal quasi-crystalline structure. Such novel nanostructures strongly affect the electronic states of the interface, leading to a variety of exotic physical properties and functionalities.
In this talk, I will introduce a new type of van der Waals interface, which host the in-plane polarization and resultant intrinsic photovoltaic properties. By combining the two dimensional materials with different symmetries (three-fold rotational WSe_2 and two-fold rotational black phosphorus), in-plane electronic polarization can emerge (Fig.1 A-C), which cause the intrinsic photovoltaic response (Fig.1D) [1]. Photovoltaic response at the interface can be well explained by quantum-mechanical shift current, which originates from the shift of the wave packet under the light illumination [2].

The present results provide a design principle of realizing the in-plane polar interface, which can be applicable to a variety of van der Waals nanostructures.

This work is financially supported by A3 foresight program, JST PRESTO (#JPMJPR19L1, #JPMJPR19L9) and JSPS KAKENHI (#19H00653, #19H05602, #19H01819, #19K21843, #20H05264), Japan.

[4] T. Akamatasu, T. Ideue *et al.*, Science **372**, 68 (2021)
[5] T. Morimoto and N. Nagaosa, Sci. Adv. **2**:e1501524 (2016)

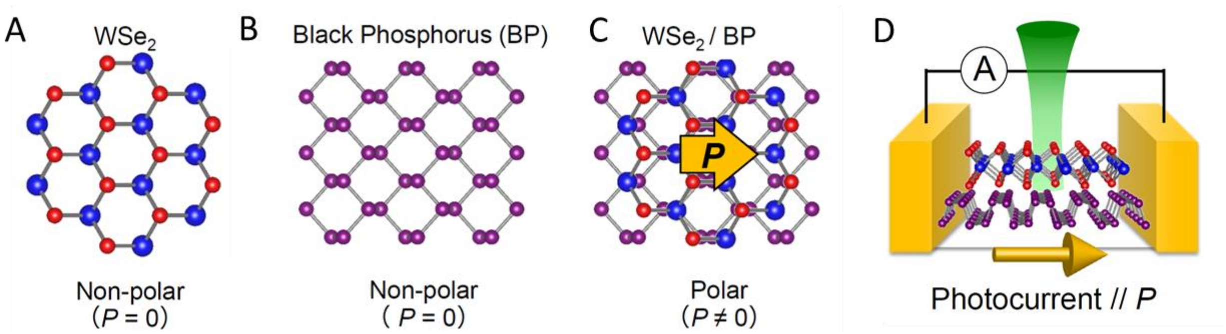


Figure 1: (A-C) Crystal structures of (A) WSe_2, (B) Black phosphorus (BP), and (C) WSe_2/BP interface. (D) Schematic of the spontaneous photovoltaic effect at WSe_2/BP interface.

5th EU-Japan Workshop on Graphene and Related 2D Materials (2021)

Title of the Presentation: Spin Communication on 2D Material Devices and Circuits

Name: Saroj Prasad Dash

Affiliation: Professor, Quantum Device Physics Laboratory, Dept. Microtechnology and Nanoscience,

Chalmers University of Technology, Gothenburg, Sweden

Short Biography:
Saroj Prasad Dash is a professor and group leader at the Quantum Device Physics laboratory, Chalmers University of Technology, Sweden. He finished his Ph.D. in Physics in 2007 from Max Planck Institute, Stuttgart, Germany. His previous positions include postdocs at the University of Twente and University of Groningen in the Netherlands for three years. The focus of his research group is on spintronics, nanoelectronics and quantum transport in two-dimensional materials, van der Waals heterostructures, semiconductors, and topological quantum materials-based nanoscale devices. He has published several seminal papers in the field of 2D materials, semiconductor, and topological materials based spintronic devices. He is a PI in several Swedish and EU grants, including larger consortiums like Swedish 2DTECH and EU Graphene Flagship.

Abstract:

Atomically thin two-dimensional (2D) quantum materials and their van der Waals heterostructures represent a novel platform to realize novel spin-based phenomena and device applications. Followed by the successful use of graphene, a vast plethora of 2D materials with complementary spintronic properties have been discovered, such as 2D insulators, semiconductors, magnets, and topological materials.

All-spin-based computing combining logic and nonvolatile magnetic memory is promising for emerging information technologies. However, the realization of a universal spin logic operation representing a reconfigurable building block with all-electrical spin current communication has so far remained challenging. Here, we used large-area CVD graphene as a robust spin interconnect (1,2), spin multiplexing (3) and finally demonstrated multifunctional spin logic gate operation (4). A reprogrammable all-electrical multifunctional spin logic gate is realized utilizing graphene buses for spin communication and multiplexing and nanomagnets for writing and reading information at room temperature (4). This gate realizes a multistate majority spin logic operation (sMAJ), which is reconfigured to achieve AND, OR, NAND, NOR and XNOR Boolean operations depending on the magnetization of inputs. These demonstrations open a platform for scalable all-electric spin logic in the all-spin domain logic-in-memory architecture.

The creation of large spin polarization and efficient control of spin current in graphene channel is required to enhance the output voltages and design of multifunctional spintronic circuits. To enhance the tunnel spin polarization of ferromagnets, we employed multilayer CVD h-BN tunnel barriers for achieving a very large and negative tunnel spin polarization (5). In order to control the spin polarization in graphene, we engineered 2D material heterostructures by combining the best of different materials in one ultimate unit and realized strong proximity induced spin-orbit coupling (6) and magnetism (7) in graphene. In nonlocal spin transport devices, we utilized graphene/MoS_2 and graphene/$Cr_2Ge_2Te_6$ heterostructures for probing proximity-induced spin interactions in graphene.

The charge-spin conversion is the fundamental physical phenomenon and pivotal for spintronics and quantum technologies. Recently discovered topological materials were predicted to provide a large CSC efficiency due to their non-trivial band structure in both bulk and surface states. Recently, we detected current-induced spin-polarization in topological insulators (8) and Weyl semimetals (9). The measurements indicated an unconventional charge-to-spin conversion in WTe_2, which is primarily forbidden by the crystal symmetry of the system (9). Such a large spin polarization can be possible in WTe_2 due to a reduced crystal symmetry combined with its large spin Berry curvature, spin–orbit interaction with a novel spin-texture of the Fermi states. Furthermore, by integrating two-dimensional graphene with a topological insulator (TI) in van der Waals heterostructures to take advantage of their remarkable spintronic properties (10) and engineer proximity-induced spin-charge conversion phenomena (11). In these heterostructures, we experimentally demonstrate a gate-tunable spin-galvanic effect (SGE) at room temperature, allowing for efficient conversion of a non-equilibrium spin polarization into a transverse charge current (11).

Finally, the discovery of van der Waals magnets opened up a new paradigm for condensed matter physics and spintronic technologies. However, the operations of active spintronic devices with vdW magnets are so far limited to cryogenic temperatures, inhibiting its broader practical applications. Here, we demonstrate room temperature spin-valve devices using vdW itinerant ferromagnet Fe_5GeTe_2 in heterostructures with graphene (12). The tunnel spin polarization of the Fe_5GeTe_2/graphene vdW interface is detected to be significantly large ~ 45 % and negative at room temperature. Lateral spin-valve device design enables electrical control of spin signal and realization of basic building blocks for device application such as efficient spin injection, transport, precession, and detection functionalities. These findings open a novel platform for electrical creation and gate-control of spin polarization and provide new opportunities for all-2D heterostructure spintronic devices and integrated spin circuits.

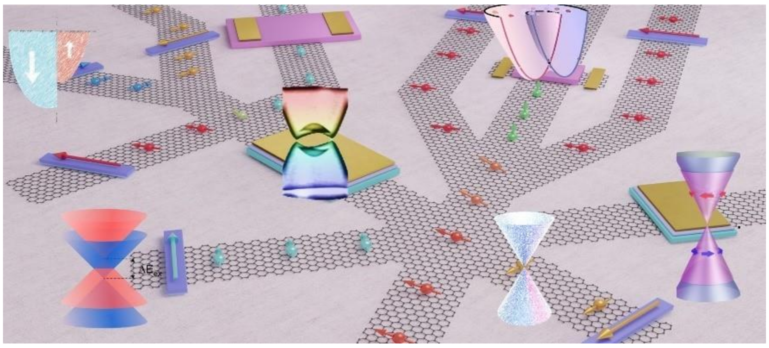


Figure 1: Schematics of 2D quantum materials van der Waals heterostructure for creation and control of spin current in the graphene circuit.

[1] Nature Communications 6, 6766 (2015).
[2] ACS Nano 14 (11), 15864-15873 (2020).
[3] Carbon 161, 892-899 (2020),
[4] ArXiv preprint arXiv:2108.12259
[5] Scientific Reports 6, 21168 (2016).
[6] Nature Communications 8, 16093 (2017).
[7] 2D Materials 7 (1), 015026 (2019).
[8] Nano Letters 15 (12) 7976 (2015).
[9] Advanced Materials, 2000818 (2020), Physical Review Research 2 (1), 013286 (2020).
[10] Science Advances 4:eaat9349 (2018),
[11] Nature Communication 11, 3657 (2020).
[12] ArXiv preprint arXiv:2107.00310 (2021).

5th EU-Japan Workshop on Graphene and Related 2D Materials (2021)

Title of the Presentation: Generation of orbital angular moment at van Hove singularity in rotationally aligned graphene/h-BN moiré superlattice

First Name: Rai

Last Name: Moriya

Affiliation: Institute of Industrial Science, University of Tokyo, Tokyo, Japan

Short Biography:
Rai Moriya received his Ph.D. from Department of Information Processing, Tokyo Institute of Technology, in 2004. From 2004 to 2009, he was working at IBM Research Division, Almaden Research Center. From 2009 to 2017, he was a research associate at Institute of Industrial Science, University of Tokyo. From 2017 to 2021, he was a project lecturer at Institute of Industrial Science, University of Tokyo. Since 2021, he has been a project associate professor at Institute of Industrial Science, University of Tokyo.

Abstract:
The superlattice potential in aligned graphene/h-BN moiré superlattice generates a series of Dirac points (DPs) and van Hove singularities (vHSs) within an experimentally accessible low energy state, providing an ideal platform to study various band properties in relation to its topology. In this work, theoretical calculations and magnetothermoelectric measurements are combined to reveal the emergence of an orbital magnetic moment at vHSs in graphene/h-BN moiré superlattices. Two different flakes of graphene encapsulated with h-BN were placed on the substrate with a separation in between the flakes of 10 µm (Fig. 1a); we use one graphene as a Joule heater to generate a temperature gradient in an aligned graphene device. Two-terminal resistance R and thermopower Vind measured in the aligned graphene are presented in Fig. 1b, showing moderate Vind at main DP and secondary DPs (SDPs), and enhanced Vind at vHSs. The magnetic field dependence of Vind signals from vHSs shown in Fig. 1c exhibited significant splitting only at the second vHS at the hole-side (2nd vHS). Comparing with theoretical calculation on the density of states of different valleys of graphene (Fig. 1d,e), we found that this phenomena is due to the large magnetic field induced splitting of K and K' valley at vHS with an effective g-factor of approximately 130. This was attributed to the emergence of an orbital magnetic moment at the second vHS.

[1] R. Moriya et al., Nature Communications **11** (2020) 5380.

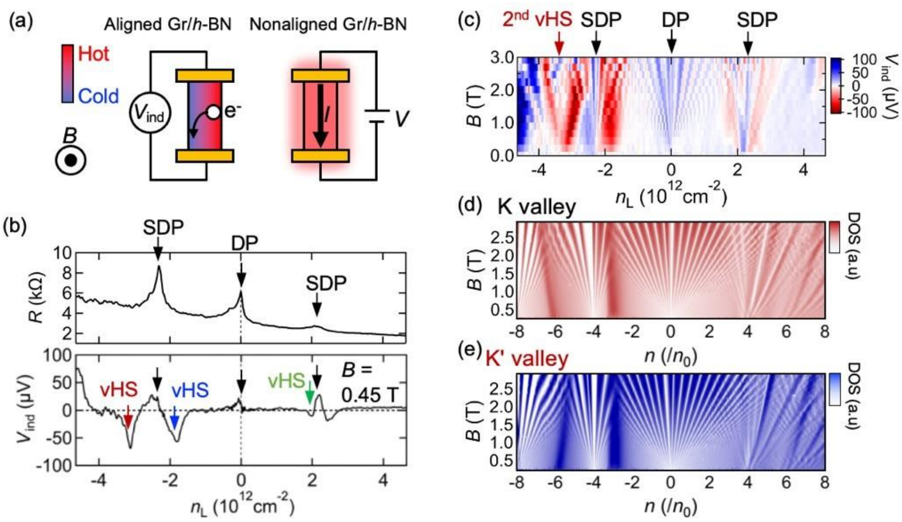


Figure 1: (a) Schema of thermoelectric measurement in a parallel graphene device. (b) R and V_{ind} versus carrier density n_L. (c) V_{ind} as a function of carrier density n_L and B. (c) Calculated DOS for K and K´ valley as a function of the normalized carrier density n/n_0 and B.

5th EU-Japan Workshop on Graphene and Related 2D Materials (2021)

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

Name: Stephan Roche

Affiliation: ICREA & Catalan Institute of Nanoscience and Nanotechnology (ICN2), CSIC and BIST, Campus de la UAB, 08193 Bellaterra (Barcelona) Spain

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

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

Abstract:

Two-dimensional materials show extraordinarily strong second- and third-order nonlinear optical response which, thanks to their unique electronic properties and despite their atomic thickness, allow a wide range of fundamental studies and technological applications. In this presentation we will discuss some of our recent results on the study of the nonlinear optical response of two-dimensional materials: gate-tunable third harmonic generation in single-layer graphene [1], optical parametric amplification in single-layer transition metal dichalcogenides [2] and all-optical switching of second-harmonic generation in MoS_2 with modulation depth close to 100% [3].

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

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

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

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

5th EU-Japan Workshop on Graphene and Related 2D Materials (2021)

Title of the Presentation: Creation of a 2D electronic system with 1D wired materials

First Name: Yasumitsu

Last Name: Miyata

Affiliation: Department of Physics, Tokyo Metropolitan University, Hachioji, Tokyo, Japan

Short Biography:
Dr. Miyata received his Ph.D. in Physics from Tokyo Metropolitan University, Japan, in 2008. He was a research fellow of the Japan Society for the Promotion of Science (JSPS) (2008-2009), and was an assistant professor at Nagoya University (2009-2013). Since 2013, he has been an Associate Professor of Tokyo Metropolitan University.

Abstract:

One-dimensional (1D) transition metal chalcogenides (TMCs) have attracted much attention lately due to their atomically-thin, wired structures (Fig.1a) and superior conducting properties [1-4]. These wires interact via van der Waals forces, aggregating into crystals of different shapes with desired properties (Fig.1b). However, relevant studies on their transport properties remain limited due to the lack of high-quality samples. Herein, we report the formation of a two-dimensional (2D) carrier gas in thin, ribbon-shaped bundles of laterally-assembled WTe atomic wires [1,2]. Wafer-scale synthesis of highly-crystalline WTe atomic wires was achieved by chemical vapor deposition (Fig.1c). The crystal structure of a WTe aggregate was observed using cross-sectional HAADF-STEM, as shown in Fig. 1d. Magnetoresistance measurements reveal that a single WTe bundle exhibits weak anti-localization and Shubnikov-de Haas (SdH) oscillation at low temperatures. Angle-dependence SdH oscillations serve as evidence for the realization of a 2D carrier gas in the WTe bundle (Fig.1e). The present finding indicates the versatility of TMC atomic wires as building blocks to produce electronic systems of desired dimensionality for future functional electronic and energy harvesting devices.

[6] J. Lin et al., Nat. Nanotech. **9** (2014) 436.
[7] H. Zhu et al., Adv. Mater. **29** (2017) 1606264.
[8] M. Nagata et al., Nano Lett. **19** (2019) 4845.
[9] J. Deng et al., Nano Lett. **20** (2020) 8866.
[10]H.E. Lim et al., Nano Lett. **21** (2021) 243.
[11]H. Shimizu et al., submitted.

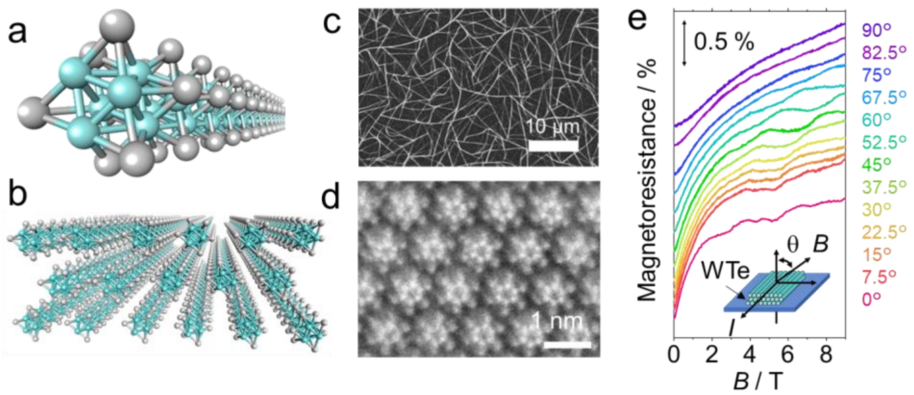


Figure 1: Schematic diagrams for (a) a WTe atomic wire and (b) a 2D aggregation from 1D WTe wires. (c) SEM image of the network of WTe bundles. (d) Cross-sectional HAADF-STEM image of a WTe bundle. (e) Magnetoresistance as a function of magnetic field *B*, recorded at different orientations (measured by the angle θ) with respect to the direction normal to the substrate.

5th EU-Japan Workshop on Graphene and Related 2D Materials (2021)

Title of the Presentation: Direct observation of the layer-number-dependent electronic structure in few-layer WTe_2

First Name: Masato

Last Name: Sakano

Affiliation: Quantum-Phase Electronics Center and Department of Applied Physics, The University of Tokyo, Tokyo, Japan

Short Biography:
Masato Sakano received a doctoral degree of engineering from The University of Tokyo, Japan in 2016. After working for the Institute of Solid State Physics, The University of Tokyo (2016-2017) as a postdoctral researcher, he has been working for the Department of Applied Physics and Quantum-Phase Electronics Center at The University of Tokyo as an assistant professor. His present research is on studying the electronic structures in strongly spin-orbit coupled materials, topological materials and two-dimensional materials by means of photoemission spectroscopy, and developing the laser angle-resolved photoemission spectroscopy system.

Abstract:

In atomically-thin two-dimensional (2D) materials, the physical property varies discretely with each increase in the number of layers from monolayer to bulk. Few-layer WTe_2 [1,2] has stacking-order driven noncentrosymmetric crystal structures, leading to the peculiar Berry curvature related switchable functionalities such as the nonlinear anomalous Hall effect [3-5] and the ferroelectricity [6]. Although those transport properties are sensitive to the formation of the band dispersions near the Fermi level, it is difficult to accurately calculate the complex band structure of few-layer WTe_2 by the first principles calculations. In our study, by using micro-focused laser angle-resolved photoemission spectroscopy (ARPES) in combination with the 2D materials manufacturing system that can freely stack atomic layers by image recognition, machine learning, and autonomous robots [7,8], we demonstrated the direct observations on the layer-number dependent band dispersions of the 2–5 layer WTe_2. It revealed the sequential changes in the band structures exhibiting the even-odd nature of the number of layers and the insulator–semimetal transition [9]. This research was partly supported by a CREST project (Grant Nos. JPMJCR15F3, JPMJCR16F2 and JPMJCR20B4) from the Japan Science and Technology Agency (JST) and Japan Society for the Promotion of Science KAKENHI (Grants-in-Aid for Scientific Research) (Grant Nos. JP20H00127, JP20H00354, JP20H01834, JP21H05232, JP21H05233, JP21H05234, JP21H05235 and JP21H05236).

[12]Z. Fei, *et al*., Nat. Phys. **13**, 677 (2017).
[13]I. Cucchi *et al*., Nano Lett. **19**, 554 (2019).
[14]K. Kan *et al*., Nat. Mater. **18**, 324 (2019).
[15]H. Wang and X. Qing npj Comput. Mater. **5**, 119 (2019).
[16]J. Xiao *et al*., Nat. Phys. **16**, 1028 (2020).
[17]Z. Fei *et al*., Nature **560**, 336 (2018).
[18]S. Masubuchi, *et al*., Nat. Commun. **9**, 1413(2018).
[19]S. Masubuchi, *et al*., npj 2D Mater. Appl. 4, 3 (2020).
[20]M. Sakano*, Y. Tanaka*, S. Masubuchi*, *et al*.,
(*equal contribution) arXiv:2103.11885 (2021).

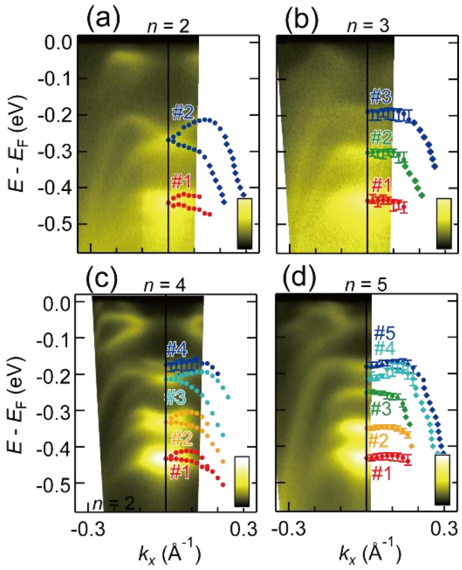


Figure 1: (a)-(d) ARPES images for 2-5 layer WTe_2.

5th EU-Japan Workshop on Graphene and Related 2D Materials (2021)

Title of the Presentation: Towards super-resolution lithographic bandgap engineering of graphene

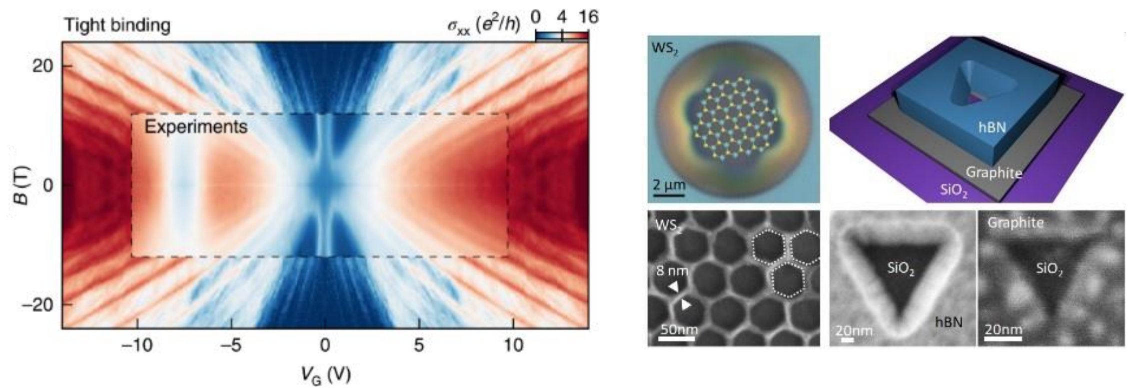
Name: Peter Bøggild

Affiliation: *Centre for Nanostructured Graphene (CNG), Technical University of Denmark, Denmark*

Short Biography:
Peter Bøggild received his PhD degree in mesoscopic physics from Copenhagen University in 1998 and became full professor in 2013. He is today leading a research group at DTU Physics, Technical University of Denmark, focusing on 2D materials, including synthesis and transfer, nanolithography, quantum transport and THz-physics, covering both basic and applied research. He is involved several large projects, including the DNRF Centre for Nanostructured Graphene, the H2020 Graphene Flagship and the Novo Nordisk Foundation challenge project Biomag, developing magnetic sensors for mapping currents in the brain.

Abstract:

After the initial excitement about graphene's high performant and scientifically rich electronic properties, one of the most obnoxious challenges have been to pattern graphene on a small scale. In theory, nanostructuring of graphene opens for the electronic and photonic properties to be "programmed" to match specific applications or to bring out entirely new physics. In practice, even low levels of edge disorder and contamination associated with even the best lithographic processes, ruins the electronic properties. I will discuss our progress in creating lithographic "nanoporous" graphene [1], where we combine encapsulation in hexagonal boron nitride (hBN), high-density lithography, and carefully tuned anisotropic etching process, to pattern graphene on the 10 nm scale (Fig. 1), and still preserve the detailed magnetotransport signatures predicted by tight-binding calculations. The surprising survival of the subtle moire-superlattice signatures associated with twisting of the crystalline interlayers opens for construction of circuits and components that exploit this emerging branch of solid-state physics. Finally, I will explain how the anomalous anisotropic etching of hBN using SF_6, can be turned into a powerful toolbox for super-resolution nanolithography, enabling downsizing of features way below conventional lithography limits [2].



[1] B. S. Jessen, L. Gammelgaard, M. R. Thomsen, D. M. A. Mackenzie, J. D. Thomsen, J. M. Caridad, E. Duegaard, K. Watanabe, T. Taniguchi, T. J. Booth, T. G. Pedersen, A-P. Jauho, P. Bøggild, Nature Nanotechnology, 14, 340-346 (2019)

[2] D. R. Danielsen, A. Lyksborg-Andersen, K. E. S. Nielsen, B. S. Jessen, T. J. Booth, P. Bøggild, and L. Gammelgaard, ACS Applied Materials & Interfaces, 13 41886 (2021)

5th EU-Japan Workshop on Graphene and Related 2D Materials (2021)

Title of the Presentation: Phase transitions in the quantum Hall magnet of bilayer graphene

First Name: Michihisa

Last Name: Yamamoto

Affiliation: RIKEN Center for Emergent Matter Science, Wako, Japan

Short Biography:
Michihisa Yamamoto received his Ph.D. (2004) in physics from the University of Tokyo. He was a research associate (2004-2014) and a lecturer (2014-2017) in the Department of Applied Physics and an associate professor (2017-2018) in Quantum-Phase Electronics Center at the University of Tokyo. He was a unit leader (2017-2020) and is a team leader since April 2020 at RIKEN Center for Emergent Matter Science.

Abstract:

The quantum Hall system can be used to study many-body physics owing to its multiple internal electronic degrees of freedom and tunability. While quantum phase transitions have been studied intensively, research on the temperature-induced phase transitions of this system is limited. This is because the coexistence of the bulk and edge states makes the temperature dependence of observables more complex than in homogeneous systems. In this study, we employed Corbino devices, which eliminate any type of edge transport to certainly measure the bulk conductivity (see Fig. 1). We measured the pure bulk conductivity of a quantum Hall antiferromagnetic state in bilayer graphene over a wide range of temperatures and revealed the two-step phase transition associated with the breaking of the long-range order, i.e., the Kosterlitz–Thouless transition, and short-range antiferromagnetic order [1].

This work was mostly done by Miuko Tanaka at the University of Tokyo in collaboration with Takashi Taniguchi, Kenji Watanabe, Kentaro Nomura and Seigo Tarucha. This work is financially supported by JSPS KAKENHI #17H01138, Japan.

[21]M. Tanaka et al., arXiv: 2108.11464.

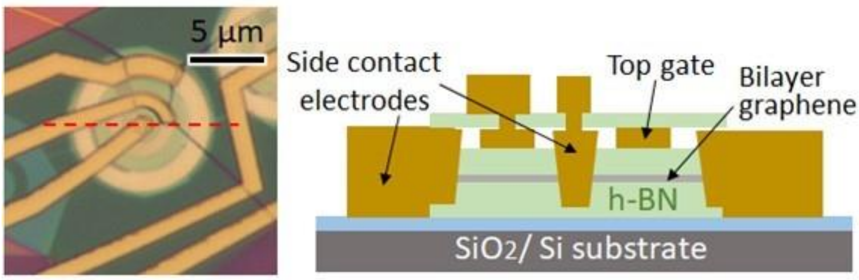


Figure 1: Optical microscope image and a schematic cross-section of a Corbino device.

5th EU-Japan Workshop on Graphene and Related 2D Materials (2021)

Title of the Presentation: Synthesis and properties of quantum materials: from twisted graphene to monolayer 1T'-$MoTe_2$

Name: Camilla Coletti

Affiliation: *Graphene Labs, Istituto Italiano di Tecnologia, 56127 Pisa, Italy*

Short Biography:

Camilla Coletti is a tenured Senior Scientist of the Istituto Italiano di Tecnologia (IIT) and coordinator of the Center for Nanotechnology Innovation (CNI@NEST) of Pisa and of the Graphene Labs. She received her PhD degree in Electrical Engineering from the University of South Florida in 2007 and from 2008 to 2011 she was an Alexander von Humboldt postdoctoral fellow at the Max Planck Institute of Stuttgart. Her research focuses on the synthesis of highly-crystalline 2D materials *via* chemical vapour deposition (CVD) and on the investigation of their electronic, chemical and structural properties.

Abstract:

In this talk I will discuss synthetic approaches based on chemical vapor deposition that allow one to obtain high mobility monolayer and twisted bilayer graphene as well as the 1T' phase of monolayer $MoTe_2$ [1-4]. The properties of these materials in terms of electrical transport and air stability will be discussed. It will be shown how at cryogenic temperatures, the mobility of CVD monolayer graphene (> 6 × 105 cm^2/Vs at ~1011 cm^{-2}) is limited by the devices' physical edges, while under perpendicular magnetic fields, early onset of Landau quantization (B ~ 50 mT) and signatures of electronic correlation, including the fractional quantum Hall effect, are observed [1]. Also, it will be presented the achievement, in dual-gated 30°-twisted bilayer graphene of simultaneous ultra-high mobility and conductivity (up to 40 mS at room temperature) [5]. Finally, it will be introduced the large-scale synthesis of monolayer 1T'-$MoTe_2$ and its stabilization via scalable hBN encapsulation [4].

[1] S. Pezzini, V. Mišeikis, S. Pace, F. Rossella, K. Watanabe, T. Taniguchi, C. Coletti, 2D Materials 7 (4), 041003 (2020).

[2] S. Pezzini, V. Miseikis, G. Piccinini, S. Forti, S. Pace, R. Engelke, F. Rossella, K. Watanabe, T. Taniguchi, P. Kim, C. Coletti, Nano Letters 20, 5, 3313–3319, (2020).

[3] C. Bouhafs, S. Pezzini, F.R. Geisenhof, N. Mishra, V. Mišeikis, Y. Niu, C. Struzzi, R.T. Weitz, A.A. Zakharov, S. Forti, C. Coletti, Carbon 177, 282-290 (2021)

[4] S. Pace, L. Martini, D. Convertino, D.-H. Keum, S. Forti, S. Pezzini, F. Fabbri, V. Mišeikis, C. Coletti, ACS nano 15 3 (2021) 4213-4225.

[5] G. Piccinini, V. Mišeikis, K. Watanabe, T. Taniguchi, C. Coletti, S. Pezzini https://arxiv.org/pdf/2109.06812.pdf