The 6th EU-JP Workshop on graphene and related 2D materials

25-26 May 2023

Convention Hall, Institute of Industrial Science, University of Tokyo, Komaba, Japan

Workshop chairs

Prof. Taiichi Otsuji
Research Institute of Electrical Communication (RIEC), Tohoku University

Prof. Jari Kinaret
Graphene Flagship Director, Chalmers University of Technology

Programme chairs

Prof. Tomoki Machida
Institute of Industrial Science, University of Tokyo

Prof. Mikito Koshino
Department of Physics, Osaka University

Dr. Camilla Coletti
IIT

Prof. Christoph Stampfer
RWTH Aachen

GRAPHENE FLAGSHIP

2.5D Materials

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Workshop activities, overview and common challenges

The 6th EU–JP Workshop on graphene and related 2D materials was held at Convention Hall, Institute of Industrial Science, University of Tokyo, Komaba, Japan in 25–26 May 2023. 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, the fourth in Pisa (Italy) in 2019, and the fifth online in 2021.

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

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

The workshop gathered 22 participants, coming mainly from academic and research institutions. At this workshop, 18 invited speakers 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 and devices, as well as applications such as biosensing and energy harvesting. Interest was expressed by many in the possibilities of forming collaborative partnerships, including the encouragement of students' visiting exchanges.

At the start of the workshop, 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). 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 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 have had a general discussion session to exchange information on the status of Europe and Japan. We also discussed how and where we would hold future joint workshops.

The previous workshop was held online in 2021, due to the influence of COVID−19; this year, we were very happy to have a face−to−face workshop to maintain the good relationship between Europe and Japan. The next joint workshop will be held in Europe, the exact location to be established soon.

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Programme Japan-EU Workshop

The 6th Graphene Flagship EU-Japan Workshop on Graphene and related 2D materials

May 25, 2023		
12:00 - 12:40	**Get-together with Lunch**	
Session 1: *Chair: Tomoki Machida (University of Tokyo, Japan)*		
12:40 – 12:45	*Taiichi Otsuji*	Opening address
12:45 – 13:00	*Jari Kinaret*	Graphene Flagship: a look at its ten years' voyage and the way ahead
13:00 – 13:15	*Hiroki Ago*	Current status of 2.5D
13:15 – 13:45	*Camilla Coletti*	Moving from fundamental studies to industrial applications with CVD−grown 2D materials
13:45 – 14:15	*Yasumitsu Miyata*	1D nanostructures based on transition metal chalcogenides
14:15 – 14:40	***Coffee break***	
Session 2: *Chair: Susumu Okada (University of Tsukuba)*		
14:40 – 15:10	*Vladimir Fal'ko*	Ferroelectric domain structures in twistronic TMD bilayers
15:10 – 15:40	*Mikito Koshino*	Moire phonons in twisted materials
15:40 – 16:10	*Mar Garcia Hernandez*	Are 2D materials limited to Van der Waals layered materials?
16:10 – 16:30	***Coffee break***	

Session 3: *Chair: Vladimir Fal'ko (University of Manchester)*		
16:30 – 17:00	*Rai Moriya*	Momentum− and twist−controlled resonant tunneling device based on few−layer WSe2
17:00 – 17:30	*Marco Romagnoli*	Graphene based photonics for optical communications
17:30 – 18:00	*Jiang Pu*	Monolayer in−plane heterostructure light−emitting devices with tunable composition distribution
From 18:00	**Banquet at restaurant**	

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2.5D Materials

May 26, 2023		
Session 4: *Chair: Camilla Coletti (Istituto Italiano di Tecnologia)*		
10:30 – 11:00	*Kostas Kostarelos*	Clinical Translation of Graphene–based Neural Interface Devices
11:00 – 11:30	*Yuki Shiomi*	Giant nonreciprocal magneto–transport in Weyl–semimetal WTe2 induced by diverging Berry curvature
11:30 – 12:00	*Laura Ballerini*	2D materials to modulate brain networks and synapses
12:00 – 12:30	*Toshiaki Kato*	Fabrication of high quality Janus TMD by in–situ monitoring plasma functionalization
12:30 – 13:30	**Lunch**	
Session 5: *Chair: Yasumitsu Miyata (Tokyo Metropolitan University)*		
13:30 – 14:00	*Francesco Bonaccorso*	The path toward 2D materials industrialization
14:00 – 14:30	*Yuya Shimazaki*	Electrically controlled homo bilayer moiré semiconductor probed by exciton spectroscopy
14:30 – 15:00	*Inge Asselberghs*	Enabling 2D–materials process–transfer from lab–to–fab
15:00 – 15:20	***Coffee break***	
Session 6: *Chair: Mikito Koshino (Osaka University, Japan)*		
15:20 – 15:50	*Lin Yung–Chang*	Bilayer graphene intercalation: A study of interlayer coupling and the atomic structure of intercalants
15:50 – 16:20	*Andrea Ferrari*	Layered Materials for Quantum Technologies
16:20 – 16:50	*Susumu Okada*	Electronic Properties of heterostructures of 2D Materials
16:50 – 17:05	**General discussion: research collaboration and future**	
17:05 – 17:10	**Closing remarks**	
	Dinner at restaurant KOMANI (on campus)	

List of participants

Title	Last name	First name	Institution	Country
Prof.	Kinaret	Jari	Chalmers University	Sweden
Dr.	Coletti	Camilla	Istituto Italiano di Tecnologia	Italy
Dr.	Bonaccorso	Francesco	Bedimensional	Italy
Dr.	Asselberghs	Inge	IMEC	Belgium
Prof.	Fal'ko	Vladimir	University of Manchester	United Kingdom
Prof.	Kostarelos	Kostas	University of Manchester	United Kingdom
Prof.	Ballerini	Laura	SISSA	Italy
Prof.	Garcia Hernandez	Mar	CSIC	Spain
Dr.	Romagnoli	Marco	CNIT	Italy
Prof.	Ferrari	Andrea	University of Cambridge	United Kingdom
Prof.	Machida	Tomoki	University of Tokyo	Japan
Prof.	Otsuji	Taiichi	Tohoku University	Japan
Prof.	Ago	Hiroki	Kyushu University	Japan
Prof.	Miyata	Yasumitsu	Tokyo Metropolitan University	Japan
Prof.	Koshino	Mikito	Osaka University	Japan
Prof.	Moriya	Rai	University of Tokyo	Japan
Dr.	Pu	Jiang	Tokyo Tech	Japan
Prof.	Shiomi	Yuki	Univeristy of Tokyo	Japan
Prof.	Kato	Toshiaki	AIMR, Tohoku University	Japan
Dr.	Shimazaki	Yuya	RIKEN	Japan
Dr.	Yung–Chang	Lin	AIST	Japan
Prof.	Okada	Susumu	Univerisy of Tsukuba	Japan

6th Japan-EU Workshop on Graphene and Related 2D Materials (2023)

Title of the Presentation: Moving from fundamental studies to industrial applications with CVD−grown 2D materials

First Name: Camilla

Last Name: Coletti

Affiliation: Istituto Italiano di Tecnologia, Italy

Short Biography:

Camilla Coletti is a tenured Senior Scientist of the Istituto Italiano di Tecnologia (IIT) and principal investigator of the research line 2D Materials Engineering. She is the coordinator of the Center for Nanotechnology Innovation (CNI@NEST) of Pisa and of the Graphene Labs. She received her MS degree from the University of Perugia in 2004 and her PhD degree from the University of South Florida in 2007 (both in electrical engineering). Her research is currently focused on: (i) synthesis and integration of scalable 2D materials for optoelectronics, photonics and biomedicine (ii) engineering van der Waals heterostructures. She is the author of more than 150 peer−reviewed publications, contributed to several book chapters and holds 3 international patents.

Abstract:
To make 2D materials appealing for several applications at high technology readiness levels, requirements such as high−quality, scalability and contamination control have to be satisfied. In this talk, I will discuss wafer−scale growth approaches of high−quality graphene and transition metal dichalcogenides via chemical vapor deposition (CVD) [1−3] and discuss how these scalable 2D material can be adopted in industrial applications, from sub−THz wireless transmission [4], to Hall sensors and power distribution. Furthermore, I will present results on the field of twistronics − such as large and small angle twisted bilayer CVD graphene [5,6], which are exciting playgrounds for fundamental studies.

[1] M.A. Giambra, V. Mišeikis, S. Pezzini, S. Marconi, A. Montanaro, F. Fabbri, V. Sorianello, A.C. Ferrari, C. Coletti, M. Romagnoli, ACS nano 15 (2), 2021.
[2] N Mishra, S Forti, F Fabbri, L Martini, C McAleese, B Conran, PR Whelan, A Shivayogimath, BS Jessen, L Buß, J Falta, I Aliaj, S Roddaro, JI Flege, P Bøggild, KBK Teo, C Coletti, Small 15 (50), 2019.
[3] S. Pace, L. Martini, D. Convertino, D.-H. Keum, S. Forti, S. Pezzini, F. Fabbri, V. Mišeikis, C. Coletti, ACS nano 15 (3), 2021.
[4] A. Montanaro, G. Piccinini, V. Mišeikis, V. Sorianello, M.A. Giambra, S. Soresi, L. Giorgi, A. D'Errico, K. Watanabe, T. Taniguchi, S. Pezzini, C. Coletti, M. Romagnoli, https://assets.researchsquare.com/files/rs-1835036/v1/b71c7e98-a56d-4193-9e58-0b1fd485cfc1.pdf?c=1659648787
[5] 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), 2020.
[6] G. Piccinini, V. Miseikis, P. Novelli, K. Watanabe, T. Taniguchi, M. Polini, C. Coletti, S. Pezzini, Nano Lett. 22, 13, 5252–5259, 2022.

6th EU-Japan Workshop on Graphene and Related 2D Materials (2023)

Title of the Presentation: 1D nanostructures based on transition metal chalcogenides

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:

Transition metal chalcogenides (TMCs) are attractive materials with a wide range of nanostructures and physical properties. In particular, recent advances in growth techniques have enabled the fabrication of various 1D forms of TMCs. In this talk, we report on our recent progress in the fabrication and characterizations of such TMC−based 1D nanostructures including nanotubes, nanoscrolls, nanowires, nanoribbons, and 1D interfaces (Figure 1). For example, the edges of layered transition metal dichalcogenides (TMDCs) can be used to grow TMDC nanoribbons with controlled edge structure by chemical vapor deposition (CVD) [1]. This process also creates in−plane heterostructures with 1D interfaces that exhibit various functions such as chiral or wavelength−tunable electroluminescence [2,3], directional exciton−energy transport [4], and band−to−band tunneling [5]. Isolated boron nitride (BN) nanotubes have enabled the templated synthesis of single−wall TMDC nanotubes [6]. In addition to TMDCs, we have recently achieved the wafer−scale growth of bundles of atomically−thin W_6Te_6 wires by salt−assisted CVD [7]. The W_6Te_6 bundles can be tailored into thin, nanoribbon−like structure, forming a 2D carrier gas [8]. Such ribbon−shaped bundles have been further used for the template synthesis of layered nanoribbons of WS_2, WSe_2 and WTe_2 [9] and for the synthesis of metal−intercalated ternary TMC [10]. These TMC−based 1D nanostructures would provide opportunities for exploring low−dimensional physics and novel device applications.

References

[1] Y. Kobayashi, et al., ACS Nano, 13 (2019) 7527.
[2] N. Wada, et al., Adv. Func. Mater., 32 (2022) 2203602.
[3] J. Pu, et al., Adv. Mater. 34 (2022) 2203250.
[4] M. Shimasaki, et al., ACS Nano, 16 (2022) 8205.
[5] H. Ogura, et al., ACS Nano 17 (2023) 6545.
[6] S. Furusawa, et al., ACS Nano, 16 (2022) 16636.
[7] H.E. Lim, et al., Nano Lett., 21 (2021) 243.
[8] H. Shimizu, et al., ACS Appl. Nano Mater. 5 (2022) 6277.
[9] H.E. Lim, et al., ACS Appl. Nano Mater., 5 (2022) 1775.
[10] R. Natsui et al., ACS Nano 17 (2023) 5561.

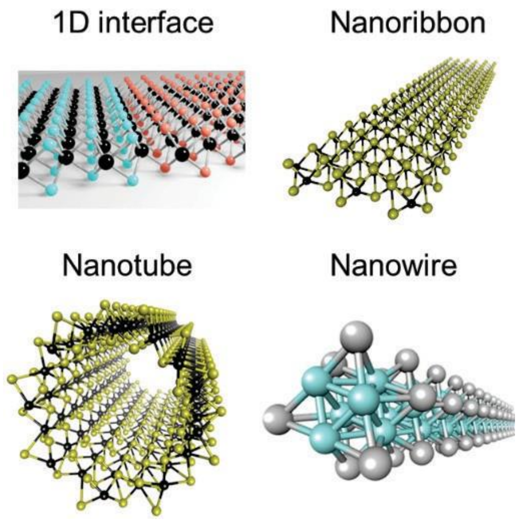

Figure 1: Structure models of TMC−based 1D nanostructures.

6th Japan-EU Workshop on Graphene and Related 2D Materials (2023)

Title of the Presentation: Ferroelectric domain structures in twistronic TMD bilayers

First Name: Vladimir

Last Name: Falko

Affiliation: University of Manchester

Short Biography:

Vladimir Falko MAE is condensed matter theorist responsible for several advances in the theory of electronic and optical properties of atomically thin two−dimensional crystals and their heterostructures (graphene, transition metal dichalcogenides, post−transition metal chalcogenides), and he worked on various general aspects of quantum transport and fundamentals of nanoelectronics. His current interest is focused on 2D materials twistronics. He is Professor of Condensed Matter Theory at the University of Manchester and Director of the National Graphene Institute, and he leads WP Enabling Science in Graphene Flagship.

Abstract:

We discuss lattice structure and physical properties of twisted bilayers of transition−metal dichalcogenide. We show that for ‘marginally’ (small−angle) lattice reconstruction results in the neworks of domains with the energertically preferential stacking and domain walls, which are similar to dislocations in bulk crystals. In some cases, such domains feature weak interfacialferroelectric polarisation, switchable by the mututal sliding of the two monolayers. This gives rise tothe tunability of domain structure by an out−of−plane electric field, manifested in the hysteretic field−effect transistor operation and readable optically by the linear Stark shift of the interlayer excitons.

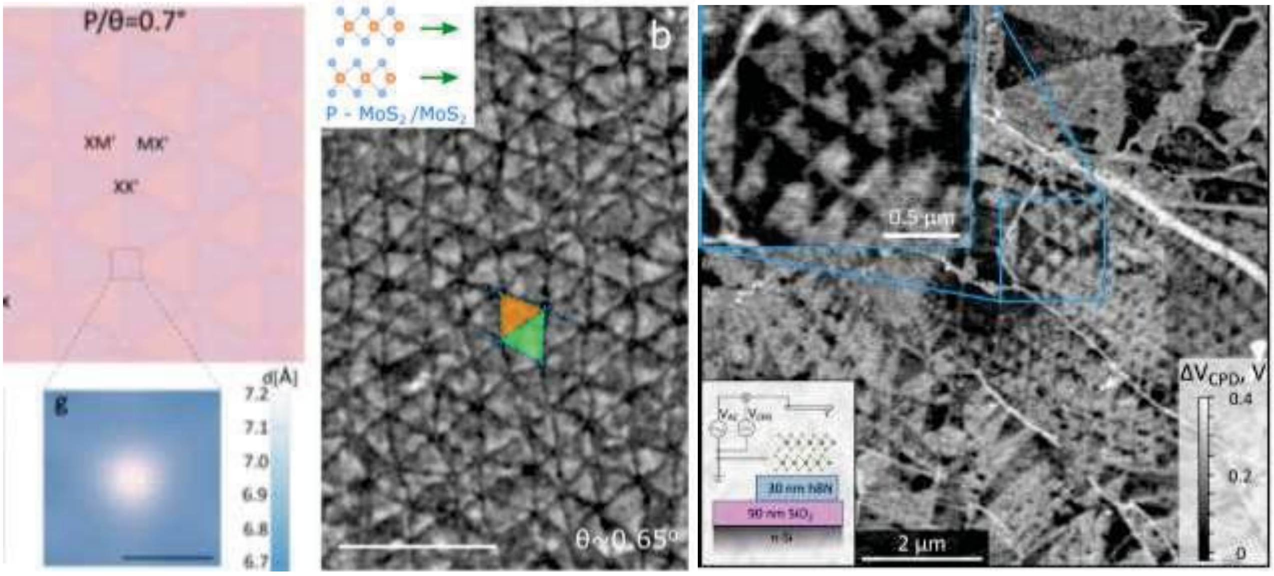

Figure 1: Calculated (left) and measured using STEM (middle) domain structure of reconstructed MoS_2/MoS_2 bilayer with parallel orientation of unit cells (R−type). Right: SKPM map of a large−area twistronic bilayer demonstrating ferroelectric polarization of domains.

6th Japan-EU Workshop on Graphene and Related 2D Materials (2023)

Title of the Presentation: Are 2D materials limited to Van der Waals layered materials?

First Name: Mar

Last Name: Garcia−Hernandez

Affiliation: CSIC, Consejo Superior de Investigaciones Científicas, Spain

Short Biography:
Madrid (1959). Prof. Mar Garcia−Hernandez has a long trajectory in Experimental Condensed Matter Physics and Material Science. Her research in strongly correlated oxides heterostructures with application in spintronics is a central topic in her lab as well as 2D materials. She leads the WP "Enabling Materials" of FG. She has published more than 300 SCI papers and leads the 2D Foundry group at ICMM/CSIC.

Abstract:

During the last decades, there has been enormous advances in the synthesis of 2D Van der Waals (VdW) materials, their heterostructures and twisted homostructures, that have attracted the attention of the scientific community. However, the representation of robust orders like ferroelectricity, ferromagnetism or superconductivity, although extremely interesting from a fundamental viewpoint, is scarce among these materials. Here we propose a strategy to incorporate highly correlated states by combining 2D VdW with non VdW ultrathin complex transition metal oxides (TMOs) in hybrid architectures [1]. We also explore the new physics emerging from twisted layers of TMOs that render new property landscapes only attainable with TMOs as freestanding layers [2].

[1] Sergio Puebla et el. Nano Letters 22, 7457−7466, (2022)
[2] Gabriel Sanchez− Santolino et al arXiv preprint arXiv:2301.04438, (2023)

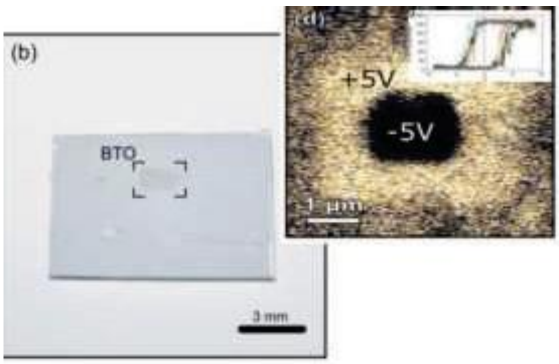

Figure 1: Delaminated $BaTiO_3$ BTO) at the mm scale. Free standing BTO layers keep the ferroelectric functionality at RT

6th EU-Japan Workshop on Graphene and Related 2D Materials (2023)

Title of the Presentation: Momentum− and twist−controlled resonant tunneling device based on few−layer WSe_2

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, he has been working 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:
Few−layer (FL) TMD exhibits subbands in both the conduction band (CB) and valence band (VB) owing to out−of−plane quantum confinement. Resonant tunneling (RT) due to the subbands demonstrated a considerably larger peak−to−valley ratio than that of other 2D material−based RT [1]. Here, we show that by combining the subband RT and controlling the tunnel twist angle ϑ_{tunnel} between the FL WSe_2 layers, momentum− and twist−controlled RT can be achieved in the FL WSe_2/FL h−BN/FL WSe_2 junction. Under electron doping of WSe_2 layers, the momentum of the source FL WSe_2 is fixed at the CB Q valley; then, RT exhibits significant ϑ_{tunnel} dependence owing to the angular dispersion of the CB subbands of drain FL WSe_2. In hole doping, the momentum of the source is fixed at the VB Γ valley, and we observed no ϑ_{tunnel} dependence of RT owing to the isotropic nature of the Γ valley. This demonstrates that momentum− and angle−sensitive RT spectroscopy can be realized by simultaneously selecting the momentum of the source material while controlling ϑ_{tunnel}. Furthermore, we applied this method to twisted bilayer WSe_2 to probe its momentum−dependent band reconstruction under a moiré potential.

[1] Kei Kinoshita, Rai Moriya et al., Nano Lett. **22** (2022) 4640.

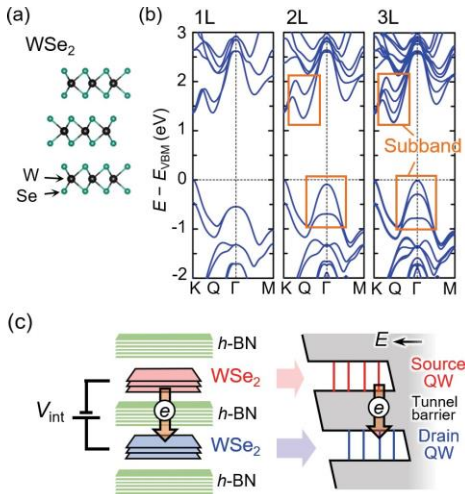

Figure 1. (a) Crystal structure of 3L WSe_2. (b) Band structures of 1 to 3L WSe_2. (c) Schematics of vdW double quantum well device including few−layer (FL) WSe_2/FL *h*−BN/FL WSe_2 tunnel junction.

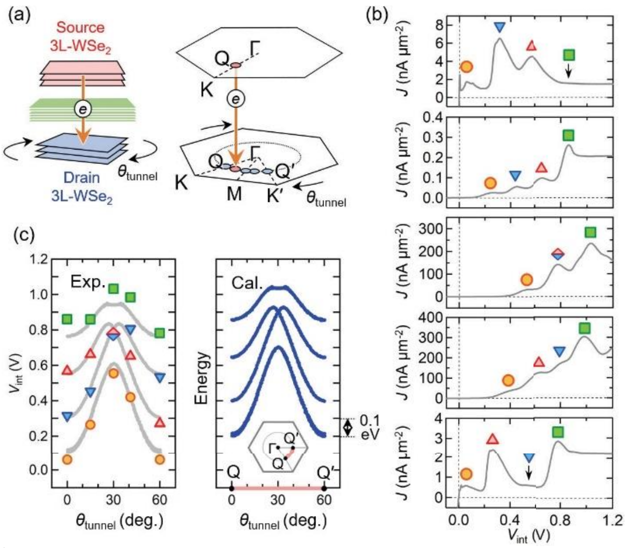

Figure 2. (a) Schematics of tunnel junction and momentum−conserved electron resonant tunneling in *k*−space. (b) I−V_{int} characteristics measured at 2 K. (c) (Left) V_{int} positions of the observed peaks plotted against the twist angle. (Right) Subband energy calculations of Q−Q' angular direction.

6th Japan-EU Workshop on Graphene and Related 2D Materials (2023)

Title of the Presentation: Graphene based photonics for optical communications

First Name: Marco

Last Name: Romagnoli

Affiliation: Consorzio Nazionale Interuniversitario per le Telecomunicazioni (CNIT)

Short Biography:

Head of Advanced Technologies for Photonic Integration and Scientific Responsible at CNIT PNTLab (Photonic Networks and Technologies) in Pisa and former Director in R&D dept. His expertise is in particular in the area of photonic technologies for telecommunications. After a Laurea Degree in Physics at the University of Rome (La Sapienza), in 1983 he started his activity at IBM Research Center in San Jose. In 1984 he joined Fondazione Ugo Bordoni in the Optical Communications Department working on optical components and transmission systems. In 1998 he joined Pirelli. In Pirelli R&D Photonics served as director of Design and Characterization and Chief Scientist. In 2001 he pioneered the activity on Si Photonics and started the development platform for optical components, specifically silica based PLC’s, SiN and Si. In Oct 2010 he joined PhotonIC Corp, a Si−Photonics company, as Director of Boston Operations and visiting scientist at MIT (MassachusettsInstitute of Technology). In this period he contributed to the demonstration of the electrically pumped Germanium laser. Presently he is involved in the field of Photonic Integration and in particular in Graphene Photonics for optical telecom, datacom, sub−THz and quantum communications.

Abstract:
Graphene is an ideal material for optoelectronic applications. Its photonic properties give several advantages and complementarities over Si photonics. For example, graphene enables both electro−absorption, electro−refraction modulation. It can be used for optical add−drop multiplexing with voltage tuning, eliminating the current dissipation used for the thermal detuning of microresonators, for thermoelectric−based ultrafast optical detectors that generate a voltage without transimpedance amplifiers and for direct sub−THz optoelectronic conversion. In this presentation a vision for graphene−based integrated photonics will be provided along with a review of graphene−based transceivers and a comparison with existing technologies.

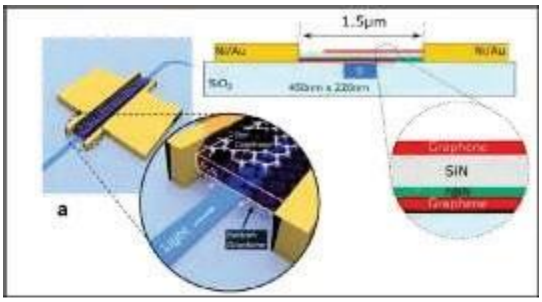

Figure: example of graphene modulator cross section in a silicon photonics platform

6th EU-Japan Workshop on Graphene and Related 2D Materials (2023)

Title of the Presentation: Monolayer in−plane heterostructure light−emitting devices with tunable composition distribution

First Name: Jiang

Last Name: Pu

Affiliation: Dept. of Physics, Tokyo Institute of Technology, Tokyo, Japan

Short Biography:
Dr. Jiang Pu is an associate professor in Department of Physics at Tokyo Institute of Technology, Japan. He received his B.E and M.E degrees in Applied Physics from Waseda University, Japan. He completed his Ph.D. in the Leading Graduate Program in Science and Engineering at Waseda University in 2017. During his Ph.D., he also was selected as the Research Fellowship for Young Scientists from Japan Society of Science. After receiving his Ph.D., he was assigned as an assistant professor in Department of Applied Physics at Nagoya University, from Apr. 2017 to Mar. 2023.

Abstract:

Atomically thin transition metal dichalcogenides (TMDCs) are an attractive material for functional optoelectronic applications because of their diverse bandgaps, robust exitonic emission/absorption, and unique quantum (spin−valley) properties [1]. In particular, the in−plane heterostructures based on TMDC monolayers provide opportunities to directly modulate band structures and lattice strains by the spatial distribution of constituent elements, leading to further control of light−emitting capability. However, it is still challenging to create light−emitting devices and to explore the electroluminescence (EL) properties using the in−plane heterostructures. Here, we demonstrate the EL influenced by tunable composition distribution in monolayer in−plane heterostructures through by adopting the electrolyte−based light−emitting device structures (Fig. 1: Top) [2].

In this talk, we focus on two types of monolayer in−plane heterostructure light−emitting devices. One is the realization of light−emitting devices with atomically sharp heterojunction interfaces that is grown by the chemical vapor deposition (CVD). We directly observed interfacial EL in various TMDC heterojunctions (Fig. 1: Middle), in which their EL was significantly affected by the interfacial strains. As a result of strain effects, we can generate room−temperature chiral EL at steep heterojunction interfaces [3]. The other is the demonstration of light−emitting devices using the composition graded monolayer TMDC alloys synthesized by the CVD (Fig. 1: Bottom). The spatial composition gradient directly reflects the light−emitting energy varied from 2.1 eV to 1.7 eV. In this device, we utilized the spatial control of the recombination zone in the electrolyte−based light−emitting devices [4]. As a consequence, we can achieve wide−range continuous and reversible color−tunable light−emitting devices (Fig. 1) [5]. Our results provide a new approach for exploring quantum light sources and developing the broadband optical applications based on monolayer semiconductors.

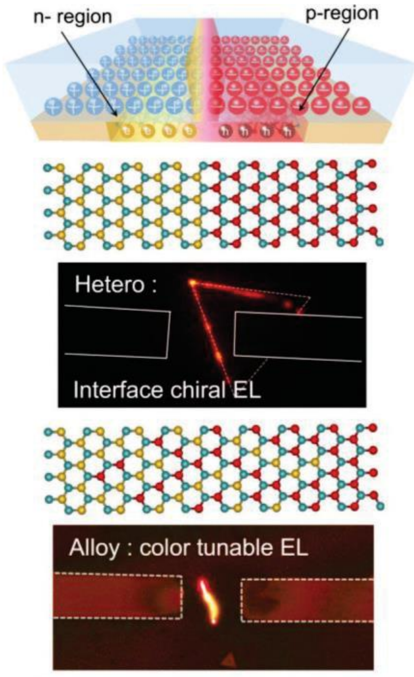

Fig. 1 In-plane hetero-device

[1] J. Pu, T. Takenobu Adv. Mater., **30** (2018) 1707627.
[2] J. Pu et al., Adv. Mater., **33** (2021) 2100601.
[3] N. Wada, J. Pu et al., Adv. Funct. Mater., **32** (2022) 2203602.
[4] H. Ou, J. Pu, et al., ACS Nano, **15** (2021) 12911.
[5] J. Pu et al., Adv. Mater., **34** (2022) 2203250.

6th EU-Japan Workshop on Graphene and Related 2D Materials (2023)

Title of the Presentation: Giant nonreciprocal magneto−transport in Weyl−semimetal WTe_2 induced by diverging Berry curvature

First Name: Yuki

Last Name: Shiomi

Affiliation: Department of Basic Science, University of Tokyo

Short Biography:
Oct. 2018− Present: Associate Prof., University of Tokyo
Apr. 2012−Oct. 2017: Assistant Prof., Tohoku University
Apr. 2007−Mar. 2012 PhD. student, University of Tokyo

Abstract:

The concept of Berry curvature has led to many breakthroughs in condensed matter physics and is essential for various transport phenomena. The Berry curvature strongly modifies the electron motion and manifests as anomalous and quantum Hall effects in the linear response regime.Recently, the Berry curvature is found to also drive the nonlinear transport responses as exemplified by a nonlinear Hall effect under time−reversal symmetry induced by the Berry curvaturedipole. However, an effect of the Berry curvature on the nonreciprocal magneto−transport effect, another class of the nonlinear transport phenomena allowed only when both time−reversal and spatial−inversion symmetries are broken, is still elusive. Here, we report the Berry curvature induces a large nonreciprocal magneto−transport response in Weyl−semimetal WTe_2 [1]. We experimentally demonstrate that the nonreciprocal magneto−transport signals are enhanced when the Fermi level is located near the Weyl points. Notably, the maximal figure of merit reaches 1.2×10^{-6} $m^2T^{-1}A^{-1}$, which is approximately 20 times larger than the previously reported largest value in bulk materials. Our semiclassical calculation shows that the diverging Berry curvature at the Weyl points strongly enhances the nonreciprocal responses. Our results reveal that the Berry curvature plays a crucial role in nonreciprocal magneto−transport.

[1] Tomoyuki Yokouchi, Yuya Ikeda, Takahiro Morimoto, and Yuki Shiomi, Phys. Rev. Lett. 130 (2023) 136301.

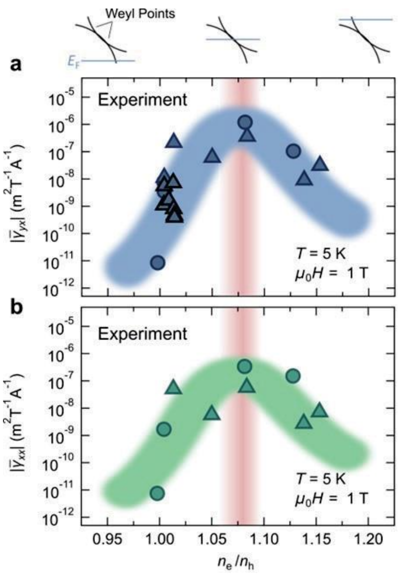

Figure 1: Magnitude of nonreciprocal magneto−transport as a function of the ratio between electron carrier density (n_e) and hole carrier density (n_h)

Title of the Presentation: 2D materials to modulate brain networks and synapses

First Name: Laura

Last Name: Ballerini

Affiliation: International School for Advanced Studies – SISSA Trieste, Italy

Short Biography:

Laura Ballerini research focuses on the interactions between neurons and nanomaterials or bioactive–nanodevices. Her scientific strategy is the convergence between biophysics, nanotechnology and neurophysiology, potentially leading to a new generation of nanomedicine applications in neurology. After a post doc at UCL, London UK, she became associate and then full professor of Physiology at the International School for Advanced Studies–SISSA, Trieste, Italy.

Abstract:
By virtue of nano–scaled dimensional domains combined with peculiar chemical–physical properties graphene–based nanomaterials (GBNs) are increasingly engineered in advanced drug–delivery platforms or in interfacing devices to treat central nervous system (CNS) diseases. GBNs developed to interface neuronal functions might propel new biomedical devices, enabling CNS modulation. This new class of materials can improve exploring fundamental biological phenomena as well as contribute to clinical applications. I will present our results concerning GBNs interfacing neurons, I will describe the ability of such materials to regulate neuronal functions by modulating synaptic activity in vitro and in vivo.

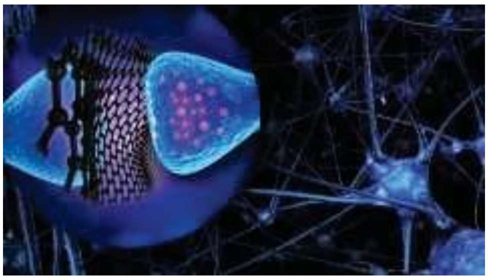

Figure: Sketched small graphene oxide flakes interfacing neuronal synapses in neural circuits.

6th EU-Japan Workshop on Graphene and Related 2D Materials (2023)

Title of the Presentation: Fabrication of high quality Janus TMD by in−situ monitoring plasma functionalization

First Name: Toshiaki

Last Name: Kato

Affiliation: Advanced Institute for Materials Research (AIMR), Tohoku University

Short Biography:

Dr. Toshiaki Kato has completed his Ph.D from Tohoku University, Japan, in 2007. He was a visiting researcher at Stanford University from 2008 to 2009. He joined the faculty of the Tohoku University in 2007 and he is currently an associate professor of Electrical Engineering. His research interests have ranged from structural−controlled synthesis to optoelectrical device application of layered nano materials such as carbon nanotubes, graphene, graphene nanoribbon, and transition metal dichalcogenides.

Abstract:

In−situ monitoring is known to be a very useful method to identify the detailed mechanism of crystal growth and functionalization. Up to now, we realized in−situ monitoring CVD synthesis of WS_2 for the first time [1]. Time evolution of optical image combined with auto image analysis can reveal two step nucleation of WS_2 known as a kind of non−classical nucleation [2]. The defect formation mechanism such as sulfur and tungsten vacancy can be also revealed with this method.

We have also established in−situ monitoring system of Janus TMD formation, which is known as novel structure of TMD including asymmetric chalcogen atoms in vertical direction. Our in−situ monitoring functionalization system enables to measure Raman and photoluminescence spectra during the Janus formation with mild H_2 plasma reaction. Q−mass spectroscopy has been also introduced to monitor the gas phase species. Detailed systematic measurements reveals that PL peak of monolayer WSe_2 strongly suppressed soon after starting H_2 plasma irradiation. Then, peak position was up shifted and intensity gradually increases with plasma irradiation time. The final peak position is around 1.8 eV, which corresponds to that of Janus WSeS. Clear SH_x mass peaks are also identified by Q−mass spectroscopy during the plasma process, denoting these can be the dominant precursors causing the atomic substitution of top Se atom to S in WSe_2.

Innovative device applications such as integrated quantum dot array and novel type solar cells have also been demonstrated with 2D materials [3,4]. The averaged visible transparency of TMD−based solar cell reaches nearly 80%, which can be regarded as invisible solar cells [3].

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[2] X. Qiang, Y. Iwamoto, A. Watanabe, T. Kameyama, X. He, T. Kaneko, Y. Shibuta, T. Kato, Scientific Reports, **11** (2021) 22285−1−9.
[3] X. He, Y. Iwamoto, T. Kaneko, T. Kato, Scientific Reports, **12** (2022) 11315−1−8.
[4] T. Kato, *et al*., Communications Materials, **3** (2022) 103−1−7.

6th Japan-EU Workshop on Graphene and Related 2D Materials (2023)

Title of the Presentation: The path toward 2D materials industrialization

First Name: Francesco

Last Name: Bonaccorso

Affiliation: BeDimensional S.p.A., via Lungotorrente Secca 30R, 16163 Genova, Italy

Short Biography:
Francesco Bonaccorso is the Deputy of the workpackage Innovation of the Graphene Flagship, and He was responsible in defining the S&T roadmap for the project. He is the Scientific Director of BeDimensional SpA and visiting Scientist at the Istituto Italiano di Tecnologia. He gained the PhD from the University of Messina. In 2009 he was awarded a Royal Society Newton International Fellowship at Cambridge University, and elected to a Research Fellowship at Hughes Hall, Cambridge,where he also obtained a MA. He is author of 14 patents and more than 190 publications that have been cited more than 36000 times. He was featured as 2016 Emerging Investigator by J. Mater. Chem. A and in 2019 by ChemPlusChem. In 2018 he was recognized as Highly cited Scientist by Clarivate Analytics. In 2019 he received the Magister Peloritanus by Accademia Peloritana dei Pericolanti and ExAllievi Eccellenti by the University of Messina. He co−founded Cambridge Graphene Ltd and BeDimensional SpA.

Abstract:
In this presentation we will provide an overview of the strategy of BeDimensional in the development of industrial−scale, reliable, inexpensive production processes of graphene and related two−dimensional materials (GRMs).[1−3] This is a key requirement for their widespread use in several application areas,[1−8] providing a balance between ease of fabrication and final product quality. In this context, we will show the effectiveness of the production of GRMs by wet−jet milling[3] and the route towards future Industrial scale up, maintaining the high−quality production ruled by the ISO standard.
Afterward, we will provide a brief overview on some key applications of the as−produced GRMs, with particular focus on the energy sector. In this context, the production of GRMs in liquid phase by wet−jet milling[3] represents a simple and cost−effective pathway towards the development of GRMs−based energy devices, presenting huge integration flexibility compared to other production methods. We will provide an insight into some application areas such as anticorrosion coatings and energy conversion and storage devices.[4−10]

[1] F. Bonaccorso, et. al., Adv. Mater., **28**, (2016) 6136.
[2] F. Bonaccorso, et al., Materials Today, **15**, (2012) 564.
[3] A. E. Del Rio Castillo et. al., Mater. Horiz., **5**, (2018) 890.
[4] E. Pomerantseva, et al., Science **366** (2019) eaan8285.
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[9] S. Bellani, et al., Chem. Soc. Rev., **50**, (2021) 11870.
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6th EU-Japan Workshop on Graphene and Related 2D Materials (2023)

Title of the Presentation: Electrically controlled homo bilayer moiré semiconductor probed by exciton spectroscopy

First Name: Yuya

Last Name: Shimazaki

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

Short Biography:
Yuya Shimazaki received his PhD from University of Tokyo (2016), where he studied electronic transport properties of graphene. He worked as a postdoctoral researcher at ETH Zurich, Switzerland in Quantum Photonics Group, where he studied electronic and excitonic properties of transition metal dichalcogenide heterostructure by optical spectroscopy. Currently he works as a Research Scientist at RIKEN CEMS, Japan. His research interest is exploration and engineering of condensed matter physics in van der Waals (vdW) heterostructures.

Abstract:

The discovery of correlated electronic states and superconductivity in magic angle twisted bilayer graphene triggered enormous attention to moiré lattice systems realized in vdW heterostructures. Semiconductor transition metal dichalcogenides such as $MoSe_2$ are alternative appealing materials to form moiré lattice due to its heavy effective mass and strong excitonic resonances which allows optical access. In this talk, I will present a series of optical spectroscopic studies of an electrically controlled homo bilayer moiré lattice system formed by $MoSe_2$ with a monolayer hBN tunnel barrier in between (Fig. 1). By precisely gate controlling the electron density, electrons are trapped in the moiré lattice system. The existence of moiré subbands is confirmed by monitoring the shift of exciton resonances of $MoSe_2$ which is proportional to the electron density. At the filling of one electron per moiré site, the trapped electrons showed collective inter−layer transfer behaviour as the modulation of energy detuning between layers, which manifests the existence of correlated electronic states [1]. The existence of spatial periodic order of trapped electrons is confirmed from additional resonance in the optical reflection spectrum at energies corresponding to the Umklapp scattering of excitons [2]. Last but not least, the hBN layer between $MoSe_2$ functions as a tunnel barrier on the hole side, where the close band alignment of $MoSe_2$ and hBN results in coherent tunnelling on the meV order. This tunnel coupling facilitates the realization of hybrid state of intra− and interlayer excitons under the application of an electric field [1], as well as a tunnel−coupled moiré lattice system and exciton−hole Feshbach resonances [3].

[1] Y. Shimazaki et al., Nature, **580** (2020) 472.
[2] Y. Shimazaki et al., Phys. Rev. X, **11** (2021) 021027.
[3] I. Schwartz, Y. Shimazaki et al., Science, **374** (2021) 336.

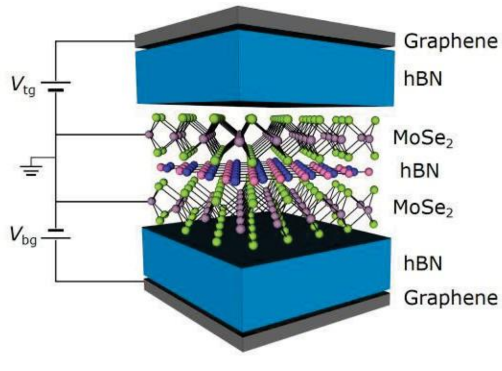


Figure 1: Schematic sketch of $MoSe_2$/hBN/$MoSe_2$ van der Waals heterostructure.

6th Japan-EU Workshop on Graphene and Related 2D Materials (2023)

Title of the Presentation: Enabling 2D−materials process−transfer from lab−to−fab.

First Name: Inge

Last Name: Asselberghs

Affiliation: imec, Leuven, BELGIUM

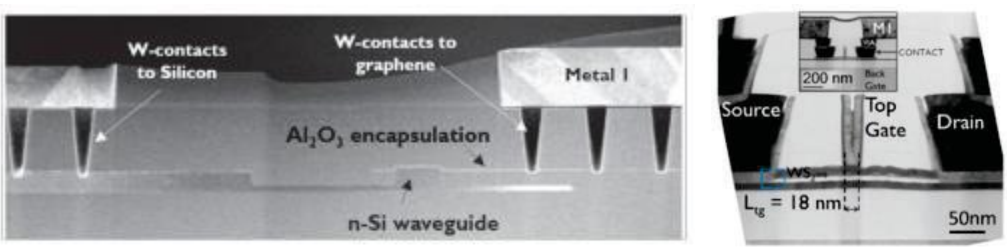
Short Biography:

Inge Asselberghs is Program Manager Process and Module Innovation at imec. She received the M.Sc. and Ph.D. degrees in chemistry from the University of Leuven, Leuven, Belgium. After a Post−Doctoral Fellowship in nonlinear optics, she joined imec in 2011, specializing in 2D−materials processing, device fabrication, and characterization. Her research interest covers new materials, process set−up, and integration pathfinding from the laboratory scale to fab infrastructure. She holds the position of division leader of the 2D−experimental pilot line, an EU funded initiative working on the enablement of 2D−materials−based device fabrication in an industry−relevant environment.

Abstract:
Over a decade, success stories with 2D−materials are moving from “intriguing science” to “unique applications” in various applications fields like sensors, photonics, spintronics and electronics [1] to name a few. While each of these applications, require a different set of challenges to be addressed, many commonalities are found in enabling the process transfer from lab−to−fab. While the performance gap between natural crystals and synthetic layers has almost vanished, like reported by Liu et al. [2] showing the mobility improvement up to 120 cm2/Vs for bilayer MoS2, other integration aspects like automated layer transfer [3] and interface control are key for outstanding device performance and wafer−uniformity [4−5−6]. Here, pathfinding activities will be highlighted in enabling process transfer from lab to fab.

[1] Lemme et al., Nat Commun (2022). https://doi.org/10.1038/s41467−022−29001−4
[2] Liu et al, Nature (2022). https://doi.org/10.1038/s41586−022−04523−5
[3] Brems et al. (2023) VLSI TSA, T8−5.
[4] Wu et al. (2021) doi: 10.23919/VLSICircuits52068.2021.9492495
[5] Asselberghs et al. (2020) IEEE International Electron Devices Meeting (IEDM), doi: 10.1109/IEDM13553.2020.9371926
[6] Smets et al. (2021) IEEE International Electron Devices Meeting (IEDM), doi: 10.1109/IEDM19574.2021.9720517.

Figure 1: TEM view of a wafer−scale integrated graphene photonics device (left) and TMDC based transistor (right) taken from [4] and [5], respectively.



6th EU-Japan Workshop on Graphene and Related 2D Materials

Title of the Presentation: Bilayer graphene intercalation: A study of interlayer coupling and theatomic structure of intercalants

First Name: Yung−Chang

Last Name: Lin

Affiliation: National Institute of Advanced Industrial Science andTechnology (AIST)

Short Biography:

2019.10 Senior Researcher in AIST, Japan
2015−2019 Researcher in AIST, Japan
2012−2015 Postdoctoral Research, AIST, Japan
2012 Ph.D. Electrical Engineering, National Tsing Hua University, Taiwan
2007 M.S. Electrical Engineering, National Tsing Hua University, Taiwan
2005 B.S. Physics, National Central University, Taiwan

Abstract:

The interlayer coupling of bilayer graphene is known to be strongly dependent the twist angle between the two graphene layers. The stacking of hexagonal lattice of graphene layers will result in unique moire pattern in real space according to the twist angle, and which results inangle−dependent energy band hybridization of the bilayer graphene (BLG). Stacking BLG with specific twist angle is recently found to generate flat band at Fermi level and result in superconductivity when the twist angle is around 1.1 degree [1]. In this presentation, we will firstly discuss the interlayer coupling phenomenon of BLG. The interband transition between the vanHove singularities (vHSs) depending on and the relation with the twist angle is characterized by using electron energy loss spectroscopy (EELS) [2]. The interlayer spacing of BLG is expected to be expanded with an intercalant. We demonstrate that BLG is completely decoupled when a single layer of metal chloride is intercalated in the van der Waals gap of BLG, leading to charge transfer between the intercalant and BLG. Here, the BLG serves as robust ultrathin supporting layer and enables the study of visualization of the atomic structure of the intercalants. In the nanospace between BLG, the metal chlorides were found to have change to form unique structure which is never seen in 3D space [3]. The polymorphic phases and phase transitions of intercalated metal chlorides will also be discussed in this presentation.

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[2] Y.C. Lin et al., Nano Lett., 21 (2021) 10386−10391.
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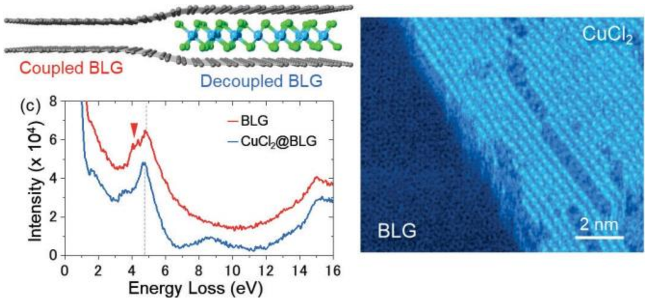

Figure 1: Coupled BLG and decoupled BLG with $CuCl_2$ intercalation.

6th EU-Japan Workshop on Graphene and Related 2D Materials

Title of the Presentation: Geometries and Electronic Properties of heterostructures of 2D Materials

First Name: Susumu

Last Name: Okada

Affiliation: University of Tsukuba

Short Biography:
Department of Physics, University of Tsukuba from (2001−)
Institute of Material Science, University of Tsukuba (1998−2001)

Abstract:

Two−dimensional (2D) nanomaterials exhibit versatile physical properties depending on the constituent elements and their covalent network topologies. In addition to the intrinsic properties arising from their geometries, formation of hybrid structures with other nanoscale and bulk materials causes further variation in the electronic properties of resultant hybrids. In this talk, we report novel 2D carbon networks that exhibit unusual electronic structure caused by the delicate balance of electron transfer between and within the constituent nanostructures [1,2,3]. We also report the electronic structure and electrostatic properties of 2D nanostructures under the external electric field where we demonstrated that the electronic properties are sensitive not only on the geometries but also on the external electric field [4,5]. Finally, we report the electronic structures of heterostructures consisting of various 2D materials [6,7,8,9].

These works are in collaboration with H. Zhang, H. Nakajima, N. Ichinose, M. Maruyama, Y. Gao, T. Mizoguchi, K. Nagashio, R. Kitaura, and Y. Hatsugai, and are supported by the JSPS Grant−in−Aid for Scientific Research on Innovative Areas 'Science of 2.5 D Materials' [KAKENHI grant numbers JP21H05232, JP21H05233].

[1] M. Maruyama, N. T. Cuong, and S. Okada, Carbon 109 (2016) 755.
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[3] T. Mizoguchi, Y. Gao, M. Maruyama, Y. Hatsugai, and S Okada, Phys. Rev. B 107 (2023) L121301.
[4] M. Maruyama, K. Nagashio, and S. Okada, Phys. Rev. Appl. 14 (2020) 044028.
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[8] M. Maruyama and S. Okada, J. Appl. Phys. 131 (2022) 134303.
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