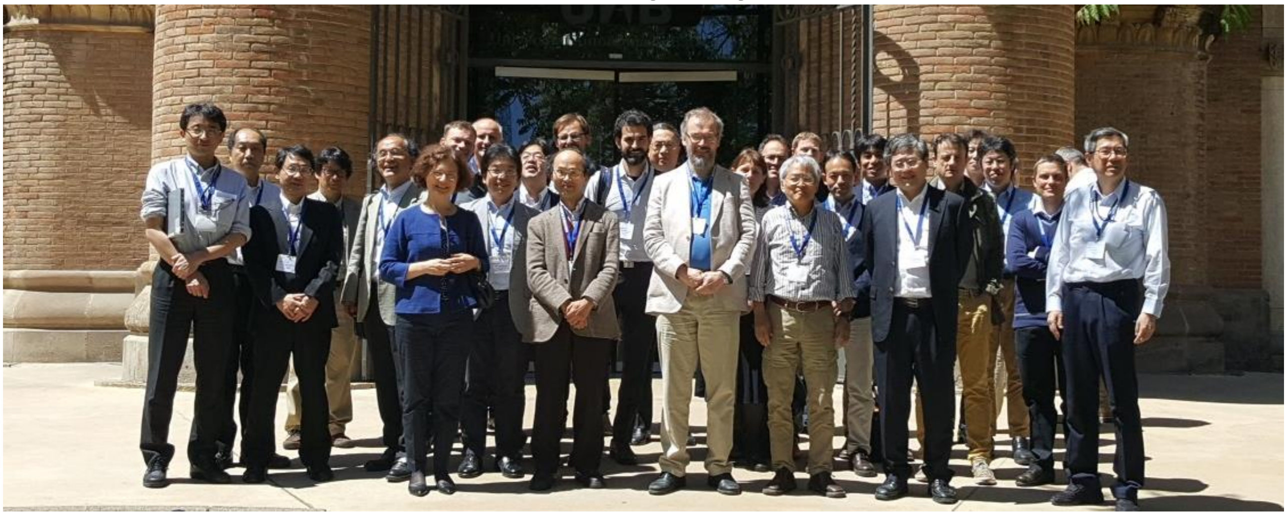
Graphene Flagship EU – Japan Workshop

Graphene and related 2D materials and heterostructures

Casa Convalescència, UAB Campus, Barcelona, Spain

6-8 May 2017

Workshop Report



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Overview

The second Graphene Flagship EU – Japan Workshop was held at the Casa Convalescència, Universitat Autònoma de Barcelona Campus in Barcelona (Spain) during 6-8 May 2017. The workshop provided the opportunity for Japanese and European researchers to discuss and exchange on the progress in the areas of graphene and related two-dimensional (2D) materials (GRM), fundamental physical phenomena and devices. The aim was to facilitate scientific exchanges and identify needs and mechanisms for future collaborations. This was a follow up to the first Japan-EU Workshop held in Tokyo, Japan from 31 October – 2 November, 2015[1].

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

- Prof. Toshiaki Enoki (Japan)
- Prof. Yoshihiro Iwasa (Japan)
- Dr. Seiichiro Kawamura (Japan)
- Prof. Jari Kinaret (Sweden)
- Dr. Atsushi Kurobe (Japan)
- Prof. Alberto Morpurgo (Switzerland)
- Prof. Taiichi Otsuji (Japan)
- Prof. Stephan Roche (Spain)
- Prof. Riichiro Saito (Japan)

The workshop gathered **31 participants** (17 from the Japan and 14 from Europe), coming mainly from academic and research institutions.

European participants included the Graphene Flagship Director, Work Package Leaders and Deputies and senior researchers mostly from Divisions 1 and 3 (WP1 Enabling Research, WP2 Spintronics, WP3 Enabling Materials, WP5 Biomedical Technologies, WP6 Sensors, WP7 Electronic Devices, WP8 Photonics and Optoelectronics, WP9 Flexible Electronics)

Participants from Japan included representatives of selected projects supported by the Japan Science and Technology Agency (JST) though the CREST[2] programme and by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) through the SATL programme[3].

The workshop broadly covered the areas of:

- Graphene and related 2D materials with emphasis on materials synthesis and characterisation with special focus on Boron Nitride (BN) and Transition Metal Dichalcogenides (TMDs)
- Study of fundamental physical properties of graphene/2D related (GRM) materials and heterostructures including 2D superconductivity, topological and transport properties, spin – and valley- tronics
- Terahertz (THz), plasmonic and optoelectronic devices based on GRM including detectors, emitters, modulators and sensors

The programme featured 23 scientific presentations that showcased the breadth of activities and topics covered by the respective research groups in the field of 2D materials synthesis, characterisation, properties and devices, each followed by questions and discussions. The final discussion session addressed future research challenges and opportunities for collaboration. This report summarises the main conclusions of the discussions and the envisaged way forward in terms of collaborations. For more details about the scientific content of the presentations, we refer to the Abstracts section.

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[1] http://iwasa.t.u-tokyo.ac.jp/JP-EU_WS/JP-EU_WS_overview.html
[2] https://www.jst.go.jp/kisoken/crest/en/
[3] http://flex.phys.tohoku.ac.jp/satl/index.html

Common interests and challenges

The discussions following the scientific presentations as well and the wrap-up sessions and the final discussion allowed to identify a number of common scientific challenges that Japanese and European researchers are currently working on or that should be addressed in the future:

Materials

- Improve and diversify the growth techniques of high-quality hexagonal boron nitride (h-BN) as a crucial material for further developing 2D heterostructures and devices. The highest quality materials is developed by NIMS in Japan and many active collaborations and exchanges are already taking place with European research groups. Both thin and thick material is needed, together with its large scale transfer and integration into practical devices.
- Improve the large-scale growth of Transition Metal Dichalcogenides (TMDs) in particular transition metal dichalcogenides family (MoS_2, WSe_2 …)
- Solve issues related to the transfer of 2D materials from one substrate to another including by dry transfer techniques
- Benchmark the level of impurities between different materials providers in particular from commercial providers

Fundamental phenomena

- Superconductivity in atomic and two dimensional semiconductors is a new area where activities are emerging. Progress in the understanding of the underlying theory has been achieved and the next step would be to develop experiments on controlled systems.
- Thermoelectricity in low dimensional materials (1D and 2D)
- Ballistic carrier or heat transport in van der Waals junctions of 2D crystals such as graphene, hexagonal boron nitride (h-BN), and transition-metal dichalcogenides (TMDs)
- Theoretical studies of topological states in TMDs

Devices

- Terahertz detectors, emitters, lasers and modulators based on GRM could provide opportunities for developing “niche” products. Their possible advantage over and/or compatibility with silicon-based technologies have to be established. Graphene can for example enhance gain in THz light emitters and graphene-based modulators have excellent performance exceeding other systems. Future developments in the field may go towards developing THz lasing at 300K with graphene and BN heterostructures.
- Graphene channel Field Effect Transistor (FET) are promising for optoelectronics applications including image sensors and detectors, however the developments of these devices requires significant advances in processing technologies
- Graphene waveguides
- Spin- and valley-tronic devices

Opportunities for collaboration

Projects and activities in Japan

Currently there are several programmes and activities in Japan supporting GRM research and networking:

- The Fullerenes, Nanotubes and Graphene Research Society (FTNG)[4] is chaired by S. Maruyama (University of Tokyo) organisers a number of meetings and conferences
- CREST (2014 – 2020) programme "Development of Atomic or Molecular Two-Dimensional Functional Films and Creation of Fundamental Technologies for Their Applications" coordinated by A. Kurobe (Toshiba) has run a series of three calls (2014, 2015, 2016) resulting in s selection of 11 funded projects out of 186 proposals for a total budget of about 23 million USD[5].
- Graphene Consortium led by M. Hasegawa at the National Institute of Advanced Industrial Science and Technology (AIST) gathers over 100 companies interested in GRM technologies.
- Graphene Oxide Symposium coordinated by T. Matsumoto (Kumamoto University)
- Science of Atomic Layers (SATL) Grant-in-Aid for Scientific Research on Innovative Areas by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) is coordinated by R. Saito (Tohoku University) and is running for the period April 2013 to March 2018[6].

Graphene Flagship related activities in Europe

- Exchange/mobility grant scheme for researchers supported by Graphene Flagship is now in place and offer the possibility for young researchers to visit research groups overseas for extended periods of time. So far one grant has been awarded for a visit to Japan (University of Kyoto)
- Graphene Flagship organises a number of events throughout Europe[7]
- A network of European national research funding organisation FLAG-Era is supporting the Graphene Flagship by launching calls every two years[8]. FLAG-ERA is also interested in developing activities with international partners that would support the Graphene Flagship.

Follow-up activities

Participants discussed how to further develop their activities and continue collaborations during the final discussion session. The two workshops held so far have been appreciated by all participants as they provided the opportunity to exchange in an open way about the most recent developments, discuss and address common challenges. Some recommendation and suggestions for the future are:

- Broaden the scope of the next workshop and include chemistry of 2D materials
- Showcase concrete applications enabled by GRM
- Establish contacts with industries, though for example the Graphene Consortium in Japan, and possibly organise a visit of a Graphene Flagship delegation and introduce it to Japanese companies.

The next Japan-EU workshop is scheduled to take place in Sendai (Japan) in November 2018.

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[4] http://fntg.jp/
[5] https://www.jst.go.jp/kisoken/crest/en/research_area/ongoing/areah26-4.html
[6] http://flex.phys.tohoku.ac.jp/satl/index.html
[7] https://graphene-flagship.eu/interact
[8] https://www.flagera.eu/graphene/

Besides the existing mobility and exchange grants, two funding mechanisms have been identified that could provide additional support for research collaborations between Japan and Europe. These should be further investigated and discussed with the respective funding agencies representatives.

- Core-to-core programme of the Japan Society for the Promotion of Science (JSPS) [9] in particular the Advanced Research Networks provides support for research institutions in Japan to engage in collaborations with researchers abroad in the form of joint research projects, seminars, and researcher exchanges. The counterpart research institutions are expected to obtain project funding from science-promotion agencies or other funding organizations in their respective countries.
- European Interest Group (EIG) CONCERT-Japan [10] is an initiative by the research funding organisations aiming to support and enhance science, technology and innovation (STI) cooperation between European countries and Japan via the implementation of multilateral joint funding.

[9] http://www.jsps.go.jp/english/e-c2c/index.html
[10] http://www.concert-japan.eu/

Program

Saturday May 6 (Materials)

9:00 – 9:30 – Registration and opening (Stephan Roche, Alberto Morpurgo and Jari Kinaret)

SESSION 1 Chairman: Jari Kinaret

9:30 – 10:00 – Takashi Taniguchi (NIMS) *Issues in synthesis high quality hexagonal Boron Nitride single crystals and TMDC crystals by using solution growth process*

10:00 – 10:30 – Annick Loiseau (ONERA, France) *Enabling BN 2D Material*

10:30 – 11:30 –Coffee Break & discussions

SESSION 2 Chairman: Toshiaki Enoki

11:30 – 12:00 – Hiroki Ago (Kyushu Univ.) *Syntheses of high-quality graphene and related 2D materials for enhancing their applications*

12:00 - 12:30 – Mar Garcia Hernandez (CSIC, Spain) *Scalable synthetic methods in the flagship*

12:30 – 13:00 – Christoph Stampfer (RWTH, Aachen, Germany) *High-mobility single- and bi-layer graphene from chemical vapor deposition on reusable copper*

13:00 – 14:30 Lunch

SESSION 3 Chairman: Taiichi Otsuji

14:30 – 15:00 - Frank Koppens (ICFO Spain) *Optolectronics with 2d materials: science and applications*

15:00 – 15:30 - Shuji Hasegawa (Univ. Tokyo) *Atomic-Layer Superconductors*

15:30 – 16:00 - Francesco Mauri (La Sapienza, Italy) *Enhancement of spin-susceptibility, electron-phonon coupling and superconductivity by electron-electron interaction in doped 2D semiconductors*

16:00 – 17:30 – Coffee Break & discussions (**moderated by Chairpersons of the day**)

Sunday May 7 (Physics)

SESSION 5 Chairman: Alberto Morpurgo

9:30 – 10:00 – Yoshihiro Iwasa (Univ. Tokyo) *Superconducting and excitonic transport in noncentrosymmetric 2D materials*

10:00 – 10:30 – Ermin Malic (University of Chalmers, Sweden) *Exciton dynamics in atomically thin 2D materials*

10:30 – 11:30 – Coffee Break & discussions

SESSION 6 Chairman: Frank Koppens

11:30 – 12:00 – Taiichi Otsuji (Tohoku Univ.) *Terahertz light amplification and emission in graphene-based plasmonic heterostructures*

12:00– 12:30 – Alessandro Tredicucci (CNR-Italy) *Graphene and THz; are they really made for each other?*

12:30– 13:00 – Riichiro Saito (Tohoku Univ.) *Thermoelectricity and THz optics of two dimensional materials*

13:00 – 14:30 Lunch

SESSION 7 Chairman: A. Kurobe

14.30-15:00 – Andreas Kis (EPFL,Switzerland) *2D dichalcogenide electronic materials and devices*

15.00-15:30 – Tomoki Machida (Univ. Tokyo) *Quantum transport in van der Waals junctions of graphene and 2D materials*

15.30-16:00 – M. S. Bahramy (RIKEN) *Ubiquitous formation of type-II Dirac fermions and topological surface states in transition-metal dichalcogenides*

SESSION 8
16.00-17:00 – Coffee Break & discussions (**moderated by Chairpersons of the day**)
18:00: Visit Sagrada Familia
20:00: Dinner

Monday May 8 (Devices)
SESSION 5 Chairman: Yoshihiro Iwasa

09:00 – 09:30 – Masashi Shirashi (Kyoto) *Spin-orbitronics using graphene and carbon nanotubes*

09:30 – 10:00 - Sergio Valenzuela (ICN2, Spain) *Spin and Hot-Carrier Transport in Graphene-Based Devices*

10:00 – 11:00 – Coffee Break & discussions

SESSION 6 Chairman: Hideo Aoki

11:00 - 11:30 – Michihisa Yamamoto (Univ. Tokyo) *Graphene-based valleytronics and superconductor electronics*

11:30 – 12:00 – Irina Grigorieva (University of Manchester, UK) *Superconductivity induced by alkali-metal doping: superconducting graphene and phosphorene*

12:00 – 12:30 – Tsutomu Nojima (Tohoku Univ.) *Electrochemical approach to induce high temperature superconductivity in FeSe electric double layer transistors*
12:30 – 14:00 Lunch

SESSION 7 Chairman: Stephan Roche
14:00 – 14:30 – Hideo Aoki (Univ. Tokyo) *Designing topological and superconducting properties for graphene-related materials*

14:30 - 15:00 – Taishi Takenobu (Nagoya Univ.) *Electric Double Layer Functionalization of Large-Area Transition Metal Dichalcogenide Monolayer Films*

15:00 – 15:30 - Paco Guinea (IMDEA, Spain) *Strains and electrons in two dimensional materials*

15:30 – 16:30 – Coffee Break & discussions

SESSION 8
16:30 – 18:00 – Round table **(Scientific summary & Funding opportunities)**
Atsushi Kurobe (2dCREST), Riichiro Saito (Science of Atomic Thin Layers (SATL)) and Jari Kinaret (graphene Flagship international program)

End of workshop

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30. Prof. Sergio Valenzuela, *ICN2, **Spain,*** sov@icn2.cat
31. Prof. Michihisa Yamamoto, *University Tokyo, **Japan,*** yamamoto@ap.t.u-tokyo.ac.jp

Abstracts

List of presentations

Name	Title
Prof. Ago Hiroki	Syntheses of high-quality graphene and related 2D materials for enhancing their applications
Prof. Aoki Hideo	Designing topological and superconducting properties for graphene-related materials
Dr. Bahramy M. S.	Ubiquitous formation of type-II Dirac fermions and topological surface states in transition-metal dichalcogenides
Prof. Grigorieva Irina	Superconductivity induced by alkali-metal doping: superconducting graphene and phosphorene
Dr. Guinea Francisco	Topological quantum computing and Andreev states in two dimensional materials. Novel results
Prof. Hasegawa Shuji	Atomic-Layer Superconductors
Prof. Iwasa Yoshihiro	Superconducting and excitonic transport in noncentrosymmetric 2D materials
Prof. Kis Andreas	2D dichalcogenide electronic materials and devices
Prof. Koppens Frank	Graphene-CMOS integration for optoelectronic applications
Dr. Loiseau Annick	Enabling BN 2D Material
Prof. Machida Tomoki	Quantum transport in van der Waals junctions of graphene and 2D materials
Prof. Malic Ermin	Exciton dynamics in atomically thin 2D materials
Prof. Mauri Francesco	Enhancement of spin-susceptibility, electron-phonon coupling and superconductivity by electron-electron interaction in doped 2D semiconductors
Prof. Nojima Tsutomu	Electrochemical approach to induce high temperature superconductivity in FeSe electric double layer transistors
Prof. Otsuji Taiichi	Terahertz light amplification and emission in graphene-based plasmonic heterostructures
Prof. Saito Riichiro	Thermoelectricity and THz optics of two dimensional materials
Prof. Shiraishi Masashi	Spin-orbitronics using graphene and carbon nanotubes
Prof. Stampfer Christoph	High-mobility single- and bi-layer graphene from chemical vapor deposition on reusable copper
Prof. Takenobu Taishi	Electric Double Layer Functionalization of Large-Area Transition Metal Dichalcogenide Monolayer Films
Dr. Taniguchi Takashi	Issues in synthesis high quality hexagonal Boron Nitride single crystals and TMDC crystals by using solution growth process
Prof. Tredicucci Alessandro	Graphene and THz; are they really made for each other?
Prof. Valenzuela Sergio	Spin and Hot-Carrier Transport in Graphene-Based Devices
Dr. Yamamoto Michihisa	Graphene-based valleytronics and superconductor electronics

Syntheses of high-quality graphene and related 2D materials for enhancing their applications

Prof. Hiroki Ago
Global Innovation Center (GIC), Kyushu University

Short biography:

Hiroki Ago received his PhD from Kyoto University in 1997. He stayed at Cavendish Laboratory, Cambridge University, supported by JSPS during 1997-1999. Then, he worked at National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba as a researcher for four years. In 2003, he moved to Kyushu University as an associate professor of Institute for Materials Chemistry and Engineering. In 2016, he became a full professor of Global Innovation Center (GIC) of Kyushu University in 2016. His current research focuses on exploring science and applications of nanomaterials, particularly graphene and related 2D materials.
He received Iijima Award from the Fullerene-Nanotube Research Society of Japan (2006), Young Scientist Award from the Minister of Education, Culture, Sports, Science and Technology (MEXT), Japan (2008), and Best Paper Award from the Japan Society of Applied Physics (2014).

Abstract:

The recent development of graphene research has opened a new field of atomically thin, two-dimensional (2D) layered materials. For realizing various applications, it is important to establish a production method of high-quality, large-area 2D materials. We have recently developed a new method, heteroepitaxial chemical vapor deposition (CVD), in which crystalline Cu(111) thin film deposited on c-plane sapphire is used as a metal catalyst. In our method, the as-grown monolayer graphene is completely free from multi-layers graphene, and more importantly, the orientation the hexagonal lattice of the monolayer graphene is well controlled by the underlying the Cu(111) film [1-4]. Currently, 4-inch graphene can be grown on a Cu(111)/sapphire substrate.
This method has been developed to the synthesis of bilayer graphene using epitaxial Cu-Ni alloy film [5]. Highly-uniform bilayer graphene with >90% coverage was obtained by controlling the dissolved carbon concentration by the Cu-Ni ratio. Intercalation in this unique material has been recently demonstrated, resulting in low sheet resistance and high optical transmittance [6].
In addition to graphene, other 2D materials, such as transition metal dichalcogenides (TMDCs) and hexagonal boron nitride (h-BN), have attracted increased interest. Here, our progress on the synthesis and device applications of graphene-TMDC heterostructures is also presented [7-9]. Both vertically stacked and in-plane connected heterostructures have been realized. We expect that the syntheses of high-quality graphene and other 2D materials such as h-BN [10] as well as their heterostructures will open a new avenue for realizing large-area, functional electronic and photonic devices.
These works are supported by JSPS KAKENHI grant numbers JP15H03530, JP15K13304, and JP16H0091, and PRESTO-JST (JPMJPR1322-13417571).

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[1] B. Hu et al., Carbon, 50, 57 (2012). [2] Y. Ogawa et al., J. Phys. Chem. Lett., 3, 219 (2012). [3] H. Ago et al., Appl. Phys. Express, 6, 075101 (2013). [4] H. Ago et al., Chem. Mater., 27, 5377 (2015). [5] Y. Takesaki, Chem. Mater., 28, 4583 (2016). [6] [9] H. Kinoshita et al., submitted. [7] H. Ago et al., ACS Appl. Mater. Interfaces, 7, 5265 (2015). [8] R. M. Yunus et al., Phys. Chem. Chem. Phys., 17, 25210 (2015). [9] H. Ago et al., ACS Nano, 10, 3233 (2016). [10] Y. Uchida et al., Phys. Chem. Chem. Phys., 19, 8230 (2017).

Designing topological and superconducting properties for graphene-related materials

Prof. Hideo Aoki
Department of Physics, University of Tokyo, Japan

Short biography:

Hideo Aoki is a theoretical condensed-matter physicist. He was born in 1950 and bred in Tokyo, Japan. After a PhD from department of physics, University of Tokyo in 1978, he became a research associate there, and a visiting scholar in the Cavendish Laboratory, University of Cambridge, UK for 1980-1982. In 1986 he became a faculty member of the department of physics, University of Tokyo, then a full professor in 1998 until he retired in 2016 and became an emeritus professor. So far he has published more than 200 papers in refereed journals, 20 review articles, and coauthored and edited 7 books, primarily on superconductivity, electron correlation, integer and fractional quantum Hall effect, topological and graphene systems, and most recently on non-equilibrium physics and collective modes in superconductors.
Aoki continues research as a guest researcher at Electronics and Photonics Research Institute, Advanced Industrial Science and Technology (AIST), Tsukuba, Japan, as well as at University of Tokyo. Aoki is married and has a daughter who is now working in Germany as a postdoc in molecular biology.

Abstract:

Flat-band ferromagnetism initiated by Lieb in the 1980's has a unique mechanism where the magnetism arises from unusual "Wannier" orbits. In systematically looking for realisation of the flat bands in two dimensions, graphene-related materials provide an ideal arena, where Shima and Aoki[1] have proposed back in the 1990's that some classes of long-period graphene with antidot arrays accommodate flat bands, along with Dirac cones, for a group-theoretical reason. The system, nowadays dubbed carbon nanomesh, is attracting renewed interests. In our most recent proposal, a new kind of nanomesh, i.e. 2D metal-organic framework (MOF), is designed [2]. There, a kagome MOF comprising radical molecules has a virtue that flat bands arise, without doping, right at the Fermi energy, which is required for the ferromagnetism. A spin-density functional confirms the ferromagnetism residing on the light elements. If we consider the spin-orbit interaction from metallic atoms, the flat band is shown to become topological. Thus we end up with an organic ferromagnetic topological system, indicative of an avenue for designing.
We can also design superconductivity for flat-band systems, where a simplest model is a quasi-1D diamond chain. Density matrix renormalisation group is used to detect a long-tailed pairing correlation for the Hubbard model on the diamond chain when the Fermi energy is close to, but away from, the flat band, where the superconductivity does not involve the usual Fermi surface nesting but comes from virtual pair scattering to highly entangled flat-band states.[3] Intriguingly, the superconducting phase sits adjacent to a topological phase. Extension of such superconductivity to 2D frameworks like Lieb lattice will be interesting. The work on the MOF is a Tokyo-MIT collaboration, while the work on the diamond chain is a collaboration with Japan Atomic Energy Agency.
[1] N. Shima and H. Aoki, Phys. Rev. Lett. 71, 4389 (1993).
[2] M. G. Yamada, T. Soejima, N. Tsuji, D. Hirai, M. Dinca and H. Aoki, Phys. Rev. B 94, 081102(R) (2016).
[3] K. Kobayashi, M. Okumura, S. Yamada, M. Machida and H. Aoki, Phys. Rev. B 94, 214501 (2016).

Ubiquitous formation of type-II Dirac fermions and topological surface states in transition-metal dichalcogenides

Dr. Mohammad Saeed Bahramy
Quantum-Phase Electronics Center and Department of Applied Physics, University of Tokyo, Japan

Short biography:

Mohammad Saeed Bahramy received his PhD from the department of materials science and engineering at Tohoku University in 2007. He then became a JSPS post-doctoral researcher at Tohoku University (until 2010) and later a special postdoctoral researcher at RIKEN (until 2013). He was appointed as a lecturer at the University of Tokyo's department of applied physics in 2013. Concurrently, he is also serving as a unit leader at the RIKEN center for emergent matter science. His research interests include the first-principles study of topological quantum phenomena, two-dimensional electron gas systems, low dimensional thermoelectric systems, strongly correlated electron systems, and superconductivity.

Abstract:

Transition---metal dichalcogenides (TMDs) have attracted a great deal of attention in the recent years due to their unique properties. They range from metals and superconductors to strongly spin---orbit---coupled semiconductors and charge--- density---wave systems, with their single---layer variants one of the most prominent current examples of two---dimensional materials beyond graphene. Their varied ground states largely depend on the transition metal d---electron--- derived electronic states, on which the vast majority of attention has been concentrated to date. Here, we focus on the chalcogen---derived states. From density---functional theory calculations together with spin--- and angle--- resolved photoemission, we find that these generically host type---II three---dimensional bulk Dirac fermions as well as ladders of topological surface states and surface resonances. We demonstrate how these naturally arise within a single p---orbital manifold as a general consequence of a trigonal crystal field, and as such can be expected across a large number of compounds. We demonstrate their existence in six separate TMDs, opening routes to tune, and ultimately exploit, their topological physics.

Superconductivity induced by alkali-metal doping: superconducting graphene and phosphorene

Prof. Irina Grigorieva
University of Manchester, United Kingdom

Short biography:

Irina Grigorieva is Professor of Physics at the School of Physics and Astronomy, University of Manchester, UK. She received her PhD in 1989 from the Institute of Solid State Physics, Russian Academy of Sciences and subsequently worked in leading physics laboratories in the UK (University of Bristol), Netherlands (University of Nijmegen) and Belgium (University of Leuven). She joined the University of Manchester in 2001. Grigorieva is an expert in mesoscopic physics and nanotechnology, having worked in several research fields, including mesoscopic superconductivity, physics, chemistry and technology of two-dimensional (atomically thin) crystals and their heterostructures, as well as mass transport through atomically thin membranes and nanochannels. Her current research is focused on magnetic properties of pristine and functionalized graphene and their applications in spintronics and on superconductivity of two-dimensional and layered materials induced by intercalation. Grigorieva has published 90 papers in refereed journals, including 26 articles in Nature group journals (h-index 37). She was a principal contributor to the famous first papers on graphene.

Abstract:

I will review our recent findings of superconductivity in alkali-metal-coated graphene and phosphorene. Despite graphene's long list of exceptional electronic properties and many theoretical predictions regarding the possibility of superconductivity in graphene, its direct and unambiguous experimental observation has not been achieved. We searched for superconductivity in weakly interacting, metal decorated graphene crystals assembled into so-called graphene laminates, consisting of well separated and electronically decoupled graphene crystallites. We found robust superconductivity in a variety of Ca-doped graphene laminates, with different separations between individual graphene crystals and/or the latter being separated by layers of insulating boron nitride. They become superconducting at temperatures (T_c) between ≈4 and ≈6 K, with T_c's strongly dependent on the confinement of the Ca layer and the induced charge carrier concentration in graphene. We found that Ca is the only dopant that induces superconductivity in graphene above 1.8 K among several dopants used in our experiments, such as potassium, caesium and lithium. By revealing the tunability of the superconducting response through doping and confinement of the metal layer, our work shows that achieving superconductivity in free-standing, metal decorated monolayer graphene is conditional on an optimum confinement of the metal layer and sufficient doping.

In the case of phosphorene, we were able to achieve superconductivity by intercalating different alkali/alkali-earth metals (Li, K, Rb, Cs, Ca) into single crystals of black phosphorus. This made black phosphorus into a superconductor with a critical temperature, $T_c = 3.8 \pm 0.05$ K and other characteristics of the superconducting state (critical magnetic field, anisotropy, flux pinning) independent of the intercalant. We attribute such highly unusual universal superconductivity to intrinsic superconductivity of heavily-doped individual phosphorene layers, while the intercalated layers of metal atoms play mostly a role of charge reservoirs.

Topological quantum computing and Andreev states in two dimensional materials. Novel results.

Dr. Francisco Guinea
IMDEA Nanoscience, Spain

Short biography:

Francisco Guinea received his Ph. D. at the Universidad Autónoma de Madrid. Since then, he has worked at the KITP Santa Barbara, USA, CSIC, Spain, and Imdea, Spain. He has been visiting professor at the University of Michigan, USA, University of California at San Diego, USA, Boston University, USA. He works in theoretical condensed matter physics. His main topics of research are the physics of semiconductors and superconductors, strongly correlated systems, and statistical mechanics and pattern formation. During the last years, his research has focused on models for the novel properties of graphene and other two dimensional materials.

Abstract:

Intensive efforts are being applied to the development of new materials and platforms for topological quantum computing. We review how graphene-superconductor junctions and quasi-two dimensional superconductors can applied to quantum computing. We outline procedures to generate the basic ingredient of a topological qubit, the Majorana fermion, using two dimensional materials.

Superconducting atomic-layer 2D materials

Prof. Shuji Hasegawa
University of Tokyo, Japan

Short biography:

He received his DSc. in Physics (Application Doctor) from The University of Tokyo in 1991 for research on electron holography done at Hitachi Company (1985-1990) under supervision of Dr. Akira Tonomura. In 1991-1994, he was a research associate in a research group of Professor Shozo Ino at the Department of Physics, University of Tokyo. Since 1994, he promoted to be an associate professor and a Principal Investigator conducting his own group of experimental surface physics in the Department. Since 2009 he is a full professor. He is the Department Chair in 2016-2017. He supervised 17 DSc. students and 27 MS students.
His interest has been focused on transport of not only electric charges but also spins at crystal surfaces and 2D materials. He has published about 200 original papers and about 20 review articles and book chapters including three books (in Japanese) of single work.

Abstract:

One or two atomic layers grown on crystal surfaces are recently found to be superconducting: a monolayer of Pb [1,2,3], two atomic layers of In [1,2], Ga [4], and Tl [9], and a monolayer of Tl+Pb alloy [5] on Si(111) surface, a single unit layer of FeSe [6,7] film, Ca-intercalated double-layer graphene [8], and so on. Interesting issues of these 'atomic-layer superconductors' may be multi-fold; (1) Large fluctuation due to two-dimensionality (2D), (2) Influence of substrates, (3) symmetry breaking, (4) Control by external ways.
According to Mermin-Wagner Theorem, 2D lattices do not have phase transitions due to large fluctuation. This means no superconductivity in monatomic layers. But in reality, superconduc-tivity occurs even in monatomic layers, with large fluctuation such as Aslamazov-Larkin- Maki-Thompson corrections due to the amplitude fluctuation, and Berezinskii-Kosterlitz- Thouless (BKT) transitions and a Bose metal phase [9] due to phase fluctuation.
The superconducting transition temperatures T_C of most of the known atomic-layer supercon-ductors are lower than those of the bulk materials, with an exception of a single unit-layer FeSe film which shows T_C higher than 100 K (the bulk T_C is a few K) [6,7]. This example indicates possibility to enhance TC by making materials as thin as monolayer thick on suitable substrates.
Since the material surfaces are in a situation of break-down of space-inversion symmetry, spin degeneracy in electronic states can be lifted (Rashba effect) [5]. Superconductivity at surfaces and monolayers are then novel because singlet- and triplet- Coopers can be mixed (parity-broken superconductivity). Actually, scanning tunnelling spectra taken from the superconducting (Tl+Pb) monolayer is not reproduced by BCS theory. A pseudo-gap is found beyond the upper critical field and at the vortex core.
This work is based on collaboration with the groups of A. A. Saranin, A. V. Zotov in Russia, and Y. Hasegawa at ISSP of Univ. Tokyo.
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Excitonic Hall Effect in 2D materials

Prof. Yoshihiro Iwasa
University of Tokyo and RIKEN, Japan

Short biography:

Professional Preparation
Ph.D., Department of Applied Physics, University of Tokyo, 1986
M.E., Department of Applied Physics, University of Tokyo, 1983
B. E., Department of Applied Physics, University of Tokyo, 1981

Experience & Employment
Team Leader, RIKEN, 2010-present
Professor, Quantum Phase Electronics Center, University of Tokyo, 2010 - present
Professor, Institute for Materials Research, Tohoku University, 2001 - 2009
Associate Professor, Japan Advanced Institute of Science and Technology, 1994 - 2001
Visiting Researcher, AT&T Bell Laboratories, Murray Hill NJ, 1993 - 1994
Lecturer, Department of Applied Physics, University of Tokyo, 1991 - 1994
Research Associate, Department of Applied Physics, University of Tokyo, 1986 – 1991

Honors and Awards
Honda Frontier Prize (2015),
The Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology (2014),
Superconductivity Science and Technology Award (2010),
Yazaki Science Prize (2006),
Japan IBM Science Prize (2004),
Daiwa Adrian Prize (2004),
Materials Science Research Award (2002).

Abstract:

Nanostructured materials with highly crystalline and well-defined structures such as graphene and nanotubes have been an extremely fruitful platform for novel physical properties and functionalities. Transition metal dichalcogenides (TMDs) is one of the members of 2D materials with the peculiar structure that is the honeycomb lattice with broken inversion symmetry. This noncentrosymmetric structure was known to be responsible for wealthy physical properties. including massive Dirac Fermions with band gaps, valleytronics, and the unique 2D superconducting properties1. Another important aspect of this research field is the materials fabrication. Major streams were exfoliations and chemical vapour deposition (CVD), however, growing epitaxial thin films with in-plane orientation in millimeter scale is still challenging. In this presentation, after a brief introduction of the group activity, we will discuss on the latest results on excitonic properties and thin film growths. Topics include (1) Excitonic Hall effect in MoS_2 monolayer. (2) Molecular beam epitaxy (MBE) growth of WSe_2 and its field effect transistor.
Reference [1] Y. Saito, T. Nojima, and Y. Iwasa, Nat. Rev. Mater. 2, 16094 (2016)

2D dichalcogenide electronic materials and devices

Prof. Andreas Kis
EPFL, Switzerland

Short biography:

Andras Kis is currently a Professor in Electrical Engineering at EPFL, Lausanne. He started research on 2D semiconductors in 2008, after joining EPFL and has made fundamental contributions to the study of the electronic properties of atomically thin TMDCs. His pioneering work on MoS_2 transistors was the first demonstration of high-quality device on a 2D semiconductor.

Prior to joining EPFL as faculty, Kis was a postdoctoral researcher at UC Berkeley in the group of Alex Zettl. He received his Ph.D. in physics from EPFL in 2003 and received his MSc in physics from the University of Zagreb, Croatia. His major awards include the Latsis prize in 2004, ERC starting grant in 2009 and ERC consolidator grant in 2015, both awarded for research in the area of electrical properties of 2D transition metal dichalcogenides.

Abstract:

The discovery of graphene marked the start of research in 2D electronic materials which was expanded in new directions with MoS_2 and other layered semiconducting materials. They have a wide range of promising potential applications, including those in digital electronics, optoelectronics and flexible devices. Combining 2D materials in heterostructures can increase their reach even further.

In my talk, I will present our recent efforts in growing 2D semiconducting transition metal dichalcogenides (TMDCs) and heterostructures using a variety of techniques such as CVD and MBE, starting from epitaxial growth of MoS_2 on sapphire with a high degree of control over lattice orientation. Next, I will show our work on atomically thin rhenium disulphide (ReS_2) liquid-electrolyte gated transistors with atypical behaviour at high charge densities related to the peculiar band structure of this material. I will finish by presenting new results on spin/valley transport in semiconducting monolayer TMDC materials.

Graphene-CMOS integration for optoelectronic applications

Prof. Frank Koppens
The Institute of Photonics Sciences (ICFO), Barcelona, Spain

Short biography:

Prof. Frank Koppens obtained his PhD in experimental physics at Delft University, at the Kavli Institute of Nanoscience, The Netherlands. After a postdoctoral fellowship at Harvard University, since August 2010, Koppens is a group leader at the Institute of Photonic Sciences (ICFO). The quantum nano-optoelectronics group of Prof. Koppens focuses on both science and technology of novel two-dimensional materials and quantum materials.

Koppens has received four ERC grants, the Christiaan Hugyensprijs 2012, the Premis Nacional de Reserca, and the IUPAP young scientist prize in optics. Prof. Koppens is leader of the optoelectronics workpackage of the graphene flagship (1B€ project for 10 years). In total, Koppens has published more than 60 refereed papers (H-index 38).Total citation >10.000.

Abstract:

Integrated circuits based on CMOS (complementary metal-oxide semiconductors) are at the heart of the technological revolution of the past 40 years, as these have enabled compact and low cost micro-electronic circuits and imaging systems. However, the diversification of this platform into applications other than microcircuits and visible light cameras has been impeded by the difficulty to combine other semiconductors than silicon with CMOS.

We show for the first time the monolithic integration of a CMOS integrated circuit with graphene as a high-resolution image sensor and operate it as a digital camera. We integrated graphene and the image sensor read-out circuit with a pixel yield of 99.8%. Subsequently the graphene was coated with a layer of colloidal quantum dots to sensitize it to UV, visible and infrared light (300 – 2000 nm) [2, 3]. This demonstration of a graphene-CMOS image sensor is a major leap towards 3d integrated circuits based on 2d materials and Si-CMOS that can perform even more complex tasks than Si-CMOS alone. The natural layer-by-layer stackability of these 2d materials opens a wealth of possibilities for enhancing the functionality of future micro-electronics, sensor arrays, low-power integrated photonics and CMOS imaging systems.

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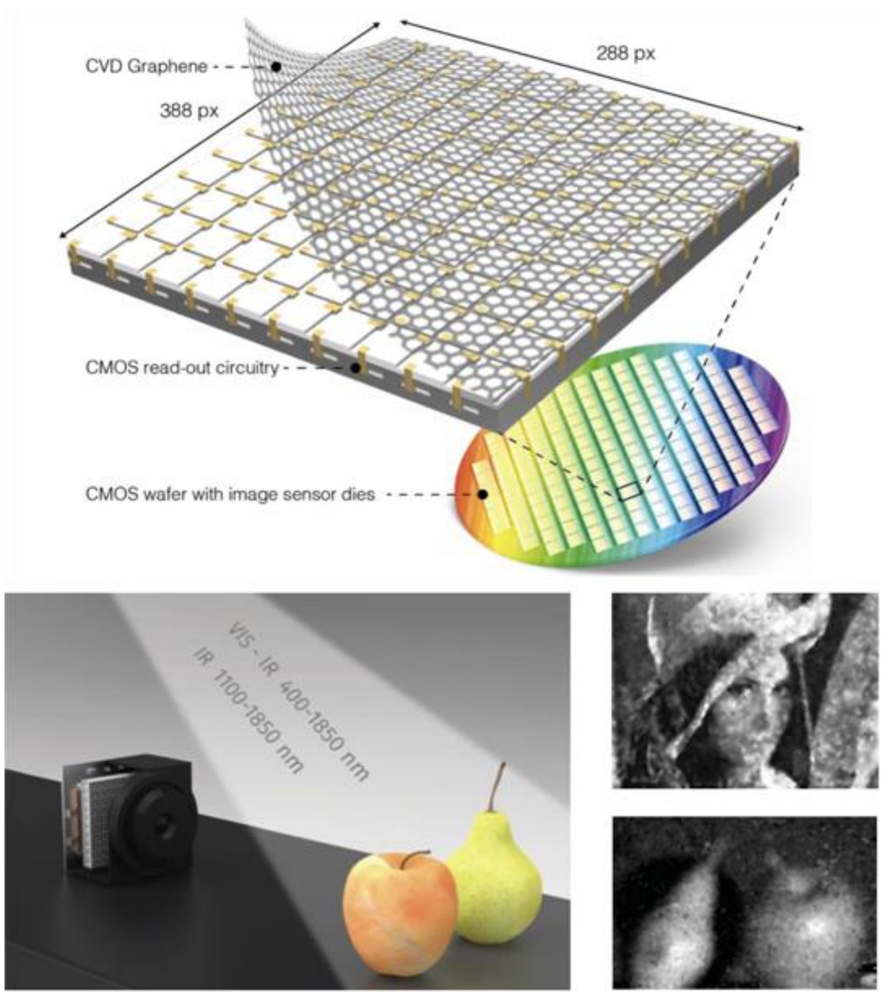
CVD Graphene
388 px
288 px
CMOS read-out circuitry
CMOS wafer with image sensor dies
VIS - IR 400-1850 nm
IR 1100-1850 nm

Enabling BN 2D Material

Dr. Annick Loiseau
Laboratoire d'Etude des Microstructures (LEM), CNRS-ONERA, France

Short biography:

1985; Thèse de Doctorat d'Etat, U. Paris 6
1985; Junior Scientist ONERA
1990; Master of Research ONERA
1996; Director of Research ONERA
1998; Head of the Federative Research Programon carbon nanostructures at Onera
1998 -2008 ; Head of the Research Network (GDR) on nanotubes at CNRS
2009-; Head of the Research Network (GDR GNT) on Science of Graphene and Nanotubes at CNRS

Abstract:

Hexagonal boron nitride is a wide band gap semiconductor (6.4 eV), which can be synthesized, as graphite, its carbon analog, as bulk crystallites, nanotubes and layers. These structures meet a growing interest for deep UV LED and graphene engineering. It is therefore highly desirable to achieve the synthesis of high quality BN layered materials to be used in 2D based devices either as support or as capping layers or as dielectric layers. This talk will first review the Graphene Flasghip effort on this challenging issue. It is also highly desirable to have a better comprehension of the optical and electronic properties of thin BN layers, in correlation with their structural properties and to better know how these properties can interplay those of 2D layers when used in heterostructures. In this talk, we shall review recent advances made thanks to the development of appropriate spectroscopies to the UV range - cathodoluminescence (CL) at 4K, angular resolved Low loss EELS and Raman spectroscopy - combined with ab initio simulations and tight binding modeling. Thanks to these tools, h-BN has been shown to display original optical properties, governed, in the energy range 5.5 – 6 eV, by strong excitonic effects easily trapped at structural or chemical defects [1-2]. We shall discuss the interplay between structure, defects and spectroscopic properties of BN layers and how these properties can be further exploited for the characterization of these nanostructures and for sample benchmarking [2 - 4]. Finally a particular focus will be made to the investigation of the dielectric properties of pristine free-standing layers using angular resolved Electron energy loss spectroscopy (EELS) implemented in Transmission Electron Microscopy (TEM). This technique offers a unique way to investigate dielectric response related to valence band and plasmon excitations with the advantage to get access to their q dispersion and their symmetry properties [5]. In this talk, we shall review the capabilities of this technique implemented in a dedicated TEM machine equipped with a monochromator and in column energy filter and its application to BN and other 2D materials including Black Phosphorus [6-7].

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Quantum transport in van der Waals junctions of graphene and 2D materials

Prof. 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
1998	Ph. D, University of Tokyo

Abstract:

Recent advances in transfer techniques of atomic layers have enabled one to fabricate van der Waals junctions of two-dimensional (2D) crystals such as graphene, hexagonal boron nitride (h-BN), and transition-metal dichalcogenides (TMDs). Here, we present our recent experiments on quantum transport in van der Waals junctions of various 2D crystals. (i) First, we discuss ballistic and coherent carrier transport in graphene npn junctions. In particular, we demonstrate a quantum Hall edge-channel interferometer in a high-quality graphene pn junction under high magnetic field, where the co-propagating quantum Hall edge channels traveling along the pn interface functions as a built-in Aharanov-Bohm-type interferometer. We also demonstrate tunable collimation and reflection of ballistic Dirac fermion in a sawtooth-shaped npn junction. (ii) High-quality Josephson junctions can be built by connecting two exfoliated crystal flakes of a layered 2D superconductor, NbSe2. Current-voltage measurements show characteristic features of Josephson effect. Application of an in-plane magnetic field induces a periodic modulation of the critical current due to the phase shift in supercurrent, Fraunhofer pattern, which can be observed only when a well-defined cavity is formed in the Josephson junction. Further, Andreev reflection at vdW junctions of NbSe2 and graphene will also be discussed. (iii) We study quantum Hall effect and cyclotron resonance absorption in monolayer, bilayer, and twisted bilayer graphene.

Exciton dynamics in atomically thin 2D materials

Prof. Ermin Malic
Department of Physics, Chalmers University of Technology, Gothenburg, Sweden

Short biography:

Ermin Malic works in the field of microscopic modelling of many-particle physics in low-dimensional nanomaterials. He graduated in physics from Technische Universität Berlin, Germany, in 2005. While working on his Ph.D. thesis, he was a visiting researcher at the Massachusetts Institute of Technology (MIT) in Cambridge, USA, and the University of Modena and Reggio Emilia, Italy. During his studies, he was a fellow of the Studienstiftung des deutschen Volkes and the Friedrich-Ebert Stiftung. He received the prestigious Walter-Schottky, Karl-Scheel, and Chorafas Awards for outstanding scientific research. After finishing his habilitation at the TU Berlin including post-doctoral research stays in Barcelona and San Sebastian, in 2015 he became Assistant Professor and in 2016 Associate Professor at the Chalmers University of Technology in Gothenburg, Sweden. Ermin Malic has published 83 original scientific papers including a book on the carrier dynamics and optics in graphene and carbon nanotubes. His group is now focusing on microscopic modelling of ultrafast phenomena and exciton physics in atomically thin 2D materials.

Abstract:

Monolayers of semiconducting transition metal dichalcogenides (TMDs) build a new class of atomically thin two-dimensional materials. They exhibit a remarkably strong Coulomb interaction giving rise to the formation of tightly bound excitons. In addition to optically accessible bright excitonic states, there is also a variety of dark states that turn out to play a crucial role for optics and dynamics in these materials. To model the exciton physics, we apply a microscopic approach combining the Wannier equation with 2D material Bloch equations. In this talk, we review our recent work focusing on microscopic understanding of the optical fingerprint and ultrafast exciton dynamics in monolayer TMDs. In particular, we investigate the microscopic origin of the homogeneous linewidth of excitonic transitions including radiative and non-radiative phonon- assisted relaxation channels [1]. We predict a novel sensor mechanism for molecules based on activation of dark excitons resulting in the appearance of new peaks in optical spectra of TMDs [2]. Finally, we provide a microscopic view on the time- and energy-resolved formation and thermalization of bright and dark excitons as well as their impact on the photoluminescence in 2D materials [3].

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Enhancement of spin-susceptibility, electron-phonon coupling and superconductivity by electron-electron interaction in doped 2D semiconductors

Prof. Francesco Mauri
Università la Sapienza, Italy

Short biography:

Nov. 2015 - , Professore Ordinario, Università di Roma la Sapienza
Oct. 2015 - ..., Fellow of the American Physical Society
Jul. 2012 - Oct. 2015, Directeur de recherche at the CNRS
Sep. 2001 - ..., Member of the "Institut Universitaire de France"
Sep. 1998 - Jun. 2012, Professeur d'Universitè, Universitè Pierre et Marie Curie, Paris Jan.
1997 - Aug. 1998, Maître assistant, IRRMA, Universitè de Geneva
Nov. 1994 - Dec. 1996, Miller Research Fellow, University of California at Berkeley

Abstract:

In two-dimensional multivalley semiconductors, at low doping, even a moderate electron-electron interaction enhances the response to any perturbation inducing a spin or valley polarization. If the valley polarization is due to the electron-phonon coupling, the electron-electron interaction results in an enhancement of the superconducting critical temperature. By performing first-principles calculations beyond density functional theory [1], and/or using range-separeted hybrid functionals [2] we prove that this effect accounts for the unconventional doping dependence of the superconducting transition temperature (Tc) and of the spin susceptibility measured in LixZrNCl. Finally, we discuss what are the conditions for a maximal Tc enhancement in weakly doped two-dimensional semiconductors.

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Electrochemical approach to induce high temperature superconductivity in FeSe electric double layer transistors

Prof. Tsutomu Nojima
Institute for Materials Research, Tohoku University, Japan

Short biography:

Tsutomu Nojima was born in 1963 in Hiroshima, Japan. He received the Ph.D. degree in science from Hiroshima University in 1991. After being Research Associate at Department of Physics, Chiba University (1991-1998), he became Associate Professor at Center for Low Temperature Science, Tohoku University in 1999. Now he is Associate Professor at Institute for Materials Research, Tohoku University. He also was a visiting scientist of Prof. J. Aarts group at Kamerlingh Onnes Laboratory, Leiden University, the Netherlands during 1997-1998.

He has studied the vortex matter physics as well as the superconducting properties in magnetic field in conventional superconductors, cuprates, and MgB_2 and iron pnictides, especially in the thin film form, since he was a Ph. D. student. His recent research interest includes the electric-field-induced superconductivity realized by a technique of electric double layer transistor, which has developed as a growing research field of highly crystalline 2D superconductivity, together with the superconductivity at the interfaces, atomic layers grown by MBE, mechanically exfoliated 2D materials .

Abstract:

The superconductivity in the thin limit or at the interface has been a new trend to explore novel quantum phenomena, which are accelerated by the discovery of high transition temperature (Tc) superconductivity in monolayer FeSe on SrTiO3 with gap closing temperature of 65 K in in-situ spectroscopy and the onset Tc of 40 K in ex-situ transport measurements [1]. It has been proposed that the high-Tc superconductivity originates from the interfacial effects between the film and substrate including electronic band modulation, charge transfer, and electron-phonon coupling. However, it has not been clearly concluded so far what effect plays a central role.

The electric double layer transistor (EDLT), which can accumulate the wide range of conduction carriers around interface between solid and ionic liquid electrostatically, is a good playground for the thin film superconductor researches. On the other hand, we have recently developed another aspect of EDLT, an electrochemical etching induced at higher gate voltages and temperatures beyond the usual electrostatic region, which enable us to tune the film thickness close to one-unit cell using the identical sample [2]. In this talk, we demonstrate our systematic studies on the superconductivity in EDLT of FeSe as a function of thickness, substrate material, and electric field by employing the combination of electrostatic and electrochemical means [3].

The maximum value of the onset Tc reaches 40 K for all the FeSe on various substrates, such as SrTiO3, MgO and KTaO3, with thinning. In addition, we found a universal relationship between the Hall coefficient in normal state and Tc regardless of different film thickness and substrate materials. The finding evidences that the high-Tc superconductivity at around 40 K does not primarily originate from a specific interface combination but from a charge carrier filling at specific electronic band structure. We will also discuss the actual length scales of charge accumulation layers at the Ionic liquid/FeSe and FeSe/substrate interfaces, which can be estimated by the thickness dependence of Tc and RH.

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Terahertz light emission and lasing in graphene-based 2D heterostructures

Prof. Taiichi Otsuji
Tohoku University, Japan

Short biography:

Taiichi Otsuji is a professor at the Research Institute of Electrical Communication (RIEC), Tohoku University, Sendai, Japan. He received the B.S. and M.S. degrees in electronic engineering from Kyushu Institute of Technology, Fukuoka, Japan, in 1982 and 1984, respectively, and the Dr. Eng. degree in electronic engineering from Tokyo Institute of Technology, Tokyo, Japan in 1994. From 1984 to 1999 he worked for NTT Laboratories, Kanagawa, Japan. In 1999 he joined Kyushu Institute of Technology as an associate professor, being a professor in 2002. He joined RIEC, Tohoku University, in 2005. His current research interests include terahertz emission and detection in atomically thin 2D heterostructure material systems and their applications. He is authored and co-authored more than 240 peer-reviewed journal articles. He was awarded the Outstanding Paper Award of the 1997 IEEE GaAs IC Symposium, and has been an IEEE Electron Device Society Distinguished Lecturer since 2013. He is a Fellow of the IEEE, a senior member of the OSA, and a member of the JSAP, MRS, and IEICE.

Abstract:

Graphene has attracted considerable attention due to its massless and gapless energy spectrum. Carrier-injection pumping of graphene can enable negative-dynamic conductivity in the terahertz (THz) range, which may lead to new types of THz lasers [1].

The dual-gate graphene channel transistor (DG-GFET) structure serves carrier population inversion in the lateral p-i-n junctions under complementary dual-gate biased and forward drain biased conditions, promoting spontaneous incoherent THz light emission. A laser cavity structure implemented in the active gain area can transcend the incoherent light emission to the single-mode lasing.

We designed and fabricated the distributed feedback (DFB) DG-GFET [2]. The GFET channel consists of a few layer (non-Bernal) epitaxial graphene [3], providing an intrinsic field-effect mobility exceeding 100,000 cm^2/Vs [4]. The teeth-brash-shaped DG forms the DFB cavity having the fundamental mode at 4.96 THz. The modal gain and the Q factor at 4.96 THz were simulated to be ~5 cm^{-1} and ~240, respectively [2]. THz emission from the sample was measured using a Fourier-transform spectrometer with a 4.2K-cooled Si bolometer. Broadband rather intense (~10~100 μW) amplified spontaneous emission from 1 to 7.6 THz and weak (~0.1~1μW) single-mode lasing at 5.2 THz [2] were observed at 100K in different samples.

When the substrate-thickness dependent THz photon field distribution could not meet the maximal available gain-overlapping condition, the DFB cavity cannot work properly, resulting in broadband LED-like incoherent emission. To increase the operating temperature and lasing radiation intensity, further enhancement of the THz gain and the cavity Q factor are mandatory. Plasmonic metasurface structures promoting the superradiance and/or instabilities [5] as well as double-graphene-layered van der Waals heterostructures promoting photon/plasmon-assisted resonant tunnelling [6] are promising for giant THz gain enhancement.

This work was financially supported by JSPS-KAKENHI No. 16H06361 and No. 16K24374, Japan.

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Thermoelectricity and THz optics of two dimensional materials

Prof. Riichiro Saito
Deptartment 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) and Toho University (2015.4-2016.3).

His main field of research is "Physical Properties of Carbon Nanotubes". The same title of book was published from Imperial College Press (1998) (CI = 8,579) with Prof. Gene Dresselhaus and Prof. Mildred S. Dresselhaus. He got 13th Japan IBM prize (Physics, 1999), Hsun Lee research Award (2006), The Japan Carbon Award for Innovation Research (2008). Somiya Award, International Union of Materials Research Societies (2009). He is a project eader of Science of Atomic Layer (SATL), JSPS KAKENHI GrantNumber JP25107001 and JP15K21722, Japan since 2013-2018.

He has published 297 original papers with total citation is 26,604 (average citation per article = 91.11, h-index=73). Google scholar scitation index is 46,660. His ReseacherID web page is as follows http://www.researcherid.com/rid/B-1132-2008.

Abstract:

In this talk, we would like to present two topics on two dimensional materials; thermoelectricity and absorption of THz electro-magnetic wave.

Thermoelectricity is defined by generation of electric power by heat in the circuit that contains high and low temperature electrodes. Because of the different energy distributions of electrons or holes at the two electrodes, the electric voltage appears between the two electrodes. This phenomenon is known as the Seebeck effect. In order to get a high efficiency of the electric power for a given heat, low dimensional materials has been preferentially adopted because of so-called "confinement enhancement effect" on the Seebeck coefficient in the low dimensional materials, which was predicted by Hicks and Dresselhaus (HD) in 1993. Since 1993, significant increases of thermoelectric properties have been reported according to the HD theory. However, even though they fabricated nano-structures for thermoelectric power devices, the efficiency of thermoelectricity does not always increases for some materials. In the last year, we have solved this problem in which we found that so called "thermal de Broglie length" is an important length for discussing the confinement effect of nano-structure in the enhancement of thermoelectricity (Nguyen et al, PRL 117, 036602-1-5, (2016)). This theory can explain a general phenomenon of the enhancement of thermoelectricity.

The second topic is to switch on/off of THz electromagnetic wave (EM) by the gate voltage. When the THz EM is shed to doped graphene, the plasmon is excited which absorbs the EM significantly. We calculated the absorption of the EM as a function of the incident angle to the graphene plane and the Fermi energy. We show that almost 100% absorption of the EM is possible for doped graphene when the Fermi energy is sufficiently large and the angle is larger than the critical angle above which the EM would perfectly reflect in the case of non-doped graphene (M. S. Uktary et al. APEX, 8, 055102 (2015)). This story is further extended to two monolayer graphene (C. B. Reynold et al. J. Phys. D: Appl. Phys., 49, 195306, (2016) and to silicene

(M. S. Ukhtary, Appl. Phys. Lett. 109, 063103 (2016)). Our theoretical prediction is partially reproduced by THz measurement (Y. Harada et al., ACS Photonics 4, 121-126, (2017)).

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Spin injection and ambipolar spin conversion in single-layer graphene

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Short biography:

Masashi Shiraishi was born in Hyogo, Japan in 1968. He obtained B.E. (1991), M.E. (1993), and PhD (2003) degrees from Kyoto University, Japan. He worked in SONY Corporation Research Center as a research scientist from 1993 to 2004, and was an associate professor (2004-2010) and professor (2010-2013) at Graduate School of Engineering Science, Osaka University. Since 2013, he is a professor at Department of Electronic Science and Engineering, Kyoto University. He has been working in solid-state physics, such as semiconductor spintronics, spin-orbitronics and topological insulators physics.

Abstract:

The small spin-orbit interaction of carbon atoms in graphene promises a long spin diffusion length and the potential to create a spin field-effect transistor. However, for this reason, graphene was largely overlooked as a possible spin-charge conversion material. In this presentation, an electric gate tuning of the spin-charge conversion voltage signal in single-layer graphene is reported [1]. Using spin pumping from an yttrium iron garnet ferrimagnetic insulator and ionic liquid top gate, we determined that the inverse spin Hall effect is the dominant spin-charge conversion mechanism in single-layer graphene. From the gate dependence of the electromotive force we showed the dominance of the intrinsic over Rashba spin-orbit interaction, a long-standing question in graphene research. Our study shows a simple spatial inversion symmetry breaking is not sufficient for generating the inverse Rashba-Edelstein effect, which is contrary to a conclusion in the other study [2].

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High-mobility single- and bi-layer graphene from chemical vapor deposition on reusable copper

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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 and is member of the Young Scientist community of the World Economic Forum since 2014.

Abstract:

Over the past years many promising applications of graphene have been demonstrated on individual devices. In order to advance from basic research towards scalable industrial applications, large area high quality graphene is needed. One promising approach to achieve this is chemical vapor deposition (CVD) of graphene on copper. However, so far the charge carrier mobility of CVD grown graphene has been significantly lower than what has been observed in devices fabricated from exfoliated graphene. I will show that the electronic quality of CVD graphene depends critically on the transfer method and we present a novel dry transfer technique for CVD-grown graphene crystals that yields devices encapsulated in hexagonal boron nitride (hBN) with carrier mobilities up to 350,000 cm2/Vs [1,2]. The quality of the devices can also be independently propped by Raman spectroscopy providing insights on the small-scale strain inhomogeneity of graphene [3,4]. In addition to the diffusive transport in such samples, we demonstrate an elastic mean free path exceeding one micrometer at temperatures of up to 200 K using Hall cross devices. By investigating large samples we furthermore conclude that the mean free path can exceed 25 micrometer at 2 K [2]. Thus, in summary we show that the electronic properties of CVD-grown ”synthetic” graphene can in principle match those of ultrahigh-mobility exfoliated ”natural” graphene.

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Electric Double Layer Functionalization of Large-Area Transition Metal Dichalcogenide Monolayer Films

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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:

In this talk, we would like to report on electric double layer functionalization of large-area transition metal dichalcogenide (TMDC) monolayers.
Firstly, we fabricated ion-gel-gated EDLTs (Electric Double Layer Transistors) using large-area transition metal dichalcogenide (TMDC) monolayers, MoS2 and WSe2, grown by chemical vapor deposition method [1-4]. In these devices, the Fermi level of TMDCs can be continuously shifted by applying gate voltage, and we can induce both hole and electron transport in these devices. The hole mobility of WSe2 can be enhanced up to 90 cm2/Vs at high carrier density of 1014 cm-2, whereas the MoS2 showed electron mobility of 60 cm2/Vs. By the combination of p-type WSe2 and n-type MoS2, we fabricated CMOS inverters [5]. In addition, the high density carrier accumulation leads to insulator-to-metal transition even in polycrystalline large-area TMDC monolayers films.
Based on these technique, we also realized pn junction by EDL carrier doping, and performed electroluminescence and photo-detection by diode-like structure, so called EDLED (Electric Double Layer Light-Emitting Device) [6] and EDLPD (Electric Double Layer Photo-Detector) [7]. Moreover, we also investigated the electric field modulation spectroscopy of TMDC monolayers and the clear signature of quantum confined Stark effect was observed.

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Issues in synthesis high quality hexagonal Boron Nitride single crystals and TMDC crystals by using solution growth process

Prof. Takashi Taniguchi
NIMS, Japan

Short biography:

Takashi Taniguchi received his Ph.D. from Tokyo Institute of Technology (TIT) in 1987. He joined the faculty of Engineering at TIT in 1987 as a research associate. He moved to National Institute for Research in Inorganic Materials (NIRIM) in 1989 as a researcher of high pressure group. From 2004, NIRIM was reorganized as National Institute for Materials Science (NIMS). His research subjects involve materials synthesis under high pressure and development of high pressure apparatus for the materials science. One of his major subjects of study is to obtain high purity hexagonal boron nitride and to realize their properties as a wide bandgap materials and also a substrate for 2D materials.

Abstract:

Hexagonal boron nitride (hBN) exhibits superior properties as a substrate of 2D opto-electronic devices such as graphene and TMDCs [1,2]. In order to realize these newly developed potential of hBN crystals further, more precise insight for its quality control is important.

An another issue is to fabricate fine hBN crystals with high quality via conventional route. Although high pressure synthesis process has an advantage to use reactive alkali-base solvent such as Ba-BN, search for the alternative synthesis route without pressure is important for the practical application of hBN. Since hBN is thermodynamically stable at high temperatures and at atmospheric pressure, it should be possible to obtain high-quality hBN crystals at atmospheric pressure by using an appropriate solvent. Ni or Co-base metal base solvents seem useful to obtain high quality hBN crystals, though the yield of the crystals is less than those of high pressure process.

In this paper, recent studies for properties of BN obtained at high pressure and ambient pressure with respect to impurity control will be reported. Particularly the present issue to improve their properties further is to eliminate residual carbon and oxygen impurities.

On the other hands, liquid phase crystal growth process is applicable for other 2D materials such as graphite, black phosphor (BP) and TMDs such as MoS2,WS2,WSe2,,. In this paper, recent trials of crystal growth for hBN, graphite, BP and TMDs at high pressure will be also introduced.

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Graphene and THz; are they really made for each other?

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Short biography:

Alessandro Tredicucci was born in Chiavari, Italy, in 1968 and is presently Full Professor of Condensed Matter Physics at the Physics Department of Pisa University. His scientific career started more than 20 years ago, first as a Ph.D. student at the Scuola Normale Superiore, then at Bell Laboratories, Lucent Technologies, Murray Hill, and finally back in Pisa at the NEST center of Scuola Normale Superiore and CNR-NANO. His research activities are now mainly concerned with devices for the generation and detection of THz radiation and with the investigation of new regimes of light-matter interaction. The demonstration of a THz quantum cascade laser, the first observation of intersubband polaritons, as well as the development of graphene-based THz detectors are among his best-known achievements. Prof. Tredicucci was the recipient of several awards, among which the S. Panizza award for opto-electronics of the Italian Physical Society, the S. Campisano prize for condensed matter physics of the CNR, the Nick Holonyak Jr. award for semiconductor optics of the OSA (of which he is also a Fellow), and the Occhialini medal of IOP and SIF. He is presently the principal investigator of the advanced grant SouLMan of the ERC.

Abstract:

Graphene, a single-layer of carbon atoms arranged in a two-dimensional honeycomb lattice, is nowadays attracting considerable attention for a variety of photonic applications, including fast photodetectors, transparent electrodes in displays and photovoltaic modules, and saturable absorbers. Owing to its high carrier mobility, gapless spectrum, tunable chemical potential, and frequency-independent absorption coefficient, it has been precognized as a very promising element for the development of detectors and modulators operating in the Terahertz (THz) region of the electromagnetic spectrum, which is still severely lacking in terms of solid-state devices.

In the last few years, progress in the realization of graphene-based THz photonic devices has advanced very rapidly. In this talk I will focus in particular on the realization of THz detectors based on antenna-coupled graphene field-effect transistors (FETs), discuss the various mechanisms involved in their operation, and examine extension to other 2D materials and integration into future THz cameras. I will also address the development and applications of electrically switchable metamaterial devices as well as the prospects for the use of graphene in a new generation of THz sources, either directly as active element, or as waveguide optical component (for instance acting as saturable absorber in laser mode-locking). Finally, schemes to implement coherent control of absorption in graphene and the possible entailing device / diagnostic applications will be analyzed.

Flagship achievements and position of the state-of-the-art of 2D materials with respect to other competing technologies will be illustrated, together with the main open challenges still to be faced.

Spin and Hot-Carrier Transport in Graphene-Based Devices

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Short biography:

Sergio O. Valenzuela is an ICREA Prof. at the Catalan Institute of Nanoscience and Nanotechnology (ICN2), The Barcelona Institute of Science and Technology. He leads the Physics and Engineering of Nanodevices group, which focuses on quantum transport, spintronics, and thermoelectricity in materials such as graphene and topological insulators. He has pioneered the use of nonlocal devices to study the spin Hall effect, thermopiles to isolate the magnon drag in ferromagnetic materials, and implemented novel qubit control and spectroscopy methods. Prof. Valenzuela received a PhD in Physics at the University of Buenos Aires, and held research positions at Harvard University and MIT. He is recipient of the Giambiagi prize, the IUPAP Young Scientist Prize and a ERC Consolidator Grant.

Abstract:

In recent years, graphene-based spintronics have shown impressive progress [1,2,3]. Spin relaxation lengths in graphene have been observed to be larger than several tens of micrometers and are already within the required range for technological applications [3]. This has been accomplished by a steady improvement of the quality of graphene and of the interfaces with contacting materials [1,3]. However, the microscopic mechanisms that determine the spin lifetime, and spin relaxation length, are still under heated debate [1,2]. This lack of understanding hampers graphene spintronics in reaching its full potential, as for applications it is desirable to achieve full control of the spin dynamics. The spin relaxation anisotropy, which can be quantified by the ratio between the spin lifetimes for perpendicular and parallel spin components to the graphene plane, is a key property that can provide information on the microscopic mechanisms that is not accessible by other means [1]. This is so because the anisotropy is determined by the preferential direction of the spin-orbit fields that may cause the spin relaxation. Despite such inherent interest, measurements of the spin lifetime anisotropy are scarce and limited to large carrier densities [5]. Here, we demonstrate a conceptually new approach that overcomes this limitation. The concept relies on spin precession measurements under oblique magnetic fields that generate an out-of-plane spin population, which is further used to evaluate the out-of-plane spin lifetime [6]. Our experiments demonstrate that the spin relaxation anisotropy of graphene on silicon oxide is independent of carrier density and temperature, and much lower than previously reported; indeed, within the experimental uncertainty, the spin relaxation is isotropic. Together with the gate dependence of the spin lifetime, this indicates that the spin relaxation is driven either by magnetic impurities or by randomly oriented spin-orbit fields, relative to the spin. These findings open the way for systematic anisotropy studies with tailored impurities and on different substrates, which are crucial to find a route to manipulate the spin lifetime in graphene and as such has important implications for both fundamental science and technological applications.

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Graphene-based valleytronics and superconductor electronics

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Short biography:

Michihisa Yamamoto was born in Shizuoka prefecture, Japan in 1976. He received his B. Sc. (1999), M. Sc. (2001), and Ph.D. (2004) in physics from the University of Tokyo. He was a research associate (2004-2014) and is now a lecturer in the Department of Applied Physics at the University of Tokyo. His research interests are transport properties in nanostructures, in particular, quantum phenomena and electronic correlation effects in mesoscopic systems.

Abstract:

Two-dimensional layer materials have intriguing intrinsic properties as well as novel properties induced by external influences. These properties allow us to control and connect varieties of quantum degrees of freedom including spin and valley.
In this talk, we first present our experimental works on graphene-based valleytronics. Valley is defined for crystalline materials by the occupation of energetically degenerate but nonequivalent structures in energy bands. Graphene has two valleys at low energy. When the spatial inversion symmetry is broken, an in-plane electric field generates a transverse valley current owing to the valley contrasting intrinsic Hall conductivity. This phenomenon is known as the “valley Hall effect”(D. Xiao, W. Yao, and Q. Niu, Phys. Rev. Lett. 99, 236809 (2007)). We demonstrated electrical generation of detection of the pure valley current using dual-gated bilayer graphene (Y. Shimazaki et al., Nat. Phys. 11, 1032 (2015)).
We then present our experiments on graphene-based gate-tunable superconductor devices. In graphene-based Josephson junctions, systematic analysis of the critical current reveals theoretically expected critical current scaling and the effects of the graphene-superconductor interface (C.-T. Ke at al., Nano Lett. 16, 4788 (2016); I. V. Borzenets at al., Phys. Rev. Lett. 117, 237002 (2016)). Furthermore, two electrons of a Cooper pair are scattered into opposite valley and spin in graphene. The spatial splitting of a Cooper pair in graphene therefore generates a non-local spin entangled state. We demonstrated such a graphene-based high efficiency Cooper pair splitter utilizing charging energy of graphene quantum dots (I. V. Borzenets at al., Sci. Rep. 6, 23051 (2016)). We also found in a graphene-based Josephson junction that the supercurrent can flow through a quantum Hall state (F. Amet et al., Science 382, 966 (2016)), as a realization of the perfect Cooper pair splitter.
The presented works are done in collaboration with Y. Shimazaki, I. V. Borzenets, and S. Tarucha at University of Tokyo, K. Watanabe and T. Taniguchi at National Institute for Materials Science, F. Amet, C. T. Ke, A. W. Draelos, Y. Bomze, and G. Finkelstein at Duke University, G. Jones, M. F. Craciun, and S. Russo at Exeter University, and R. S. Deacon at RIKEN, and supported by JSPS KAKENHI Grant Number JP25107003 and Canon Foundation.