# Graphene Flagship Japan-EU Workshop 2019
# *Graphene and related 2D materials*

Scuola Normale Superiore, Pisa (Italy), 18-20 November 2019

## Workshop Report

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## Overview

The 4th EU-Japan Workshop on Graphene and Related Materials was held during 18-20 November 2019 at Palazzo della Carovana in Pisa, Italy. 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 three workshops, the first workshop was held in Tokyo (Japan) in 2015, the second in Barcelona (Spain) in 2017 and the third in Sendai (Japan) in 2018.

The workshop started with the presentation of the JST-CREST, Japanese funding program, and of the Graphene Flagship, with the introduction of Core3 project and its shift toward higher TRL for electronics technologies. The latest products now available on the market were mentioned, such as a photodetector produced by Emberion for gas detection and spectroscopy, and the 3D Xpoint™ Technology for memory storage.

The materials discussed during the workshop were broad, including graphene, graphene nanoribbons, carbon nanotubes, chalcogenides, phosphoren, etc. The focus was directed on the study of their properties, high-quality production and characterization up to atomic scale to fulfil the modern needs for more power, more memory, energy efficiency, fast data- and tele- communication, artificial intelligence and personalized healthcare. Characterization techniques such as Low-Voltage Atomic-Scale TEM and EELS were discussed. Studies about edge and intersubband plasmons and other quasiparticles (phonons, excitons), spin relaxation, spin-to-charge conversion, cyclotron resonance, interfacial phase-change memory and exciton devices were presented. Inkjet techniques were shown for the design of heterostructure-based electronics and the design of graphene biosensors for selective detection of influenza virus. Interlayer excitons in transition metal dichalcogenides were discussed because of their great interest in the realization of next-generation photonic and valleytronic devices.

The workshop was co-organized by the European Graphene Flagship project and the Japanese Agency for Science and Technology (JST-CREST), and was co-chaired by:

- Dr. Camilla Coletti (IIT - Italy)
- Prof. Taiichi Otsuji (Tohoku University - Japan)
- Prof. Christoph Stampfer (RWTH - Germany)
- Prof. Tomoki Machida (Tokyo University - Japan).

The workshop gathered 34 speakers (18 form Japan and 16 from Europe), main of which coming from academic institutions. For details about the scientific content of the presentations, see the *Speakers and Abstracts* section.

This report summarises the main conclusion and discussion and the envisaged ways for collaboration.

## Common challenges and opportunities for collaborations

At this workshop, the 4th EU-Japan workshop, 34 speakers, presented several topics in 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, JST and JSPS (Japan Society for the Promotion of Science) are 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.

In the final discussion session, there was clear interest to continue the series of workshops by organising the next one in Japan (potentially in Okinawa or Kyoto) in 2020. This workshop will be chaired from Japanese side by Prof. Koshino Mikito. Participants discussed also about potential topics for the next workshop and suggested to focus more on unsolved issues to increase further the collaborations between Europeans and Japanese and unravel common challenges. Increased attendance of exponents from industry was also proposed and the idea was welcomed by all participants. The presence of students during the past workshop was appreciated and suggested for coming years.

The format for the 5th workshop was debated, expressing a special interest for panel sessions with longer technical discussions leaded by two chairs (one Japanese and one EU) for each session to solve common challenges and increase collaborations between Japanese and EU researchers.

## Programme

| **November 18, 2019** | | |
|---|---|---|
| **08:30** | **Registration and welcome** | |
| 09:00 – 09:10 | *Camilla Coletti/*<br>*Taiichi Otsuji* | General Chair |
| 09:10 – 09:20 | *Atsushi Kurobe* | JST CREST |
| 09:20 – 09:30 | *Jari Kinaret* | Graphene Flagship |
| **Session 1: PHYSICS 1**<br>*Chair: Takao Sasagawa* | | |
| 09:30 – 09:55 | *Riichiro Saito* | Edge plasmon of two-dimensional materials |
| 09:55 – 10:20 | *Jose H. Garcia Aguilar* | Spin-Valley Coupling Induce Room-temperature Spin-to-Charge Conversion in Graphene/Transition Metal Dichalcogenide heterostructures |
| 10:20 – 10:45 | *Mikito Koshino* | Physics of twisted 2D materials |
| **10:45 – 11:00** | ***Coffee break*** | |
| 11:00 – 11:25 | *Kazuhiro Yanagi* | Intersubband plasmons in tubular nano-carbon structures |
| 11:25 – 11:50 | *Marco Polini* | Collective excitations in twisted bilayer graphene close to the magic angle |
| 11:50 – 12:15 | *Tomoki Machida* | Cyclotron resonance absorption of mid-infrared light in van der Waals heterostructures of graphene and 2D materials |
| **12:15 – 14:00** | **Lunch** | |
| **Session 2: DEVICES 1**<br>*Chair: Camilla Coletti* | | |
| 14:00 – 14:25 | *Yasumitsu Miyata* | Growth and device applications of transition-metal-dicharcogenide in-plane heterostructures |
| 14:25 – 14:50 | *Taishi Takenobu* | Circularly polarized electroluminescence induced by strain effect |
| 14:50 – 15:15 | *Peter Bøggild* | Patterning graphene: clearing the path for graphene nanoelectronics |
| 15:15 – 15:40 | *Gianluca Fiori* | Perspectives of 2DMs based electronics |
| 15:40 – 16:05 | *Junji Tominaga* | Interfacial phase change memory: Physics and application |
| **16:45 – 18:15** | ***Guided visit of Piazza del Duomo*** | |
| **19:30 – 21:00** | **Dinner (*Osteria i Santi* Restaurant)** | |

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|---|---|---|
| ***November 19, 2019*** | | |
| **Session 3: MATERIALS 1**<br>*Chair: Toshiaki Kato* | | |
| 09:00 – 09:25 | *Ute Kaiser* | Understanding the Dynamics of Advanced Low-Dimensional Materials by Low-Voltage Atomic-Scale TEM and EELS experiments |
| 09:25 – 09:50 | *Masaki Nakano* | Superconductivity and magnetism in MBE-grown TMDC ultrathin films and heterostructures |
| 09:50 – 10:15 | *Alberto Ciarrocchi* | Excitonic valleytronic devices in 2D heterostructures |
| **10:15 – 10:45** | ***Coffee break*** | |
| 10:45 – 11:10 | *Iwao Matsuda* | Evolutions of the Dirac fermions in monatomic layers |
| 11:10 – 11:35 | *Annick Loiseau* | Momentum-resolved EELS in a TEM of free-standing black phosphorus down to the monolayer |
| 11:35 – 12:05 | *Daisuke Kiriya* | Electronic structure modification of TMDC materials by spontaneously patterned molecular dopant film |
| **12:05 – 13:30** | **Lunch** | |
| **Session 4: DEVICES 2**<br>*Chair: Christoph Stampfer* | | |
| 13:30 – 13:55 | *Taiichi Otsuji* | Graphene-based van der Waals heterostructures towards a new type of terahertz quantum-cascade lasers |
| 13:55 – 14:20 | *Cedric Huyghebaerth* | First steps of 2D material integration in 300mm silicon production line |
| 14:20 – 14:45 | *Hideyuki Maki* | Nanocarbon-based optoelectronic devices on silicon chips |
| 14:45 – 15:10 | *Max Lemme* | Graphene and 2D Optoelectronics |
| 15:10 – 15:35 | *Hitoshi Wakabayashi* | TMDC FETs using sputtering and sulfurization processes |
| **15:35 – 16:00** | ***Coffee break*** | |
| **Session 5: PHYSICS 2**<br>*Chair: Mikito Koshino* | | |
| 16:00 – 16:25 | *Francesco Mauri* | Momentum-resolved EELS with an electron microscope: phonon and quasi-particle dispersion in 2D membranes |
| 16:25 – 16:50 | *Takao Sasagawa* | Exploration of topological electronic materials having exotic quasi-particles |
| 16:50 – 17:15 | *Giulio Cerullo* | Ultrafast charge transfer in heterostructures of 2D materials |
| 17:15 – 17:40 | *Kazunari Matsuda* | Optical probing and control of excitonic states in atomically thin two-dimensional materials |
| 17:40 – 18:05 | *Christoph Stampfer* | Spin-valley coupling in bilayer graphene quantum devices |
| **19:30 – 21:00** | **Dinner (*La Pergoletta* Restaurant)** | |

| ***November 20, 2019*** | | |
|---|---|---|
| **Session 6: MATERIALS 2**<br>*Chair: Peter Bøggild* | | |
| 08:30 – 08:55 | *Kazuhiko Matsumoto* | Biomedical applications of graphene |
| 08:55 – 09:20 | *Cinzia Casiraghi* | Water-based and biocompatible inkjet printable 2D-inks: from all-printed devices to biological applications |
| 09:20 – 09:45 | *Toshiaki Kato* | CVD growth of 1 million graphene on the device |
| **09:45 – 10:15** | ***Coffee break*** | |
| 10: 15 –10:40 | *Jack Alexander-Webber* | Scalable device integration and passivation techniques for 2D materials |
| 10:40 – 11:05 | *Camilla Coletti* | Going beyond copper: wafer-scale synthesis of graphene on sapphire |
| 11:05 – 12:00 | **Discussion and conclusions** | |
| **12:00 – 13:30** | **Lunch** | |
| **13:30 – 15:00** | **Final remarks** | |

## Participants list

| Title | Last name | First name | Institution | Country |
|---|---|---|---|---|
| Dr. | Alexander-Weber | Jack | University of Cambridge | United Kingdom |
| Prof. | Bøggild | Peter | DTU – Technical University of Denmark | Denmark |
| Prof. | Casiraghi | Cinzia | The University of Manchester | United Kingdom |
| Prof. | Cerullo | Giulio Nicola | Politecnico Milano | Italy |
| Dr. | Ciarrocchi | Alberto | EPFL – Ecole polytechnique fédérale de Lausanne | Switzerland |
| Dr. | Coletti | Camilla | IIT – Istituto Italiano di Tecnologia | Italy |
| Emer. Prof. | Enoki | Toshiaki | Tokyo Institue of Technology | Japan |
| Prof. | Fiori | Gianluca | UNIPI – Universita di Pisa | Italy |
| Prof. | Garcia | José Hugo | ICN2 – Institut Català de Nanociència i Nanotecnologia | Spain |
| Dr. | Huyghebaert | Cedric | IMEC | Belgium |
| Prof. | Kaiser | Ute | Ulm Universität | Germany |
| Assoc. Prof. | Kato | Toshiaki | Tohoku University | Japan |
| Senior Rschr. | Katsumata | Yasuhiro | JST Strategic Rsch. Promotion Div. | Japan |
| Prof. | Kinaret | Jari | Chalmers University of Technology (Director, Graphene Flagship) | Sweden |
| Dr. | Kiriya | Daisuke | Osaka Prefecture University | Japan |
| Prof. | Koshino | Mikito | Osaka University | Japan |
| Rsch. Superv. | Kurobe | Atsushi | JST CREST | Japan |
| Prof. | Lemme | Max | RWTH Aachen University / AMO GmbH | Germany |
| Dr. | Loiseau | Annick | ONERA | France |
| Prof. | Machida | Tomoki | Univ. Tokyo | Japan |
| Assoc. Prof. | Maki | Hideyuki | Keio University | Japan |
| Prof. | Matsuda | Kazunari | Kyoto University | Japan |
| Prof. | Matsuda | Iwao | The University of Tokyo | Japan |
| Prof. | Matsumoto | Kazuhiko | Osaka University | Japan |
| Prof. | Mauri | Francesco | University of Rome 'La Sapienza' | Italy |
| Assoc. Prof. | Miyata | Yasumitsu | Tokyo Metropolitan University | Japan |
| Prof. | Nakano | Masaki | The University of Tokyo | Japan |
| Prof. | Otsuji | Taiichi | Tohoku University | Japan |
| Dr. | Polini | Marco | IIT – Istituto Italiano di Tecnologia | Italy |
| Prof. | Saito | Riichiro | Tohoku University | Japan |

| | | | | |
|---|---|---|---|---|
| Prof. | Sasagawa | Takao | Tokyo Institute of Technology | Japan |
| Prof. | Stampfer | Christoph | RWTH – Rheinisch-Westfälische Technische Hochschule Aachen | Germany |
| Prof. | Takenobu | Taishi | Nagoya University | Japan |
| Dr. | Tominaga | Junji | AIST – National Institute of Advanced Industrial Science and Technology | Japan |
| Dr. | Vacchi | Isabella | ESF – European Science Foundation | France |
| Prof. | Wakabayashi | Hitoshi | Tokyo Institute of Technology | Japan |
| Prof. | Yanagi | Kazuhiro | Tokyo Metropolitan University | Japan |

## Speakers and abstracts

**Atsushi Kurobe**
**Toshiba Corporation, Japan**

**Short biography:**
He has been working mainly in the area of semiconductor devices R&D and is now the Chief Fellow of Toshiba. He is also acting as the Research Supervisor of JST/CREST project on 2D Materials in Japan.

**Jari Kinaret**
**Physics, Chalmers U Technology, Sweden**

**Short biography:**
Jari Kinaret is the initiator of the Graphene Flagship and serves since October 2013 as its Director. He received his M. Sc degrees in Theoretical Physics and in Electrical Engineering at the University of Oulu in Finland in 1986 and 1987, respectively. Kinaret graduated with a Ph.D. in Physics from the Massachusetts Institute of Technology in 1992, whereupon he spent two years in Copenhagen as a post-doctoral researcher and as an Assistant Professor. In 1995 he moved to Gothenburg where he works as Professor of Physics at the Chalmers University of Technology. His research interests lie in theoretical studies of nanoscale carbon structures, with focus on nanoelectromechanical devices and graphene plasmonics. He is a member of the Royal Swedish Academy of Engineering Sciences and the board of directors of Tampere University (Finland).

# Edge Plasmon of Two-Dimensional Materials

**Riichiro Saito**
**Department of Physics, Tohoku University, Japan**

**Short biography:**

Riichiro Saito was born in 1958 and received his Ph. D. at The University of Tokyo in 1985. He became Research Associate at The University of Tokyo (1985), Associate Professor at The University of Electro-Communications (1990), and Professor at Department of Physics, Tohoku University (2003). He has been a visiting scientist at Massachusetts Institute of Technology (1991-2) at Prof. Gene Dresselhaus and Prof. Mildred S. Dresselhaus, Visiting Associate Professor at The University of Tokyo (1990-1, 1993-4, 1997-8), Visiting Professor at Shanghai University (2009.10-2011.10), Toho University (2015.4-2016.3) and Zhejiang University (2018.10-2021.9).

**Abstract:**

In this talk, we first overview our activity of surface plasmon of two-dimensional materials. In the two-dimensional semi-metal or doped- semiconductors, electrons can be collectively excited on the surface of the materials by applying external electromagnetic wave. The collective excitation is called by surface plasmon. We have investigated surface plasmon of graphene, silicone, carbon nanotubes which give a strong optical absorption compared with that by single-particle excitation. The surface plasmon generates spatially localized electric field near the surface whose electric field is enhanced significantly compared with the electric field of the incident light, which is used for surface- or tip-enhanced Raman spectroscopy. The surface plasmon is practically important for signal transmission of electron-magnetic wave on the two-dimensional surface, too.  When we consider edge of two-dimensional materials such as graphene nanoribbon, so-called edge plasmon is excited by the external electromagnetic field at the edge. The edge plasmon generates a circular rotation of electric field on the surface because of the phase difference of electric field in the parallel and perpendicular direction to the edge. The rotation of electric field can generate the scattered light with circularly-polarized light for incident linearly-polarized light. We will show the phenomena of edge plasmon by both analytically expression of the formula and numerical simulation by FDTD (finite difference time domain) method.

RS acknowledge JSPS Kakenhi (Grant No. JP18H01810).

# Spin-Valley Coupling Induce Room-temperature Spin-to-Charge Conversion in Graphene/Transition Metal Dichalcogenide heterostructures

**Jose H. Garcia Aguilar**
**Catalan Institute of Nanoscience and Nanotechnology, ICN2, Spain**

## Short biography:

José H. Garcia is a postdoctoral researcher at Prof. Roche's group at the Catalan Institute of Nanoscience and Nanotechnology (ICN2). He holds a Ph.D. in Physics from the Federal University of Rio de Janeiro and is an expert on numerical quantum transport. He pioneered an efficient method for computing Hall conductivities and applied it to study the topological properties of different graphene-based systems. His approach had been implemented in different open-source quantum transport packaged such as KWANT and Quantum KITE, and he is one of the principal authors of a recently accepted Review of Modern Physics on Quantum Transport methodologies. More recently, his research is focused on the spintronic properties of graphene/transition metal dichalcogenides heterostructures (TMDs). He was the first in predicting a measurable spin Hall angle in different graphene/TMDs heterostructures and has assisted subsequent experimental measurements of the spin Hall effect in these systems. He is now focused on understanding the effect of atomic-scale defects on the spin-orbit interaction of graphene/TMDs heterostructure, and its consequence on the spin Hall angle and spin-orbit torque.

## Abstract:

Jose H. Garcia [1],Armando Pezó [1,2], Marc Vila[1,3], Aron W. Cummings2, Stephan Roche[1,4]
[1]*Catalan Institute of Nanoscience and Nanotechnology (ICN2), CSIC, Spain.* [2] *Universidade Federal do ABC (UFABC), São Paulo, Spain.* [3] *Universidad Autonoma de Barcelona (UAB), Barcelona Spain.* [4] *Institució Catalana de Recerca i Estudis Avançats (ICREA), Barcelona Spain.*

Spintronics, a field which aims at using the electron's spin for ultra-fast low-power electronic devices, has been limited by low spin relaxation times and by the absence of a reliable spin-current source. A large spin-to-charge conversion is necessary for creating spintronic devices operating at low currents, and it is, therefore, essential for power efficiency and for departing from charge-based logic and memories. Recently, we used numerical methods for predicting a large charge-to-spin conversion in graphene/transition metal dichalcogenide heterostructures (TMDs) due to a combination of spin Hall effect and Rashba-Edelstein effect [1,2]. These effects were recently measured at room-temperature, demonstrating a mean for generating gate-dependent field-like and antidamping-like torques, placing graphene as an exciting candidate for spin-orbit torque memories (SOT-RAM) [3-5].

In this work, we developed a theory for explaining both the spin Hall effect and the Rashba-Edelstein effect in Graphene/TMDs heterostructure. We compare this theory with fully quantum mechanic calculations of the spin Hall conductivity and the non-equilibrium spin density, computed through the Kubo Formula in a system consisting of millions of orbitals. We show that the presence of spin-valley coupling can fully explain the predictions obtained previously and establish the experimental conditions for optimal spin-to-charge conversion. We will also discuss on how to tune these properties throught impurities and other atomic-scale defects.

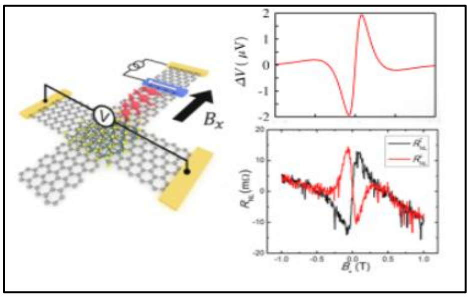


*Figure (Left)Experimental setup for measuring the Spin Hall effect. (Right) The predicted (Top) and measured (Bottom) signal.*

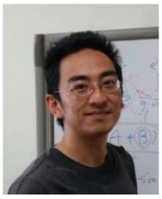
### References:

[1] José H. Garcia, et. al.,Chem. Soc. Rev., 47, 3359-3379, (2018).
[2] José H. Garcia, et. al.,Nano Lett., 17, 5078–5083, (2017).
[3] Talieh S. Ghiasi, et. al., Nano Letters Article ASAP DOI: 10.1021/acs.nanolett.9b01611 (2019).
[4] C.K. Safeer,..,José H. Garcia, et. al., Nano Lett., 19, 1074–1082, (2019).
[5] L.A. Benitez arXiv:1908.07868, (2019).

# Physics of twisted 2D materials

**Mikito Koshino**
**Osaka University, Japan**

## Short biography:



Mikito Koshino received his Ph.D. degree from University of Tokyo, Japan in 2003. He was a research associate in Tokyo Institute of Technology from 2003 to 2010, and he was an associate professor in Tohoku University from 2010 to 2016. Since 2016, he has taught in Osaka University, where he is a professor in Department of physics. His current research is focused on the theoretical study on the physical properties of two-dimensional materials and also covers the topological materials.

## Abstract:

When 2D materials having different periodicities are overlaid with each other, the interference pattern of the lattice mismatch often leads to unusual electronic properties. Here we introduce our recent works on such incommensurate van der Waals bilayer systems showing interesting physics. First, we will discuss twisted bilayer graphene, which exhibits dramatic angle-dependent phenomena such as the flat band formation and emergent superconductivity. We introduce a theoretical framework to reduce the complex systems with huge number of atoms into a simple effective lattice model by constructing the localized Wannier orbitals.[1] Then we argue about the 30-degree rotated twisted bilayer graphene, where we describe its 12-fold quasicrystalline nature with nearly flat bands in terms of the quasi-band picture.[2] Lastly, we discuss the lattice relaxation and the acoustic phonons in the twisted bilayer graphene using the continuum approach. [3] We show that the original linear dispersion of graphene's acoustic phonon is broken down into mini phonon bands separated by gaps, where, the low-energy phonon modes are regarded as collective vibrations of the domain wall network of AB/BA-stacking regions.

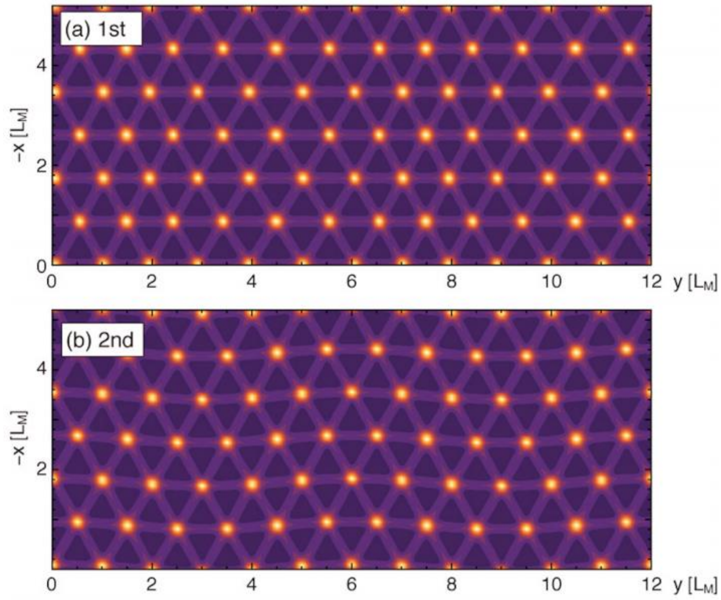


*Figure: Low-energy phonon wave functions in TBG of = 1.05 deg. [3]*

References:

[1] M. Koshino, N. F. Q. Yuan, T. Koretsune, M. Ochi, K. Kuroki, L. Fu, Phys. Rev. X 8, 031087 (2018).
[2] P. Moon, M. Koshino and Y.-W. Son, Phys. Rev. B 99, 165430 (2019).
[3] M. Koshino and Y.-W. Son, arXiv:1905.09660 (2019), to be published in PRB.

# Intersubband plasmons in tubular nano-carbon structures

**Kazuhiro Yanagi**
**Department of Physics, Tokyo Metropolitan University, Tokyo, Japan**

## Short biography:

Kazuhiro Yanagi received the Bachelor degree in 1999, and the Master degree in 2001 in Physics from Kyoto Univ., and then received the Ph. D in Physics from Osaka City Univ., Japan in 2004. After working in AIST (2005~2009), he has been working at Physics department, Tokyo Metropolitan university. He is full professor of physics in Tokyo Metropolitan University.

## Abstract:

Intersuband plasmons are well-known optical phenomena in 2D electron systems such as semiconductor quantum wells, and are important basic optical phenomena widely used in quantum cascade lasers and sensors.[1] Recently, the intersuband optical phenomena are attracting a lot of interest also in 2D layered materials.[2] Here we discuss the intersubband plasmon phenomena in quasi 1D system, which is recently observed in carbon nanotubes,[3] in comparison with the 2D systems. Intersubband plasmon phenomena are optical processes sensitive to the quantum confined directions and the amount of carriers, and thus we correctly clarified the presence of these phenomena using aligned carbon nanotube thin films with tuned Fermi-level.[3] In the carbon nanotubes, because of the quantum confinement within 1 nm space region, the energy gaps between intersubbands are widely opened, and as a result, the peak position of the intersubband plasmon absorption in nanotube is larger than those of typical quantum wells by three orders of magnitude. In conventional interband transitions in carbon nanotubes, the optical transitions are caused by the light with polarization parallel to the nanotubes axis. However, reflecting the intersubband nature, the intersubband plasmon optical absorption can response to the light with polarization perpendicular to the nanotube axis. Our observation of gate-controlled quantum plasmons in aligned carbon nanotubes will pave the way for the development of carbon-based near-infrared optoelectronic devices.

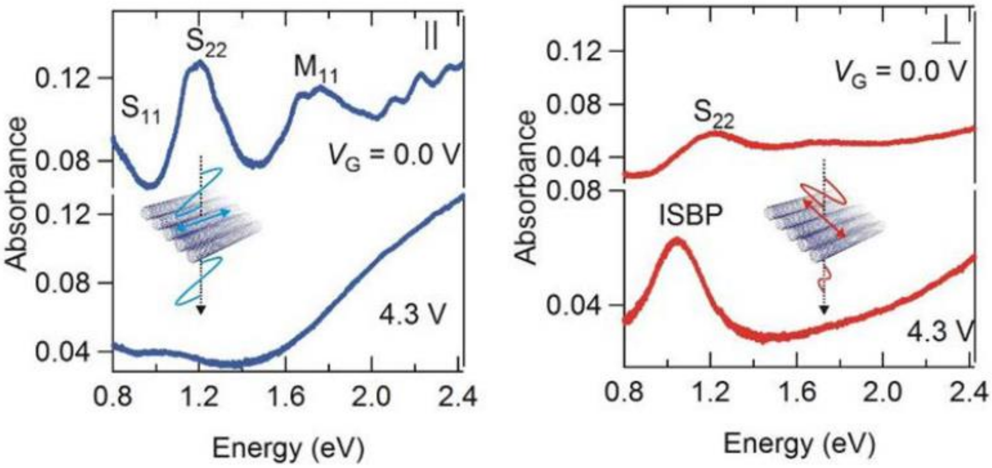


*Figure: Conventional interband optical absorption (Left) and intersubband plasmon (ISBP) optical absorption (Right) in gated and aligned carbon nanotubes.*

References:

[1] Helm, M. In Physics and Device Applications I. Semiconductors and Semimetals, 62 (2000) 1–99.
[2] Schmidt et al., Nature Nanotech. 13 (2018) 1035.
[3] Yanagi et al., Nature Comm. 9 (2018)1121.

# Collective excitations in twisted bilayer graphene close to the magic angle

**Marco Polini**
**Istituto Italiano di Tecnologia, Graphene Labs, Genova, Italy**

## Short biography:

Dr. Marco Polini graduated in Theoretical Physics in 1999 from the University of Pisa (Italy) and received his Ph.D. in Physics in January 2003 from the Scuola Normale Superiore (Pisa, Italy). He has been a postdoctoral fellow in the group of Prof. Allan MacDonald at the University of Texas at Austin (USA) and a permanent staff member of the Nanoscience Institute of the Italian National Research Council (2008-2015) in Pisa (Italy). From September 1, 2015 he holds a Senior Scientist position at the Istituto Italiano di Tecnologia (Italian Institute of Technology) in Genoa (Italy), where he leads the “Theory and technology of 2D materials” group. He also holds a contract professorship at the Scuola Normale Superiore in Pisa (Italy) and a part-time professorship at the Physics Department of the University of Manchester (UK). He has co-authored 180 publications in peer-reviewed international journals and he is a coauthor of the book “Many-body Physics in Condensed Matter Systems” (Edizioni della Normale, Pisa, 2006). According to Google Scholar, he has an h-index of 51 and his publications have been cited 13.770 times. He has carried out research at the University of Texas at Austin (USA), at the Zhejiang Normal University (China), at the Chinese Academy of Sciences in Beijing (China), at Purdue University (USA), at the University of Missouri-Columbia (USA), at Texas A&M University (USA), at the Kavli Institute for Theoretical Physics in Santa Barbara (USA), at the University of New South Wales (Australia), at the Cambridge Graphene Center (UK), at the NUS Centre for Advanced 2D Materials and Graphene Research Centre in Singapore, at the Massachusetts Institute of Technology (USA), at the Institute of Photonic Sciences –ICFO (Spain), and at the University of Manchester (UK). He is involved in WP8.

## Abstract:

The electronic properties of twisted bilayer graphene (TBG), a system composed of two nearby graphene layers rotated relative to each other by a small angle, are dramatically different from those of a single layer. TBG has recently attracted a great deal of interest, sparked by the discovery of correlated insulating and superconducting states that appear at low temperatures when the twist angle $\theta$ is close to a so-called “magic angle” $\sim 1.1°$. Several experimental probes have been used to explore the physics of TBG, including electronic transport, quantum capacitance, and scanning tunneling spectroscopy. However, probes that access the response to finite in-plane momentum $q$ and frequency $\omega$ are expected to be rich sources of information in systems where electron-electron interactions play a dominant role. One of these probes is scattering near-field optical microscopy (SNOM), which enables the measurement of the dispersion relation of collective electronic excitations, such as Dirac plasmons in graphene. In this talk, I will discuss how SNOM can unveil a different type of collective modes in charge-neutral TBG near the magic angle. In particular, a gapped collective mode with linear dispersion, akin to the bulk magnetoplasmon of a two-dimensional electron gas in a perpendicular magnetic field. This mode can be described in terms of an interband plasmon associated with the quasi-localized states originating from the moiré superlattice. In particular, it stems from an enhanced resonant profile of the dynamical conductivity attributed to stronger-than-expected nesting of the bands. This points to a more important role of the gauge field than the scalar potential contribution to the electronic band structure, equivalent to weaker interlayer coupling in the AA regions. These intriguing optical properties offer new insights, complementary to other techniques, on the carrier dynamics in this correlated electron system.

Work supported by the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 785219 “Graphene Core2”.

# Cyclotron resonance absorption of mid-infrared light in van der Waals heterostructures of graphene and 2D materials

**Tomoki Machida**
**Institute of Industrial Science, University of Tokyo, Japan**

## Short biography:

2017-present Professor, Institute of Industrial Science, University of Tokyo
2004-2017 Associate Professor, Institute of Industrial Science, University of Tokyo
2002-2004 PRESTO Researcher, Japan Science and Technology Agency
1998-2002 PD Researcher, CREST/SORST, Japan Science and Technology Agency

## Abstract:

Tomoki Machida[1,2], Kei Kinoshita[1], Yusai Wakafuji[1], Momoko Onodera[1], Miho Arai[1], Satoru Masubuchi[1], Rai Moriya[1], Kenji Watanabe[3], and Takashi Taniguchi[3]

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Charge carriers in graphene, massless Dirac fermions, form a unique sequence of the Landau levels in high magnetic fields. Thus, the cyclotron resonance (CR) in graphene is distinctly different form that in conventional two-dimensional electron systems based on semiconductors. In this work, we study mid-infrared/THz photoresponse due to CR in graphene/h-BN van der Waals heterostructures, fabricated using the mechanical exfoliation and transfer technique of atomic layers. Magnetotransport measurements were carried out at low temperature and high magnetic fields. We demonstrate photoresponce signals induced by three different mechanisms: bolometric effect, photovoltaic effect, and photo-thermoelectric effect. We discuss CR in monolayer, bilayer, and trilayer graphene. In addition, we present our recent development of an autonomous robotic system for building van der Waals superlattices.

References:

[1] K. Kinoshita, R. Moriya, M. Arai, S. Masubuchi, K. Watanabe, T. Taniguchi, and T. Machida, Appl. Phys. Lett. 113, 103102 (2018).
[2] S. Masubuchi, M. Onuki, M. Arai, T. Yamaguchi, K. Watanabe, T. Taniguchi, and T. Machida, Phys. Rev. B 88, 121402 (2013).
[3] S. Masubuchi, M. Morimoto, S. Morikawa, M. Onodera, Y. Asakawa, K. Watanabe, T. Taniguchi, and T. Machida, Nature Communications 9, 1413 (2018).
[4] Y. Asakawa, S. Masubuchi, N. Inoue, S. Morikawa, K. Watanabe, T. Taniguchi, and T. Machida, Phys. Rev. Lett. 119, 186802 (2017).
[5] Y. Sata, R. Moriya, N. Yabuki, S. Masubuchi, and T. Machida, Phys. Rev. B 98, 035422 (2018).
[6] Y. Hoshi, M. Okada, R. Moriya, S. Masubuchi, K. Watanabe, T. Taniguchi, R. Kitaura, and T. Machida, Phys. Rev. Materials 2, 064003 (2018).

# Growth and device applications of transition-metal-dichalcogenide in-plane heterostructures

**Yasumitsu Miyata**
**Department of Physics, Tokyo Metropolitan University, 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. During 2013–2016, he had been a JST-PRESTO researcher in the field of "Innovative Nano-electronics through Interdisciplinary Collaboration among Material, Device and System Layers".

## Abstract:

The in-plane heterostructures based on two-dimensional materials provide a novel one-dimensional (1D) interface with unique physical properties and applications. Even though many studies on such heterostructures have been reported, there are still important challenges such as the development of a growth process of high quality heterostructures and the demonstration of functional devices. For this purpose, we have conducted the studies on chemical vapor deposition (CVD) growth and characterization of transition metal dichalcogenides (TMDCs) [1-6]. In this presentation, we report on our recent progresses of growth of TMDC-based heterostructures and their applications to light emitting diodes (LEDs). In particular, the use of organic liquid precursors enables the formation of in-plane heterostructures/superlattice, and nanometer-width quantum wires. We also fabricated electric double layer light-emitting diodes (EDLEDs) of the heterostructure [7] and observed linear electroluminescence (EL) from the 1D interface (Fig.1). Furthermore, the interface EL shows circular polarization for WS2 exciton peak even at room temperature. The present results highlight the potential of TMDC-based 1D heterointerfaces to use their unique electrical and optical properties.

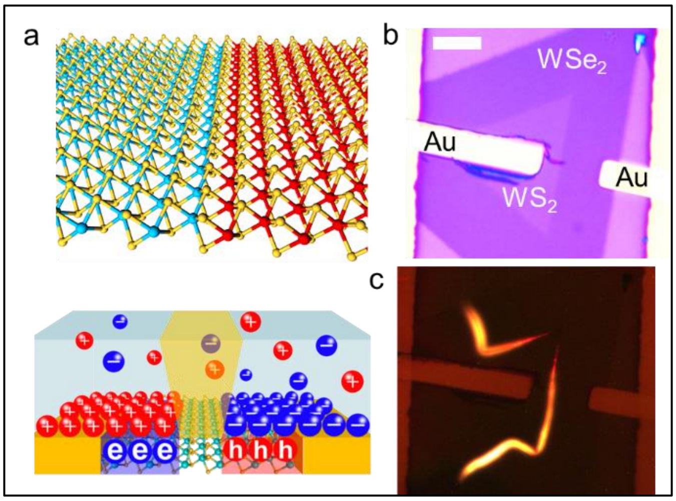


*Figure: (a) Schematic illustration of the TMDC-based in-plane heterostructure and LED. (b) Optical and (c) EL images of WS2/WSe2 LED device.*

References:

[1] Y. Kobayashi et al., ACS Nano 9 (2015) 4056.
[2] Y. Kobayashi et al., Nano Res. 8 (2015) 3261.
[3] S. Sasaki, et al., Appl. Phys. Express, 9 (2016) 071201.
[4] Y. Kobayashi et al., Sci. Rep. 6 (2016) 31223.
[5] K. Kojima et al., Nanoscale 11 (2019) 12798.
[6] Y. Kobayashi et al., ACS Nano 13 (2019) 7527.
[7] J. Pu et al., Adv. Mater. 30 (2018) 1707627.

# Circularly polarized electroluminescence induced by strain effect

**Taishi Takenobu**
**Department of Applied Physics, Nagoya University, Japan**

## Short biography:

Taishi Takenobu received his Ph.D. (materials science) from Japan Advanced Institute of Science and Technology (JAIST) in 2001. Since April 2001, he has worked in SONY corporation. From December 2001, he was assistant and associate professor of Tohoku University. From 2010, he was associate professor and professor of Waseda University, and, from March 2016, he is currently a professor of Nagoya University. His current research interests include (1) realization of electrical driven organic laser devise, (2) flexible, stretchable and printable electronics based on organic and nano materials, and (3) solid state physics and functional devices of TMDC monolayer.

## Abstract:

One of the most interesting properties of Transition metal dichalcogenide (TMDC) monolayers is spin-valley coupling, due to a non-centrosymmetric two-dimensional crystal, strong spin-orbit interaction, and non-zero Berry curvature [1]. Actually, circularly polarized light emission has been demonstrated [2,3], although the demonstrated temperature is very low (typically less than 100 K). Here, we use the electrochemical method to form p-n junction [4-7] and apply the strain effect into various forms of TMDCs, such as single crystalline flakes and lateral heterojunctions because the strain effect in TMDC materials are very interesting and it might realize the circularly polarized electroluminescence at room temperature [8-10]. Finally, we introduced the strain effect into TMDC materials and successfully obtained the circularly polarized electroluminescence at room temperature. Our approach paves a versatile way for using TMDCs in discovering new functional optoelectronic devices.

References:

[1] D. Xiao, et al., PRL 108, 196802 (2012).
[2] K. F. Mak et al., Nat. Nanotechnol. 7, 494 (2012).
[3] Y. J. Zhang, et al. Science 344, 725 (2014).
[4] J. Pu and T. Takenobu, Adv. Mater. 30, 1707627 (2018).,
[5] D. Kozawa, T. Takenobu, et al., APL 109, 201107 (2016).,
[6] J. Pu, T. Takenobu, et al. Adv. Mater. 29, 1606918 (2017).,
[7] M.-Y. Li, J. Pu, T. Takenobu, Adv. Funct. Mater. 28, 1706860 (2018).
[8] J. Lee et al., Nat. Mater. 16, 887 (2017).
[9] Q. Zhang et al., Phys. Rev. B 88, 245447 (2013).
[10] H. Rostami et al., Phys. Rev. B 92, 195402 (2015).

# Patterning graphene: clearing the path for graphene nanoelectronics

**Peter Bøggild**
**Technical University of Denmark, Denmark**

## Short biography:

Peter Bøggild obtained his PhD in low temperature mesoscopic physics at the Copenhagen University in 1998, became associate professor at Technical University of Denmark in 2002 and full professor in 2013. Peter Bøggild worked in many different areas, mainly nanomechatronics, quantum transport, nanometrology, surface engineering, material synthesis and microfabrication, but is today leading a group that focus entirely on graphene and other 2D materials - from fundamental to applied research, covering synthesis, transfer, manufacturing, metrology, electronics and fundamental transport properties. Peter Bøggild is involved in DNRF centre of excellence, CNG – Center for nanostructured graphene, in the European Graphene Flagship and the Danish Innovation Foundation project TRIM, and recently led the Innovation Foundation project DAGATE on commercialising graphene technology.

## Abstract:

After the initial excitement about graphene's high performant and scientifically rich electronic properties, one of the most obnoxious roadblocks 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. This has effectively shut down the hope of controlling transport at the quantum level, as well as trivially downscaling graphene electronic components to scales common for mainstream silicon electronics. I will discuss progress we have made in engineering the graphene edges [1,2], and focus on a recent example [3]. We show that by combining encapsulation in hexagonal boron nitride with high-density lithography, and carefully tuning the etching process, we are able 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.

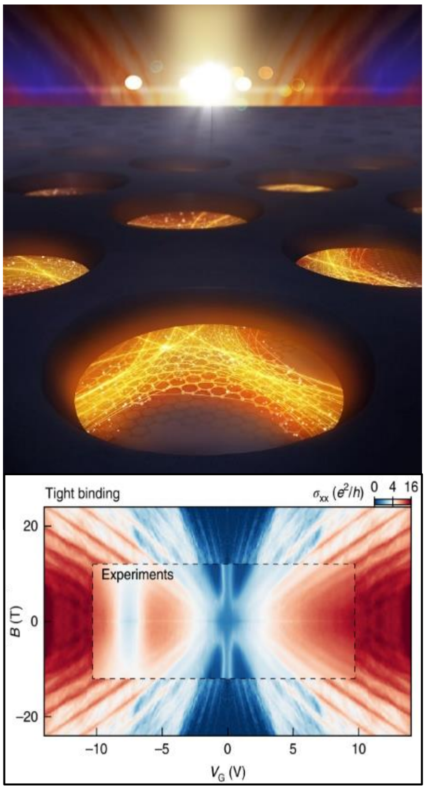


*Figure: By carefully etching holes in graphene through a protective encapsulation layer of hexagonal boron nitride (top), with a spacing of just 12 nanometers, the electronic band structure can be engineered in a deterministic way (bottom).*

References:

[1] J. M. Caridad, G. Calogero, P. Pedrinazzi, J. E. Santos, A. Impellizzeri, T. Gunst, T. J. Booth, R. Sordan, P. Bøggild, M. Brandbyge, A graphene-edge ferroelectric molecular switch, Nano Letters, 18, 8, 4675-4683 (2018)

[2] J. M. Caridad, S. R. Power, M. R. Lotz, A. Shylau, J. D. Thomsen, L. Gammelgaard, T. J. Booth, A-P Jauho, P. Bøggild, Conductance quantization suppression in the quantum Hall regime, Nature Communications, 9:659 (2018)

[3] 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, 2019, 10.1038/s41565-019-0376-3.

# Perspectives of 2DMs based electronics

**Gianluca Fiori**
**Dipartimento Ingegneria Informazione, University of Pisa, Italy**

**Short biography:**

Gianluca Fiori is Full Professor at University of Pisa, from which he obtained the PhD in 2005. Prof. Fiori's main field of activity includes the modelling, and the electrical and noise characterization of CMOS nanoscale devices, as well as the design of innovative devices based on new architectures and new materials. Prof. Fiori has a renowned expertise in performing device performance assessment against Industry requirements, through the exploitation of purposely-devised multi-scale, multi-physics in-house atomistic simulators. The experience gained along the years with respect to modeling, design and characterization of electronic devices (with a particular focus on 2DMs) has made Prof. Fiori the leading recognized expert in the field of two-dimensional based electronic devices [G. Fiori et al., 'Electronics based on two-dimensional materials' Nature Nanotechnology, Vol. 9, p. 768, 2014] [Al. et G. Fiori, 'Quantum Engineering of transistors based on 2D materials heterostructures', Nature Nanotechnology, Vol. 13, p. 183, 2018]. The PI has released, under the BSD open-source license, the in-house developed code NanoTCAD ViDES (http://vides.nanotcad.com, more than 90000 lines of code), which includes most of the physical models implemented during his research activity (as of now, 2100 total downloads and 117 papers published in international journals exploiting results obtained from the code, 35% from groups not related with the PI http://vides.nanotcad.com/vides/contact-us/publications). Recently, within the activity of the ERC-CoG PEP2D, G.F. has started an experimental activity on printed electronics through the exploitation of two-dimensional material based inks, aiming at obtaining fully printed integrated circuits on flexible substrates as paper Prof. Fiori has served as Principal Investigator in several research projects funded either by Italian Institutions as well as from the EU within FP7 and H2020 programs (securing in total approx. 7 MEUR) and he is part of the Graphene Flagship, as leader of the Working Group on 2D material based electronic for logic applications, i.e., a transversal activity within the Flagship involving different Work Packages (i.e., WPs on Electronic Devices, Biomedical Technologies, Flexible Electronics, Photonics and Optoelectronics and Enabling Materials) and aiming at developing a full 2DMs based electronic circuit for the elaboration of the signals extracted from graphene and related materials sensors and devices. Prof. Fiori is member of the editorial board of two journals of Nature's Publishing group, i.e., Scientific Reports and the new journal NPJ – 2D materials and applications.

**Abstract:**

In this talk, I will try to give some perspectives regarding the applications where two-dimensional materials could represent an enabling technology for new applications in the electronic field. I will also address the topic of printable electronics, since 2DMs have recently demonstrated their potential to obtain deposited materials through inkjet technique, with insulating, semiconducting and metallic properties, that are the main ingredients to obtain printed electronic devices. The ability to stack them one on top of the other forming heterostructures, is an adding additional degree of freedom, that could pave the way towards working devices for medium-scale level of integration.

# Interfacial phase change memory: Physics and application

**Junji Tominaga**
**Nanoelectronics Research Institute, National Institute of Advanced Industrial Science & Technology (AIST), Japan**

## Short biography:

Junji Tominaga received his Ph.D in 1991 from Cranfield Institute of Technology (Cranfield University), UK. After seven-years R&D of phase change optical discs (DVD-RW, -RAM, Blu-ray), he moved to AIST in 1997. He was the former director of Center for Advanced Near-field Optics Research (CAN-FOR). Since 2010, he has been a prime senior researcher of Nanoelectronics Research Institute in AIST.

## Abstract:

Phase change memory (PCM) is one of the most successful non-volatile memories (NVM), and Intel & Micron Technology commercialized PCM as “Optane.” PCM switching mechanism relies on the phase transition of a GeSb-Te (GST) alloy, which generates three-orders of magnitude in resistance change between amorphous and crystalline states. Recently, a new type of PCM has been intensively studied to suppress the switching energy by entropy control, and it is called interfacial phase change memory (iPCM), which is composed of multi-layered (superlattice) GST film [1, 2] . In iPCM, one-dimensional Ge atomic motions enable to further reduce the switching energy by 90~95% [3]. The superlattice is composed of Ge2Te2 and Sb2Te3 sub-layers, which are weakly bonded by van der Waals force. As well known, Sb2Te3 is a topological insulator, whereas GeTe is a normal insulator. The latter can take three different phases between the former: Te-Ge-Te-Ge, Ge-Te-Te-Ge, and Te-Ge-Ge-Te, respectively. So far, it has been reported that these are Weyl semimetal, a trivial insulator, and a Dirac semimetal [4]. Although these three elements are all non-magnetic, the Weyl phase (T-Ge-Te-Ge) sandwiched by two Sb2Te3 sub-layers may show magnetic properties since the spatial inversion symmetry is broken, lifting the spin band degenerations [5, 6]. In the presentation, the interesting spin properties coming from p-electrons are presented with the iPCM mechanism.

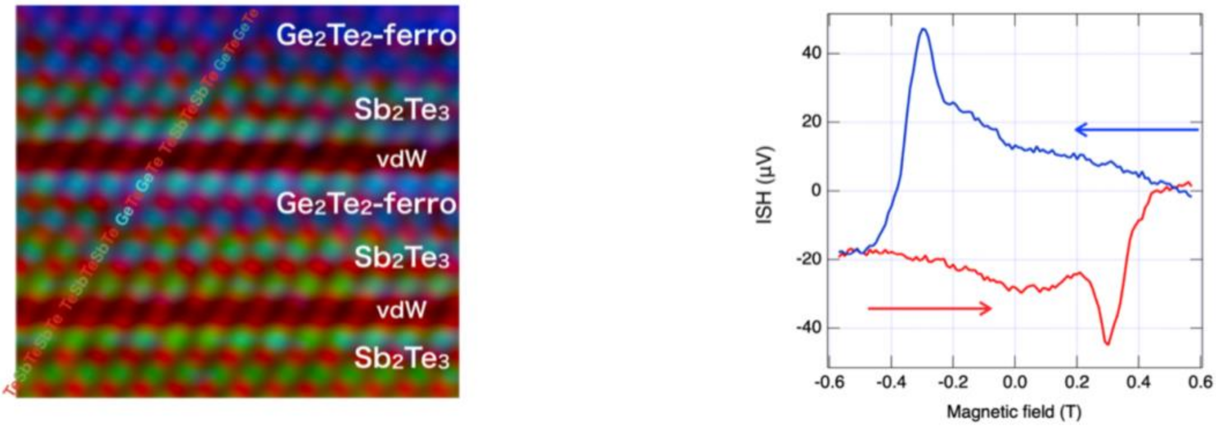


*Figure: High-resolution HAADF-EDX of the atomic arrangement of [$Ge_2Te_2$/$Sb_2Te_3$] (Left); Room temperature ISH signal using a Pt electrode (detector) - Spin current was injected from a TbFeCo electrode (Right).*

References:

[1] J. Tominaga et al., Jpn. J. Appl. Phys. 47 (2008) 5763.
[2] R. Simpson et al., Nature Nanotechnol. 6 (2011) 501.
[3] J. Tominaga et al, Phys. Status Solidi B 249 (2012) 1932.
[4] J. Tominaga, Phys. Status Solidi RRL (2018) 1800539.
[5] S. V. Eremeev et al., Sci. Rep. 6 (2016) 38799.
[6] J. Kim et al., Phys. Rev. B 96 (2017) 235304

# Understanding the Dynamics of Advanced Low-Dimensional Materials by Low-Voltage Atomic-Scale TEM and EELS experiments

**Ute Kaiser**
**Central$^{F}$facility of Materials Science Electron Microscopy, University of Ulm, Germany**

## Short biography:

Ute Kaiser is Professor at Ulm University and Head of the Central Facility of Materials Science Electron Microscopy since 2004. She graduated from Humboldt University Berlin, received her PhD in 1993 and her habilitation on TEM on semiconductor quantum materials in 2002. From 1993-2003 she was postdoc at Jena University, with extended visits at Bell Labs, Cambridge University and in Tohoku University. From 2009-2018 she was the director of the Sub-Angstrom Low-Voltage Electron Microscopy project, where she focuses on developments of low-voltage electron microscopy for application on beam-sensitive low-dimensional materials. This is one of her main research interests since then. She belongs to the highly cited researchers 2018.

## Abstract:

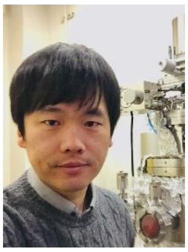
To obtain structural and electronic properties of advanced low-dimensional material at the atomic scale is a growing demand in materials science, as the function of any material is very often determined by the investigation atomic defects. A new type of transmission electron microscopes operating at electron energies between 80keV and 20keV was developed. It allows undercutting most of the materials knockon damage thresholds and enables sub-Angstroem resolution in a 4000x4000 pixels, single-exposure image by correcting not only geometrical but also its chromatic aberration. We modify properties of low-dimensional materials by the use of the electron beam not only for imaging its original structure but also for engineering 2D transition metal dichalcogenide as well as carbon nanotubes with new properties. We generate metal-atom-dimers encapsulated within single-walled carbon nanotubes and observe the dynamics of metallic bonds by exact measurements of the interatomic distance. We intercalate bilayer graphene by lithium and study the lithiation and delithiation between bilayer graphene, as well as the structure of the new high-density crystalline Li-phase.

We acknowledge DFG and the MWK Baden-Württemberg, Germany, in the frame of the SALVE project and the BadenWürttemberg Stiftung in the frame of the CleanTech program and the European Union in the frame of the Graphene Flagship.

# Superconductivity and magnetism in MBE-grown TMDC ultrathin films and heterostructures

**Masaki Nakano**
**Quantum-Phase Electronics Center and Department of Applied Physics, the University of Tokyo, Japan; RIKEN Center for Emergent Matter Science (CEMS), Japan**

## Short biography:



Masaki Nakano received his Ph.D. degree from Tohoku University (Japan) in 2009. After graduation, he worked as a postdoctoral researcher in Prof. A. Morpurgo's group at University of Geneva from 2009 to 2010, and in Prof. Y. Tokura's group at RIKEN from 2010 to 2012. Then, he worked as an assistant professor in Prof. A. Tsukazaki's group at the University of Tokyo from 2012 to 2013, and at Tohoku University from 2013 to 2014. He then worked as a project lecturer in Prof. Y. Iwasa's group at the University of Tokyo from 2014 to 2019. Since 2019, he is a project associate professor at the University of Tokyo and a Unit Leader at RIKEN Center for Emergent Matter Science (CEMS), where he is working as a principal investigator. His research interests include exploration of novel physical properties and functionalities of oxide and layered chalcogenide thin films and heterostructures grown by the state-of-the-art thin film growth technique like PLD or MBE.

## Abstract:

Researches on 2D materials have been mainly done with mechanically-exfoliated nano-thick crystals from 'top-down' approach due to its simplicity and wide applicability, while 'bottom-up' synthesis by MBE has expanded a line-up of materials under investigation even to hardly-cleavable and/or thermodynamically-metastable compounds, providing a promising route to further exploration of novel quantum phenomena emerging at the monolayer limit as well as at the heterostructures. However, those MBE-based researches have been mostly focused on spectroscopic studies using conducting graphene substrates, whereas transport studied have been less performed despite its essential importance presumably due to difficulties in sample fabrication on insulating substrates.

We have recently established a versatile route to layer-by-layer epitaxial growth of a wide variety of 2D materials and their heterostructures on insulating substrates by MBE [1-3], opening a door for exploration of emergent transport phenomena arising at the monolayer limit and at the interface between dissimilar materials even based on hardly-cleavable and/or thermodynamically-metastable compounds. In this presentation, we will introduce our recent achievements including observation of giant superconducting anisotropy in extraordinarily-strained epitaxial 2D material having thermodynamically-metastable phase that could not be achieved by conventional top-down approach, and observation of emergent itinerant 2D ferromagnetism with intrinsic spin polarization in hardly-cleavable compound that are missing in its bulk counterpart. We will also introduce emergent interface transport phenomena based on those MBE-grown quantum 2D materials.

This work was supported by Grants-in-Aid for Scientific Research (Grant Nos. 19H05602, 19H02593, and 19H00653) from the Japan Society for the Promotion of Science. M.N. was partly supported by The Murata Science Foundation.

References:

[1] M. Nakano et al., Nano Lett. 17, 5595 (2017).
[2] Y. Wang et al., Appl. Phys. Lett. 113, 073101 (2018).
[3] Y. Kashiwabara et al., Adv. Funct. Mater. 2019, 1900354 (2019).

# Excitonic valleytronic devices in 2D heterostructures

**Alberto Ciarrocchi**
**Electrical Engineering Institute and Institute of Materials Science and Engineering, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland.**

## Short biography:

Alberto Ciarrocchi was born in Pisa in 1991. After studying physics at the University of Pisa, he is now working in the laboratory of Prof. Andras Kis in EPFL, Switzerland. His research activities are mainly concerned with the study of excitons in two-dimensional materials and their heterostructures. Recently, this led to the first demonstration of room-temperature excitonic transistors and to the realization of polarization-switches based on interlayer excitons. Other research topics involve spintronics and magnetism in 2D materials.

## Abstract:

Interlayer excitons in van der Waals heterostructures of transition metal dichalcogenides (TMDCs) are of great interest due to their unique spin-valley and moiré physics. These aspects could be implemented to realize next-generation photonic and valleytronic devices, as well as exploring new physical phenomena. For example, one could imagine encoding information in the exciton valley-state, which could be then optically transmitted using polarized light. Indeed, the fact that excitons can be manipulated electrically but couple naturally to photons offers an advantageous combination with potential for relevant technological applications. Moreover, thanks to the high binding energy of excitons in TMDCs, such excitonic devices can work up at room temperature [1], making them a strong candidate for the realization of practical valleytronic devices. In this talk, I will present our recent work on the manipulation of interlayer excitons in van der Waals heterostructures. By application of electric and magnetic fields, different types of device operation can be realized, achieving control over the transport, confinement, polarization and wavelength of valley-polarized interlayer excitons [2]. The ability to effectively control the motion and properties of interlayer excitons is a significant step forward towards new device concepts which do not rely on electric charges.

References:

[1] Ciarrocchi A., Unuchek D. et al. Nature Photonics, 13, 2, (2019)
[2] Unuchek, D., Ciarrocchi A. et al. Nature, 560, 7718, (2018)

# Evolutions of the Dirac fermions in monatomic layers

**Iwao Matsuda**
**The Institute for Solid State Physics, the University of Tokyo, Japan**

**Short biography:**

Iwao Matsuda received the Ph.D in Science from the University of Tokyo, Japan in 2001. After working at Department of Physics in University of Zuerich, Switzerland, he has been working at in the University of Tokyo as a research associate (2001-2006) and as an associate professor (2006-). He has become a visiting professor in Tohoku University and the boarding member of the Japan Society of Vacuum and Surface Science since 2019.

**Abstract:**

Vapor deposition of three-dimensional (3-D) crystal on a substrate often results in formation of the novel 2-D materials with intriguing electronic states [1]. The approach has been well-known in the field of "Surface Science", which has attracted our attentions over the past decades. Triggered by fabrication of the graphene layers, researches on such monatomic sheets have extended to layers of van der Waals crystals and also to groups of Xene such as silicene, germanene and so on. A monatomic layer itself corresponds to the minimum unit of a matter and changes the functionalities depending on chemical compositions and structures. While a considerable number of monatomic layers has been reported on solid surfaces and in van der Waals crystals, novel layers have still been discovered today. Here, we present our recent works on novel monatomic layers that possess intriguing Dirac Fermions. The researches were made with soft X-ray spectroscopies, such as photoemission spectroscopy, that have been used to directly probe electronic states of monatomic layers and also to examine carrier dynamics under the operando condition.

We observed Dirac Fermions in a 2-D boron sheet, borophene, that forms spontaneously on the Ag (111) surface [2]. Furthermore, we found pairing of the Dirac cones due to Moire-periodic perturbations of the overlayer-substrate interactions [2]. The effect is found to explain the Dirac cone pairs, observed in a 2-D silicon sheet, silicene, on Ag(111)[3]. On the other hand, in the Cu2Si monolayer, we discovered the 2-D Dirac nodal line fermions when it is prepared on the Cu(111) surface[4]. However, the layer becomes a simple 2-D metal on Si(111) [5]. These cases demonstrate evolutions of Dirac Fermions, Dirac cones and Dirac nodal lines, in monatomic layers by substrates. Such a substrate effect, thus, can be regarded as a new degree of freedom to regulate the Dirac bands.

Based on this concept, we have investigated a possible electronic control of a free-standing monatomic layer that has two surfaces and no bulk in between, the extreme case of surface science. We made hydrogenation of a borophene layer that have Dirac nodal lines and synthesized a HB sheet (borophane) from a MgB2 crystal [6]. Figure 2 shows a collection of layers of honeycomb borophene in different chemical environments. The HB sheet becomes semi-metallic with electron and hole pockets at different symmetry points. The electron band originates from the B-H-B bond, while the hole band is kept from one of the Dirac bands in MgB2. The synthesis and 'extreme' surface modification of free-standing boron sheets offer the potential of designing and developing new boron-based devices.

References:

[1] Iwao Matsuda ed., (Elsevier, 2018).
[2] B. Feng, IM et al., Phys. Rev. Lett. 118 (2017) 096401.
[3] B. Feng, IM et al., Phys. Rev. Lett. 122 (2019) 196801.
[4] B. Feng, IM et al., Nature Comm. 8 (2017) 1007.
[5] M. Cameau, IM et al., Phys. Rev. Materials 3 (2019) 044004.
[6] I. Tateishi, IM et al, Phys. Rev. Materials 3 (2019) 024004.

# Momentum-resolved EELS in a TEM of free-standing black phosphorus down to the monolayer

**Annick Loiseau**
**Lab. d'Etude des Microstructures, CNRS-ONERA, LEM, France**

## Short biography:

I am a Physicist with a large expertise in Condensed Matter Physics, Nanoscience, and in Transmission Electron Microscopy (TEM) and spectroscopies techniques. Following very first studies on the plasticity of aeronautic alloys, I have focused my researches on order phenomena on lattice in metallic alloys including critical phenomena at phase transitions, incommensurate structures and a variety of quasi-crystalline phases in aeronautic alloys. From 1994, I progressively turned my researches towards Nanoscience, being leading one of the pioneering teams in France, on the synthesis, structural, electronic and optical properties of 1D and 2D objects issued from van der Waals materials. I have implemented at CNRS-Onera interdisciplinary research programs on Nanoscience, first focused on nanotubes and extended now to graphene and other 2D materials. Researches developed in this framework have included developing synthesis techniques of various kinds of single wall nanotubes and of 2D materials based on carbon, boron and nitrogen, modelling thanks to appropriate numerical simulations techniques their formation mechanisms, developing optoelectronic devices. Main achievements include first synthesis and TEM characterization of BN nanotubes, growth models of carbon nanotubes used as references worldwide, characterization metrics using TEM, electron and optical spectroscopies. Along this line, a particular effort has been focused to define appropriate investigation techniques able to study electronic and optical properties of BN materials from bulk to 2D layers, owing to their large band gap and to demonstrate the nature of their luminescence.

## Abstract:

A. Loiseau[1], E. Gaufres[1,2], L. Sponza[1], F. Fossard[1], R. Martel[3], M. Côté[4]
*[1] LEM, CNRS-ONERA, U. Paris Saclay, Chatillon, France; [2] LP2N, Institut d'optique –CNRS, Talence, France; [3] RQMP & Dpt de Chimie, U. Montréal, Canada ; [4] RQMP & Dpt de Physique U. Montréal, Canada*

Anisotropy and layer number drive the semiconducting properties of thin black phosphorus (BP), that offers promising perspectives in various fields such as electronics and photonics. However, the fast photooxidation in ambient condition, coupled to a high sensitivity to quantum confinement and dielectric environment in ultrathin BP, make very difficult the investigations on its intrinsic optical properties [1]. Further, as screening effects may strongly affect electronic and spectroscopic properties of 2D materials, it is highly desirable to investigate intrinsic properties of free-standing layers.

We have shown that Angular resolved Electron energy loss spectroscopy implemented in Transmission Electron Microscopy (ar-EELS-TEM) offers a unique way to investigate dielectric response of free-standing layers related to valence band and plasmon excitations with the advantage to get access to their q dispersion and their symmetry properties [2].

By combining this technique with suitable ab initio calculations, we have studied the dielectric response of free-standing BP layers as a function of the number of layers.

We found optical bandgap values of 1.9 eV, 1.4 eV and 1.1 eV for the mono- bi- and trilayer respectively. Moreover, by combining our results with a simple variational model, we correlate the exciton energy with the dielectric screening. We hence demonstrate that the variations of the electronic gap are sizeably larger than the variations of the binding energy. Finally, we probe and analyze the volume and surface plasmons dispersion as a function of momentum for the 1-3 BP layers and bulk and highlight a deviation and linearization of the parabolic dispersion with strong anisotropic fingerprints [3].

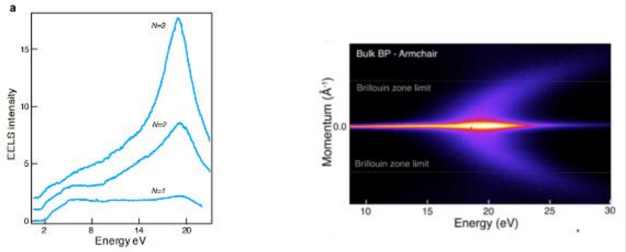


*Figure: (left) EELS spectra of suspended BP mono, bi and trilayers (N=1, 2, 3) showing the optical gap and the plasmon peak. (Right) Mapping of the plasmon energy loss along the armchair direction of BP*

References:

[1] A. Favron, E. Gaufres et al Nature Mat. 14 (2015) 826. [2] F. Fossard et al, Phys. Rev. B 96, 115304 (2017). [3] E. Gaufres et al, accepted to Nanoletters (2019).

# Electronic structure modification of TMDC materials by spontaneously patterned molecular dopant film

**Daisuke Kiriya**
**Department of Physics and Electronics, Osaka Prefecture University, Japan**

## Short biography:

Daisuke Kiriya received his Ph.D. degree in Engineering from Kyoto University in Japan in 2009 and performed his postdoctoral work at the University of Tokyo from 2009 to 2012 and the University of California, Berkeley, between 2012 and 2016. He is currently an assistant professor in the Department of Physics and Electronics at Osaka Prefecture University in Japan. His research focuses on molecular modification of nanomaterials and devices.

## Abstract:

Molecules are essential and minimum material components in chemistry, biology and materials science. We focus on the molecular modification/interaction with 2D materials including transition metal dichalcogenides (TMDCs) to use their high-performance. We have succeeded in the modulation of carrier concentration of MoS2 and generating a near-unity quantum yield of monolayer MoS2. In this presentation, I will focus on an interesting event shown in multiple molecules, pattern formation on TMDC surface to modify the electronic structure of TMDCs (Figure 1). Spontaneous pattern formation is the process known in various fields such as in biology to form organs, in physics of dewetting patterns, etc., which look complex but the formation of beautifully organized structures. An essential process forming the spontaneous pattern formation is the process of relaxation from non-equilibrium states. We found that the strong molecular electron dopant film, benzyl viologen film, can be destabilized and spontaneously form a pattern at a pitch of 200 nm scale on MoS2 or WSe2. The electronic properties of TMDCs are highly dependent on the pattern formation, and the pattern showed local carrier modulation on the TMDC surface. This work would be useful to modulate the carriers in TMDCs locally and non-destructively and to form a large number of junctions simultaneously and spontaneously under a minimum energy consumption. This work is financially supported by JSPS PRESTO, Japan.

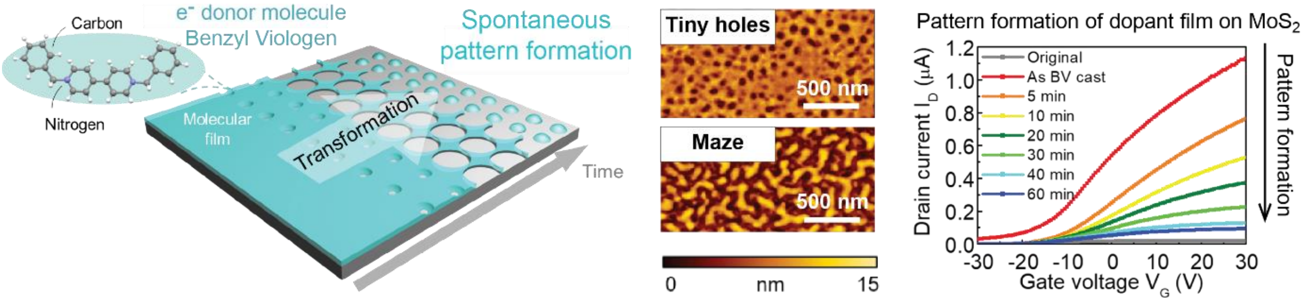


*Figure: Spontaneous pattern formation of the donor molecular film on MoS2.*

References:

[1] D. Kiriya, et al., J. Am. Chem. Soc. 136 (2014) 7853.
[2] D. Kiriya, et al., Adv. Funct. Mater. 25 (2015) 6257.
[3] M. Amani, D.H. Line, D. Kiriya et al. Science, 350 (2015) 1065.
[4] H. Ichimiya, et al. ACS NANO, 12 (2018) 10123.
[5] H. Ichimiya, et al., ACS Appl. Mater Int. 11 (2019) 15922.
[6] H. Ichimiya, et al., Appl. Phys. Exp. 12 (2019) 051014.

# Graphene-based van der Waals heterostructures towards a new type of terahertz quantum-cascade lasers

**Taiichi Otsuji**
**Research Institute of Electrical Communication, Tohoku, University, Sendai, Japan**

## Short biography:

Taiichi Otsuji received the Ph.D in Electron. Eng. from Tokyo Inst. Tech., Japan in 1994. After working for NTT Lab. (1984~1999) and Kyushu Inst. Tech. (1999-2005), he has been working at RIEC, Tohoku University as a full professor. He has been served an IEEE Electron Device Society Distinguished Lecturer since 2013. He is a Fellow of the IEEE, OSA, and JSAP, and a member of the MRS, SPIE, and IEICE.

## Abstract:

Current-injection or optical pumping makes population inversion of graphene carriers enabling lasing and/or amplification of terahertz (THz) radiation [1-3]. We've recently demonstrated 1-8-THz broadband amplified spontaneous THz emission as well as single-mode THz lasing at 5.2 THz both at 100K [3]. Introduction of a gated double-graphene-layered (G-DGL) van der Waals heterostructure in which gate-bias tuned THz radiation emission is obtained via plasmon- and/or photon-assisted quantum-mechanical resonant tunneling is a promising rout to further increase operation temperature as well as output intensity (Fig. 1) [4-5]. We experimentally demonstrated the proof of concept of such an operation mechanism [6]. The important physics behind is the acoustic plasmon modes in the DGL that can enormously enhance the quantum efficiency by orders for dc electric power to THz photo radiation power conversion in comparison with that for a simple graphenechannel transistor laser structure (Fig. 1) [5]. We have proposed a cascading of the G-DGL unit element working as a new type of THz quantum-cascade lasers (Fig. 1) [7]. The laser cavity can be structured along with the in-plane direction of the G-DGL mesa structure. The vertical G-DGL cascade structure can enlarge the mode field of the THz photon radiation to match the free-space impedance. Numerical analyses demonstrate further increase of the quantum efficiency of THz lasing by order of magnitude in comparison with a single G-DGL structure. Experimental verification is now undergoing. This work is financially supported by JSPS KAKENHI #16H06361, Japan.

References:

[1] V. Ryzhi et al., J. Appl. Phys. 101 (2007) 083114.
[2] M. Ryzhii and V. Ryzhii, Jpn. J. Appl. Phys. 46 (2007) L151.
[3] D. Yadav et al., Nanophoton. 7 (2018) 741-752.
[4] V. Ryzhii et al., Opt. Exp., 21 (2013) 31569.
[5] D. Svintsov et al., Phys. Rev. B 94 (2016) 115301.
[6] D. Yadav et al., 2D Mat. 3 (2016) 045009.
[7] A.A. Dubinov et al., Opt. Exp. 24 (2016) 279307.

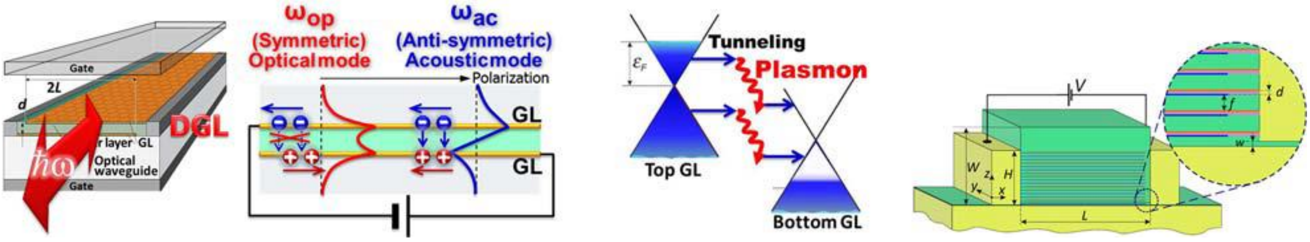


*Figure: G-DGL structure, its plasmon modes, plasmon-assisted tunneling, and G-DGL cascade.*

# First steps of 2D material integration in 300mm silicon production line

**Cedric Huyghebaerth**
**IMEC, APPM, Belgium**

**Short biography:**

Cedric Huyghebaert is currently Program manager of exploratory processes and modules at imec, dealing e.g. with the integration of nano materials as CNT and graphene and graphene related materials in functional applications. He is deputy of the wafer scale integration work package in the Graphene Flagship. He started as a junior researcher in the materials and component analyses group at imec. He studied the oxygen bean interactions during sputtering profiling of semiconductors. He received his PhD in Physics in 2006 at the KULeuven in Belgium. In 2005 he joined imecs pilot line as an integration engineer, especially dealing with the process contamination control. He was part of the packaging group from begin 2008 till begin 2010, working as a senior integration engineer dealing with 3D-stacked IC integration. From 2010 to 2019 he leads the nano-applications and – material engineering (NAME) group at imec. He (co-)authored more than 150 journal and conference papers.

**Abstract:**

The Graphene Flagship program is rapidly progressing in the development of a wide range of applications driven by silicon CMOS, and several tangible prototypes have already been realized that demonstrate the unique and beyond-state-of-the-art capabilities of graphene and related materials (GRMs). Nevertheless, large area integration is challenging and progressing at a slow pace suffering from limited reproducibility and a gap between results achieved on encapsulated flakes and synthetic materials. It is generally accepted that this is mainly due to a lack of the required infrastructure which allows to control the interfaces of the 2D materials at large scale.

In this presentation we will discuss the processing challenges that we need to research to mature the integration and access the semiconductor standards.
Different wafer level 2D-material growth methods are discussed and benchmarked.
A fully automated transfer method will be discussed, and remaining challenges are addressed.
Finally, we established an integration module for 2D materials in the 300mm line. We demonstrate the integration of graphene and MX2-based transistors using standard state of the art production tools.
We will demonstrate integrated devices where 2D material was directly deposited or growth on a template surface and transferred to the pre-processed target wafer. The major integration challenges are the limited adhesion and the fragility of the (few)monolayer 2D material.
We end up with an outlook of the remaining challenges to make 2D materials integration complete part of the Si processing portfolio in order to have 2D materials popping up in products that are put on the market in the field of microprocessors, memories, telecommunication, internet of things, sensor, healthcare and bio-applications.

# Nanocarbon-based optoelectronic devices on silicon chips

**Hideyuki Maki**
**Department of Applied Physics and Physico-Informatics, Keio University, Japan**

## Short biography:

Hideyuki Maki is an Associate Professor at Keio University, Japan. He receives B.S., M.S. and Ph.D. degrees from Waseda University, Japan, in 1998, 1999 and 2002, respectively. In the years 2002-2005, he worked as a Special Postdoctoral Researcher at Nanodevice group in Riken, Japan. From 2005, he joined Keio University as Assistant professor (2005-2009), Lecturer (2009-2012) and Associate Professor (2012-). He also worked in Holleitner group in Walter Schottky Institut, Technische Universität München (TUM) as a visiting researcher (2010-2011). He received some awards from "The Japan Society of Applied Physics" and "The Fullerenes, Nanotubes and Graphene Research Society" in Japan.

## Abstract:

Optoelectronic devices integrated on silicon chips can enable novel architectures for on-chip optical interconnects and silicon photonics. However, because the compound semiconductors cannot be directly grown on silicon wafers, these optoelectronic devices face significant challenges with respect to their integration with silicon-based platforms. Here we talk about two optoelectronic devices on silicon chips: electrically driven, high-speed light emitters based on nanocarbon materials [1-4] and single photon generation from a carbon nanotubes (CNTs) [5]. We demonstrated ultra-high-speed, highly-integrated, on-silicon-chip blackbody emitters based on nanocarbon materials in the near-infrared region including telecommunication wavelength [1-4]. We fabricated the blackbody emitters with carbon nanotube films and graphene, and we observed high-speed blackbody emission with the response speed of 1 Gbps. This high-speed response is explained by the extremely fast temperature response of the nanocarbon materials, which is dominated by their small heat capacity, high heat dissipation to the substrate and quantum thermal transport via surface polar phonons of substrates. By using these blackbody emitters with nanocarbon materials, we demonstrated short-pulsed light generation, real-time optical communications, integrated two-dimensional array emitters, capped emitters operable in air, and the direct coupling of optical fibers to the emitters. Photon antibunching from semiconductor quantum dots (sQDs) has been attracted much attention for use as single-photon sources in quantum cryptography. However, sQD based single photon sources at both room temperature and telecommunication wavelength have not been reported so far. In this study, we demonstrated the photon antibunching in a SWNT at telecommunication wavelength and room temperature [5]. These optoelectronic devices based on nanocarbon materials can open new routes to on-Sichip, small footprint and high-speed emitters for highly integrated optoelectronics and silicon photonics. This work was partially supported by PRESTO from JST, KAKENHI and Core-to-Core program from JSPS, KISTEC project, the Cooperative Research Program of "Network Joint Research Center for Materials and Devices", Spintronics Research Network of Japan, and NIMS Nanofabrication Platform in Nanotechnology Platform Project by MEXT.

References:

[1] Y. Miyoshi, Y. Fukazawa, Y. Amasaka, R. Reckmann, T. Yokoi, K. Ishida, K. Kawahara, H. Ago & H. Maki Nat. Commun. 9, 1279 (2018).
[2] T. Mori, Y. Yamauchi, S. Honda, H. Maki, Nano Lett. 14, 3277 (2014).
[3] M. Fujiwara, D. Tsuya, H. Maki, Appl. Phys. Lett., 103, 143122 (2013).
[4] N. Hibino, S. Suzuki, H. Wakahara, Y. Kobayashi, T. Sato, H. Maki, ACS Nano, 5, 1215 (2011).
[5] T. Endo, J. I-Hayase, H. Maki, Appl. Phys. Lett., 106, 113106 (2015)

# Graphene and 2D Optoelectronics

**Max Lemme**
**Micro- and Nanoelectronics, RWTH Aachen University, Germany**

**Short biography:**

Prof. Max Lemme is a Full Professor at RWTH Aachen University and the Director of AMO GmbH, Aachen. He obtained his PhD degree from RWTH in 2004. He has worked in the field of nano-CMOS devices, including FinFET and SOI-MOSFETs, novel high-k/metal gate stacks and graphene and 2D materials. The latter includes the world's first top-gated graphene MOSFET, a novel graphene-based non-volatile memory, vertical graphene transistors and graphene NEMS. He received the "NanoFutur" young researchers' award from the German Ministry for Education and Research in 2006 and a Lynen Research Fellowship from the Alexander von Humboldt Foundation in 2007. From 1998 to 2008, he worked AMO, where his last position was as Head of the Technology Department. In 2008, he joined Harvard University in Cambridge, USA, where he pioneered a helium ion-based nanolithography method for graphene and investigated graphene photodetectors. In September 2010, he became Professor at KTH, where he initiated the graphene activities within the School of ICT. He received an ERC Starting Grant and became Full Professor at the University of Siegen with a DFG Heisenberg-Professorship in 2012. In February 2017, Prof. Lemme was appointed Full professor at RWTH Aachen University and Scientific Director of AMO GmbH. He has managed several German BMBF Projects with industry partners like Infineon, AMD and Qimonda and was the coordinator of the FP 7 EU Projects "GRAND" and "GRADE". He received an ERC Proof of Concept grant for commercializing graphene photodetectors in 2018.

**Abstract:**

Graphene has been researched intensely over the past 15 years. Its intrinsic electronic and physical properties are unrivaled in many aspects. Hundreds of related two-dimensional (2D) materials with different properties have since been added to the "2D Zoo". Physicists, chemists, material scientists and engineers continue to report new highlights on a daily basis. Yet, there are no end-customer products on the market today where 2D materials are utilized as active elements in in electronics, optoelectronics or sensing, because the process technology is not yet mature. In this talk, I will introduce promising applications, for which 2D materials clearly could make a difference, such as 2D / 3D heterostructures for photodetectors [1]–[6] and graphene integrated with silicon photonics to fulfil a range of functions. I will discuss graphene photodetectors integrated into silicon waveguides that utilize the IR absorption and high carrier mobility to enable high speed operation above 120 GHz [7]. The gate-tunability of the fermi level (and the carrier concentration) in graphene further enables amplitude modulators, where the graphene can be switched via an external gate electrode from an absorbing into a transparent material [8]. The Kramers-Kronig relation translates the change in carrier concentration into a change in refractive index. Thus, phase modulation becomes feasible with graphene [8]. I will further discuss the major bottlenecks towards integration of graphene and 2D materials into semiconductor processing lines [9].

References:

[1] C. Yim et al., Sci. Rep., vol. 4, Jun. 2014.
[2] S. Riazimehr et al., Solid-State Electronics, vol. 115, Part B, pp. 207–212, Jan. 2016.
[3] S. Riazimehr et al., ACS Photonics, vol. 4, no. 6, pp. 1506–1514, Jun. 2017.
[4] C. Yim et al., Nano Letters, vol. 18, no. 3, pp. 1794–1800, Mar. 2018.
[5] S. Riazimehr et al., ACS Photonics, vol. 6, no. 1, pp. 107–115, Jan. 2019.
[6] A. Bablich et al., ACS Photonics, vol. 6, no. 6, pp. 1372–1378, Jun. 2019.
[7] D. Schall et al., ACS Photonics, vol. 1, no. 9, pp. 781–784, Sep. 2014.
[8] M. Mohsin, D. Schall, M. Otto, A. Noculak, D. Neumaier, and H. Kurz, Opt. Express, OE, vol. 22, no. 12, pp. 15292–15297, Jun. 2014.
[9] D. Neumaier, S. Pindl, and M. C. Lemme, Nature Materials, vol. 18, no. 6, p. 525, Jun. 2019.

# TMDC FETs using sputtering and sulfurization processes

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**School of Engineering and the Research Institute for the Earth Inclusive Sensing, Tokyo Institute of Technology (Tokyo Tech), Japan**

## Short biography:

Hitoshi Wakabayashi received the M.E. and Ph.D. in Electronic Engineering from Tokyo Institute of Technology, Japan in 1993 and 2003, respectively. After working at NEC Corporation (1993 ~ 2006), MIT (2000 ~ 2001) and Sony Corporation (2006 ~ 2012), he has been working at Tokyo Institute of Technology as a full professor since 2013. He has served as General Chairs for IEEE Symposium on VLSI Technology 2013, IEEE EDTM Conference 2018, JSAP/IEEE IWJT 2017 and 2019, and Directors of JSAP, JIEP and MOT-Japan in all 2019 and 2020. He is also a member of the IEEE/EDS.

## Abstract:

Moore's law is still being continued even down to 7-nm technology node [1,2,3,4]. In order to accelerate the performance beyond 7-nm FinFETs, it is required to enhance the carrier mobility even in single nano-meter thickness of channel. An atomically layered transition-metal di-chalcogenide (TMDC) film is one of the candidates [5,6], however a film-formation process is aggressively being discussed. Although a CVD process is widely investigated, it is difficult to control the number of layers in a wafer. On the other hand, a sputtering process is another candidate because of its high controllability of thickness in atomic scale [7]. For transistor characteristics, normally-on characteristics with an operation in electron accumulation-mode are frequently shown due to the Fermi-level pinning with a conduction band minimum influencing with both alkali-metal pollutions and sulphur vacancies [8]. The clean sputtering and sulfurization processes to improve the crystal quality of TMDC film because of compensation of sulphur vacancy are considered to be preferable [7-9]. Eventually, normally-off characteristics with both C-V and I-V are achieved as shown in Figs. 1 and 2 [8,10]. However, the channel mobility is needed to be enhanced further. This work is partly supported by JST CREST (JPMJCR16F4) and COI (JPMJCE1309).

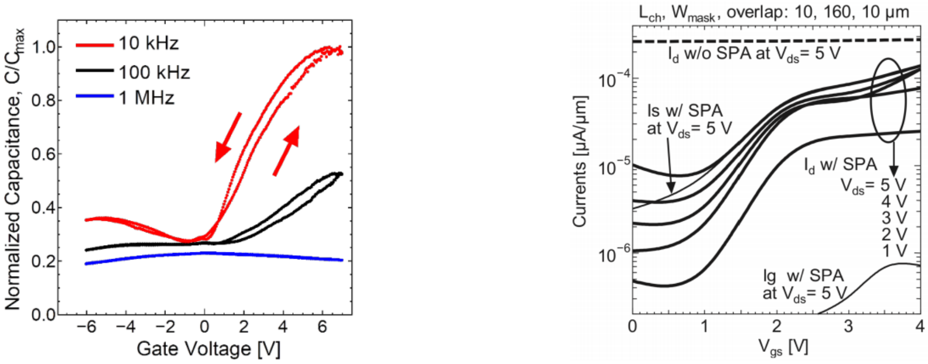

*Figure: (left) Normally-off C-V characteristics in n-type accumulation mode with top gate [10]; (right) Normally-off I-V characteristics for accumulation-mode nMISFET with top gate [8].*

References:

[1] H. Wakabayashi, et al., IEEE/TED, Vol. 53, Issue 9, 2006, p. 1961.
[2] C. Auth, et al., IEEE/IEDM, 29.1, pp. 673-676, 2017.
[3] H. Wakabayashi, S3S, 19.1 (2018).
[4] https://irds.ieee.org
[5] S. Das, et al., Nano Letter 13, 100, (2013).
[6] Ming-Yang Li, et al., NATURE, V. 567, p. 169, 2019.
[7] T. Ohashi, et al., JSAP/JJAP, 54, 04DN08, 2015.
[8] K. Matsuura, et al., IWJT, S1-3 (2019).
[9] K. Matsuura, et al., JEM, vol. 47, 7, p. 3497, (2018).
[10] H. Tanigawa, et al., JSAP/IWDTF 2019, S4-2.

# Momentum-resolved EELS with an electron microscope: phonon and quasi-particle dispersion in 2D membranes

**Francesco Mauri**
**Physics, Roma La Sapienza, Italy**

## Short biography:

Francesco Mauri is full professor of physics at the Universitá la Sapianza in Rome. His activity focuses on the prediction of the physical properties of complex materials using first-principles electronic structure methods and on the development of original theories, methods, and algorithms to treat interacting electrons and phonons. He is particularly interested in: - Simulation of spectroscopies (Raman, IR, NMR, EPR, Xanes, Inelastic X-ray scattering, EELS, ...); - Electron-phonon interaction and phonon mediated superconductivity; - Carbon nanotubes, graphene and 2D materials; - Anharmonicity, phonon-phonon interaction, CDW and thermal conduction; - Mineral-physics and geochemistry; - Amorphous materials

## Abstract:

Propagating atomic vibrational waves—phonons—determine important thermal, mechanical, optoelectronic and transport characteristics of materials. Thus, a knowledge of phonon dispersion (that is, the dependence of vibrational energy on momentum) is a key part of our understanding and optimization of a material’s behaviour. However, the phonon dispersion of a free-standing monolayer of a two-dimensional material such as graphene, and its local variations, have remained elusive for the past decade because of the experimental limitations of vibrational spectroscopy. Even though electron energy loss spectroscopy (EELS) in transmission has recently been shown to probe local vibrational charge responses, such studies are still limited by momentum space integration due to the focused beam geometry; they are also restricted to polar materials such as boron nitride or oxides, in which huge signals induced by strong dipole moments are present. On the other hand, measurements on graphene performed by inelastic X-ray (neutron) scattering spectroscopy or EELS in reflection do not have any spatial resolution and require large microcrystals. Here we provide a new pathway to determine phonon dispersions down to the scale of an individual free-standing graphene monolayer by mapping the distinct vibrational modes for a large momentum transfer [1]. The measured scattering intensities are accurately reproduced and interpreted with density functional perturbation theory [1]. The technique can be applied to study not only the dispersion of phonons but of all quasiparticles of 2D materials, including plasmons, excitons, e-h excitations, that induce charge fluctuations.

References:

[1] Ryosuke Senga, Kazu Suenaga, Paolo Barone, Shigeyuki Morishita, Francesco Mauri & Thomas Pichler, Nature 573, 247 (2019)

# Exploration of Topological Electronic Materials having Exotic Quasi-particles

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**Laboratory for Materials and Structures, Tokyo Institute of Technology, Japan**

## Short biography:

Takao Sasagawa received the B.E., M.E., and D.E. degrees from the University of Tokyo, Japan, in 1995, 1997, and 2000, respectively. From 2000 to 2006, he was a Research Associate with the Department of Advanced Materials Science, University of Tokyo. Since 2007, he has been an Associate Professor with the Laboratory for Materials and Structures, Tokyo Institute of Technology, Yokohama, Japan. His current research interests include physics and chemistry of exotic electronic materials, such as high-Tc superconductors and topological quantum matters.

## Abstract:

A new paradigm of solid-state electronic materials is rapidly being formed by deeper understandings of strong electron correlations, lower electronic dimensionality, and strong spin-orbit coupling (SOC) in compounds. For example, the combinations of SOC, crystal symmetries, and magnetic/superconducting orderings have been found to create a variety of novel quantum states such as “strong”/“weak”/“higher-order” topological insulators, topological “Dirac”/“Weyl” semimetals, topological “nodal-line”/“nodal-ring” semimetals, and topological superconductors. On the other hand, due to the theory-driven discovery, many of these intriguing topological electronic compounds have yet to be materialized. In this talk, experimentally accessible topological quantum materials (i.e. sizable (~mm$^3$) single crystals have been successfully grown in our group) will be reviewed, with some emphasis on their unique crystal structures and electronic states/properties [1-10].

References:

[1] T. Machida, T. Hanaguri, T. Sasagawa, T. Tamegai et al., Nature Materials (2019), published online.
[2] R. Noguchi, T. Sasagawa, T. Kondo et al., Nature 566, 518 (2019).
[3] M.S. Bahramy, T. Sasagawa, P.D.C. King et al., Nature Materials 17, 21 (2018).
[4] K. Iwaya, T. Hanaguri, T. Sasagawa et al., Nature Commun. 8, 976 (2017).
[5] Y.-S. Fu, T. Hanaguri, T. Sasagawa et al., Nature Commun. 7, 10829 (2016).
[6] J. M. Riley, T. Sasagawa, P.D.C. King et al., Nature Nanotech. 10, 1043 (2015).
[7] M. Sakano, T. Sasagawa, K. Ishizaka et al., Nature Commun. 6, 8595 (2015).
[8] Y.-S. Fu, T. Hanaguri, T. Sasagawa et al., Nature Physics 10, 815 (2014).
[9] Y. L. Chen, Z.-X. Shen, T. Sasagawa et al., Nature Physics 9, 704 (2013).
[10] Y. L. Chen, T. Sasagawa, Z.-X. Shen et al., Science 329, 659 (2010).

# Ultrafast charge transfer in heterostructures of 2D materials

**Giulio Cerullo**
**Dipartimento di Fisica, Politecnico di Milano, Italy**

## Short biography:

Giulio Cerullo is a Full Professor with the Physics Department, Politecnico di Milano, where he leads the Ultrafast Optical Spectroscopy laboratory. Prof. Cerullo's research activity covers a broad area known as "Ultrafast Optical Science", and concerns on the one hand pushing our capabilities to generate and manipulate ultrashort light pulses, and on the other hand using such pulses to capture the dynamics of ultrafast events in molecular and solid-state systems. Additional research topic is the application of ultrafast lasers to coherent Raman microscopy. 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 has been General Chair of the conferences CLEO/Europe 2017, Ultrafast Phenomena 2018 and will be Genereal Chair of the International Conference on Raman Spectroscopy 2020.

## Abstract:

Chiara Trovatello, Zilong Wang, Stefano dal Conte, Giulio Cerullo

Heterostructures (HS) of two-dimensional materials offer unlimited possibilities to design new materials for applications to optoelectronics and photonics. In such HS the electronic structure of the individual layers is well retained because of the weak interlayer van der Waals coupling. Nevertheless, new physical properties and functionalities arise beyond those of their constituent blocks, depending on the type and the stacking sequence of layers. In this paper we use high time resolution ultrafast transient absorption (TA) spectroscopy to resolve the interlayer charge scattering processes in HS. We first study a WSe2/MoSe2 HS, which displays type II band alignment with a staggered gap, where the valence band maximum and the conduction band minimum are in the same layer. By two-colour pump-probe spectroscopy, we selectively photogenerate intralayer excitons in MoSe2 and observe hole injection in WSe2 on the sub-picosecond timescale, leading to the formation of interlayer excitons. The temperature dependence of the build-up and decay of interlayer excitons provide insights into the layer coupling mechanisms. Next, we investigate a graphene/WS2 HS where, for excitation well below the bandgap of WS2, we observe the characteristic signal of the A and B excitons of WS2, indicating ultrafast charge transfer from graphene to the semiconductor. The nonlinear excitation fluence dependence of the TA signal reveals that the underlying mechanism is hot electron/hole transfer, whereby a tail the hot Fermi-Dirac carrier distribution in graphene tunnels through the Schottky barrier. Hot electron transfer is promising for the development of broadband and efficient low-dimensional photodetectors.

# Optical probing and control of excitonic states in atomically thin two-dimensional materials

**Kazunari Matsuda**
**Institute of Advanced Energy, Kyoto University, Japan**

## Short biography:

Kazunari Matsuda is a professor at Kyoto University. He received his BS, MS and PhD degrees in applied physics from Nagoya University in 1993, 1995, and 1998, respectively. He joined the research group of KAST as a researcher in 1998 and also the Precursory Research for Embryonic Science and Technology Program (PRESTO) of Japan Science and Technology Agency (JST) in 2002. He joined as Associate Professor at Kyoto University in 2004 and promoted full Professor in 2010. His current research interests include nano-optics, and solid-state physics of nano-materials.

## Abstract:

Atomically thin materials with a few atomic layers thickness, such as nano-carbon and two-dimensional (2D) materials, e.g. carbon nanotube, graphene and monolayer transition metal dichalcogenide have attracted a great deal of attention and intensively studied from viewpoint of fundamental physics and optical application [1-6]. These are emerging materials as new stages for studying the novel electronic and optical properties. The enhanced Coulomb interaction in atomically thin 2D materials leads to the formation of stable excitonic states such as excitons and charged exciton (trion) by optical excitation. Moreover, valley pseudospin that gives new degrees of freedom in monolayer 2D materials has attracted tremendous attention and extensively studied toward valleytronics. We studied the excitonic states and its dynamics of 2D transition metal dichalcogenide [4,5] and its hetero-structures [7] by advanced laser spectroscopy. Moreover, we will discuss the new scheme to control the excitonic valley polarization based on the understanding of valley relaxation [8,9] in monolayer transition metal dichalcogenide. This work is financially supported by JSPS KAKENHI #16H06331, Japan.

References:

[1] Y. Miyauchi, K. Matsuda, et al., Nature Photonics, 7, (2013) 715.
[2] N. Akizuki, K. Matsuda, Y. Miyauchi, et al., Nature Commun., 6, (2015) 8920.
[3] S. Mouri, Y. Miyauchi, and K. Matsuda, Nano Lett., 13, (2013) 594.
[4] D. Kozawa, K. Matsuda, G. Eda, et al., Nature Commun., 5, (2014) 4543.
[5] S. Mouri, K. Matsuda, et al., Phys. Rev. B, 90, (2014) 155449.
[6] F. Wang, K. Matsuda, et al., Nature Commun., 6, (2015) 6305.
[7] T. Yamaoka, H-E. Lim, K. Matsuda, et al., Adv. Func. Mater., 28, (2018) 1801021.
[8] Y. Miyauchi, S. Konabe, K. Matsuda, et al., Nat. Commun., 9, (2018) 2598.
[9] K. Shinokita, Y. Miyauchi, K. Matsuda, et al., Adv. Func. Mater., 29, (2019) 1900260.

# Spin-valley coupling in bilayer graphene quantum devices

**Christoph Stampfer**
**JARA-FIT and 2nd Institute of Physics, RWTH Aachen University, Germany**

## Short biography:

Christoph Stampfer is currently Professor of Experimental Solid State Physics at the RWTH Aachen University and researcher at the Forschungszentrum Jülich. He is primary interests include graphene and 2D materials research, mesoscopic transport, and micro electromechanical systems. He holds a Dipl.-Ing. Degree in Technical Physics from the TU Vienna and a Ph.D. in Mechanical Engineering from the ETH Zurich. He was a staff member at the Institute for Micro and Nano Systems of the ETH Zurich from 2003 to 2007 and staff member of the Institute for Solid State Physics (ETH Zurich) from 2007 to 2009. From 2009 till 2013 he was JARA-FIT Junior Professor at the RWTH Aachen and the Forschungszentrum Jülich. He has been awarded with an ERC Starting Grant to work on "Graphene Quantum Electromechanical Systems" in 2011 was a member of the Young Scientist community of the World Economic Forum in 2014-2106 and he has an ERC Consolidator Grant to work on "2D Materials for Quantum Technologies" in 2018.

## Abstract:

Graphene and bilayer graphene (BLG) are attractive platforms for quantum circuits. This has motivated substantial efforts in studying quantum dot (QD) devices based on graphene and BLG. The major challenge in this context is the missing band-gap in graphene, which does not allow confining electrons by means of electrostatics. A widely used approach to tackle this problem was to introduce a hard-wall confinement by etching the graphene sheet. However, the influence of edge disorder, turned out to be a road block for obtaining clean quantum devices. The problem of edge disorder can be circumvented in clean BLG, thanks to the fact that this material offers a tuneable band-gap in the presence of a perpendicularly applied electric field, a feature that allows introducing electrostatic soft confinement in BLG. Here we present gate-controlled single, double, and triple dot operation in electrostatically gaped BLG. We show a remarkable degree of control of our device, which allows the implementation of two different gate-defined electron-hole double-dot systems with very similar energy scales. In the single dot regime, we reach the very few electron/hole regime, extract excited state energies and investigate their evolution in a parallel and perpendicular magnetic field. Finally, we will show data on ultra-clean BLG quantum point contacts allowing investigating the spin-valley coupling in bilayer graphene.

# Biomedical applications of graphene

**Kazuhiko Matsumoto**
**ISIR, Osaka University, Japan**

## Short biography:

Kazuhiko Matsumoto received the Ph.D. degrees from Tokyo Institute of Technology in 1981 in Electronics Engineering. 1981~2002, he has been working with Electrotechnical Laboratory, Tsukuba, 1988~1990, he was a research associate of the Stanford University, and since 2003 he is a professor at Osaka University, Osaka, Japan. He has studied the compound semiconductor devices, single electron devices, carbon nanotube and graphene devices and their applications. He was awarded the Pioneering Research Prize of the Science and Technology Agency of Japan government, and is a Fellow of the Japan Society of Applied Physics.

## Abstract:

Using the feature of graphene, such that the two dimensional electron gas is on the surface of graphene, the carrier mobility is extremely high, it is hard to be oxidised, etc., we have succeeded in fabricating the graphene biosensor modified by sugar chain, which could selectively detect the influenza virus whether the virus infect to the human or not. The limited number of detectable virus is as small as 3. For the future real application, we should also get the information of the subtype of virus which tell us the level of the pathogenicity. In order to know the subtype of virus, we try to modify the surface of graphene by antibody of influenza virus. There are 144 kinds of subtype of influenza virus. In principle, we should use 144 antibody to know the subtype of virus. We have already succeeded in the integration of 82 graphene FET on one chip and can measure all at once. Using this integrated graphene FET chip, we try to selectively modify the surface by sugar chain and also antibodies of virus for the subtype detection(a). For this selective modification, we introduce the bio-inkjet printer, which can selectively deposit the various antibody(b). We as a first step, modify the surface of graphene by BSA and St Avidin and now checking the difference of the shift of the Dirac point. For the further future application, the automation of the measurement is necessary. For this purpose, we introduce the micro TAS system and automated pumping systems(c). These projects are undergoing. This work is financially supported by JST CREST, Japan.

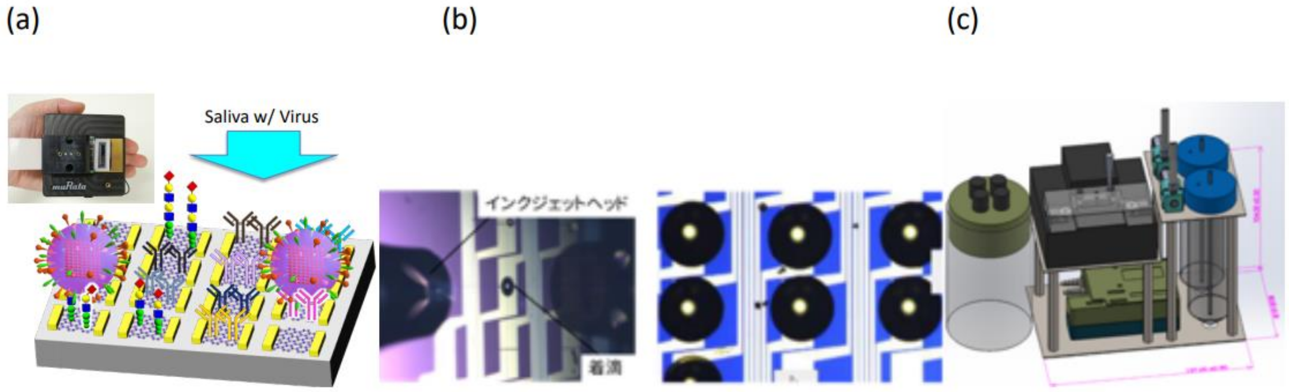

*Figure: Sugar chain & antibody modified graphene FET for the detection of virus.*

# Water-based and biocompatible 2D-inks for all printed devices

**Cinzia Casiraghi**
**Department of chemistry, University of Manchester, United Kingdom**

## Short biography:

Prof Cinzia Casiraghi graduated in Nuclear Engineering from Politecnico di Milano (Italy) and received her PhD in Electrical Engineering from the University of Cambridge (UK) in 2006. She was awarded with the Oppenheimer Research Fellowship, followed by the Humboldt Fellowship and the prestigious Kovalevskaja Award (1.6M Euro). In 2008 she became Junior Professor at the Physics Department of the Free University Berlin (Germany). In 2010 she joined the School of Chemistry, at the University of Manchester (UK). Her current research work is focused on the development of 2D inks and their applications in printed electronics, thermoelectrics, and biomedical applications. Furthermore, she is leading expert on Raman spectroscopy, used to characterise a wide range of carbon-based nanomaterials. She authored and co-authored more than 80 peer reviewed articles, collecting more than 22k citations (h-index = 45). She also served as chairperson and program committee member on top international conferences (eg Graphene Week, MRS, etc). She is recipient of the Leverhulme Award in Engineering (2016) and the Marlow Award (2014).

## Abstract:

In this talk I will review ink-jet printable formulations made of 2D materials and their use in heterostructure-based electronics. The talk will present research conducted at the interface between chemistry and electrical engineering: we have developed a general formulation engineering approach to achieve highly concentrated, and inkjet printable water-based 2D crystal formulations, which also provide optimal film formation for heterostructure fabrication [1]. I will provide specific examples of all-inkjet printed devices, such as large area arrays of photosensors on plastic [1], programmable logic memory devices [1], strain sensors on paper [2], capacitors [3] and transistors [4].

References:

[1] McManus et al, Nature Nanotechnology, 2017, doi:10.1038/nnano.2016.281.
[2] Casiraghi et al, Carbon, 2018, 129, 462.
[3] Worsley et al, ACS Nano, 2019, 13, 54.
[4] Lu et al, ACS Nano, accepted

# CVD growth of 1 million graphene on the device

**Toshiaki Kato**
**Department of Electronic Engineering, Tohoku University, Japan**

## 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:

Graphene nanoribbons (GNRs) combine the unique electronic and spin properties of graphene with a transport gap that arises from quantum confinement and edge effects. This makes them an attractive candidate material for the channels of next-generation transistors. However, the reliable site and alignment control of nanoribbons with high on/off current ratios remains a challenge. We have developed a new, simple, scalable method based on novel plasma catalytic reaction [1] for directly fabricating narrow GNRs devices with a clear transport gap [2,3]. Since the establishment of our novel GNR fabrication method, direct conversion of a Ni nanobar to a suspended GNR is now possible. Indeed, GNRs can be grown at any desired position on an insulating substrate without any post-growth treatment, and the wafer-scale synthesis of suspended GNR arrays with a very high yield (over 98%) is realized [3]. The growth dynamics of suspended GNR is also investigated through the systematic experimental study combined with molecular dynamics simulation and theoretical calculations for phase diagram analysis. It is revealed that the minimum length of GNR can be decided by the wavelength of Plateau-Rayleigh instability known as a traditional instability of fluid flow. Furthermore, unique optoelectrical property, known as persistent photoconductivity (PPC), is also observed in our suspended GNR devices. By using the PPC, GNR-based non-volatile memory operation is demonstrated [4]. We believe that our results can contribute to pushing the study of atomically thin layered materials from basic science into a new stage related to the optoelectrical applications [5-8] in industrial scale.

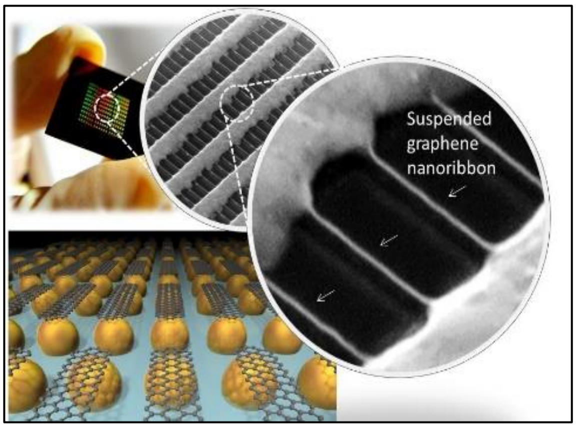

*Figure: Large-scale integration of suspended GNR arrays.*

References:

[1] T. Kato and R. Hatakeyama, ACS Nano 6, 8508-8515 (2012). [2] T. Kato and R. Hatakeyama, Nature Nanotechnology 7, 651-656 (2012).
[3] H. Suzuki et al., Nature Communications 7, 11797-1-10 (2016).
[4] H. Suzuki, N. Ogura, T. Kaneko, and T. Kato, Sci. Rep. 8, 11819-1-9 (2018).
[5] T. Kato and T. Kaneko, ACS Nano 8, 12777-12785 (2014).
[6] T. Kato and T. Kaneko, ACS Nano 10, 9687-9694 (2016).
[7] T. Akama, W. Okita, R. Nagai, C. Li, T. Kaneko, and T. Kato, Sci. Rep. 7, 11967 (2017).
[8] Q.-Y. Li, T. Feng, W. Okita, Y. Komori, H. Suzuki, T. Kato, T. Kaneko, T. Ikuta, X. Ruan, K. Takahashi, ACS Nano (2019) accepted.

# Scalable device integration and passivation techniques for 2D materials

**Jack Alexander-Webber**
**Department of Engineering, University of Cambridge, United Kingdom**

## Short biography:

Jack Alexander-Webber holds a Royal Society Dorothy Hodgkin Research Fellowship in the Department of Engineering at the University of Cambridge. He has previously held a Research Fellowship from the Royal Commission for the Exhibition of 1851 and a Junior Research Fellowship of Churchill College. He graduated from Royal Holloway, University of London with an MSci in Physics. After a summer studentship working for the National Physical Laboratory he began his DPhil in the group of Prof Robin Nicholas in the Deparment of Physics at the University of Oxford. His doctoral research was on the properties of low-dimensional nanostructures such as graphene, carbon nanotubes and III-V semiconductors with a particular focus on high magnetic field effects studied both in Oxford and at the European Magnetic Field Laboratory facilities in Grenoble and Toulouse. After completing his DPhil, Jack undertook an EPSRC Doctoral Prize fellowship at Oxford. His current research interests lie in exploring the nature of low-dimensional nanomaterials such as graphene, 2D semiconductors, and semiconductor nanowires and exploiting their exceptional properties for electronic and optoelectronic applications.

## Abstract:

Jack Alexander-Webber[1], Ye Fan[1], Oliver Burton[1], Hope Bretscher[2], Arelo Tanoh[2], Akshay Rao[2], Hannah Joyce[1], Luke Smith[2], Oliver Batey[2], Charles Smith[2], Stephan Hofmann[1]

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Low-dimensional materials such as graphene, transition metal dichalcogenides (TMDs) hold exceptional promise for future optoelectronic devices due to their unique combination of optical, mechanical and electronic properties. However, the large surface-area-to-volume ratio in these materials results in an extreme sensitivity to the local electronic environment, such as the presence of interface charge traps. We present here the development of optoelectronic devices by combining passivation techniques with the exploitation and control of naturally occurring and artificially introduced charge traps. Furthermore, using passivated 2D materials we present novel device integration strategies both for room temperature applications and for low temperature characterisation of quantum device arrays.

# Going beyond copper: wafer-scale synthesis of graphene on sapphire

**Camilla Coletti**
**CNI@NEST, Istituto Italiano di Tecnologia, Pisa, Italy**

## Short biography:

Camilla Coletti is a tenure track researcher at the Istituto Italiano di Tecnologia (IIT) where she leads the research line 2D Materials Engineering (https://www.iit.it/research/lines/2d-materials-engineering). She received her MS degree in electrical engineering from the University of Perugia in 2004 and her PhD degree in electrical engineering from the University of South Florida in 2007. She is an expert in the synthesis of highly-crystalline graphene via chemical vapor deposition (CVD) and has an extensive background in the investigation of the electronic, chemical and structural properties of 2D materials. Her research is currently focused on: (i) synthesis and integration of scalable 2D materials for optoelectronics and photonics; (ii) interface engineering of 2D heterostructures. She is actively involved in the Graphene Flagship Programme since 2013 (currently in WP1, WP3, WP10, WP15 and SH4). She is author of more than 90 peer-reviewed publications, authored 4 book chapters, edited 1 book, holds 2 international patents and delivered more than 40 invited talks at international conferences. She is involved in WP1, WP3, WP10, WP15 and SH4.

## Abstract:

The adoption of graphene in electronics, optoelectronics and photonics is hindered by the difficulty in obtaining high quality material on technologically-relevant substrates, over wafer-scale sizes and with metal contamination levels compatible with industrial requirements. To date, the direct growth of graphene on insulating substrates has proved to be challenging, usually requiring metal-catalysts or yielding defective graphene. In this work, we demonstrate a metal-free approach implemented in commercially available reactors to obtain high-quality monolayer graphene on c-plane sapphire substrates via chemical vapour deposition (CVD). Raman spectroscopy and electrical transport measurements reveal high quality graphene with mobilities consistently above 2000 cm2/Vs. We scale up the process to 4-inch and 6-inch wafer sizes and demonstrate that metal contamination levels are within the limits for back-end-of-line (BEOL) integration. The growth process introduced here establishes a method for the synthesis of wafer-scale graphene films on a technologically viable basis.

References:

[1] N. Mishra et al., https://arxiv.org/abs/1907.01610 - Small, in press