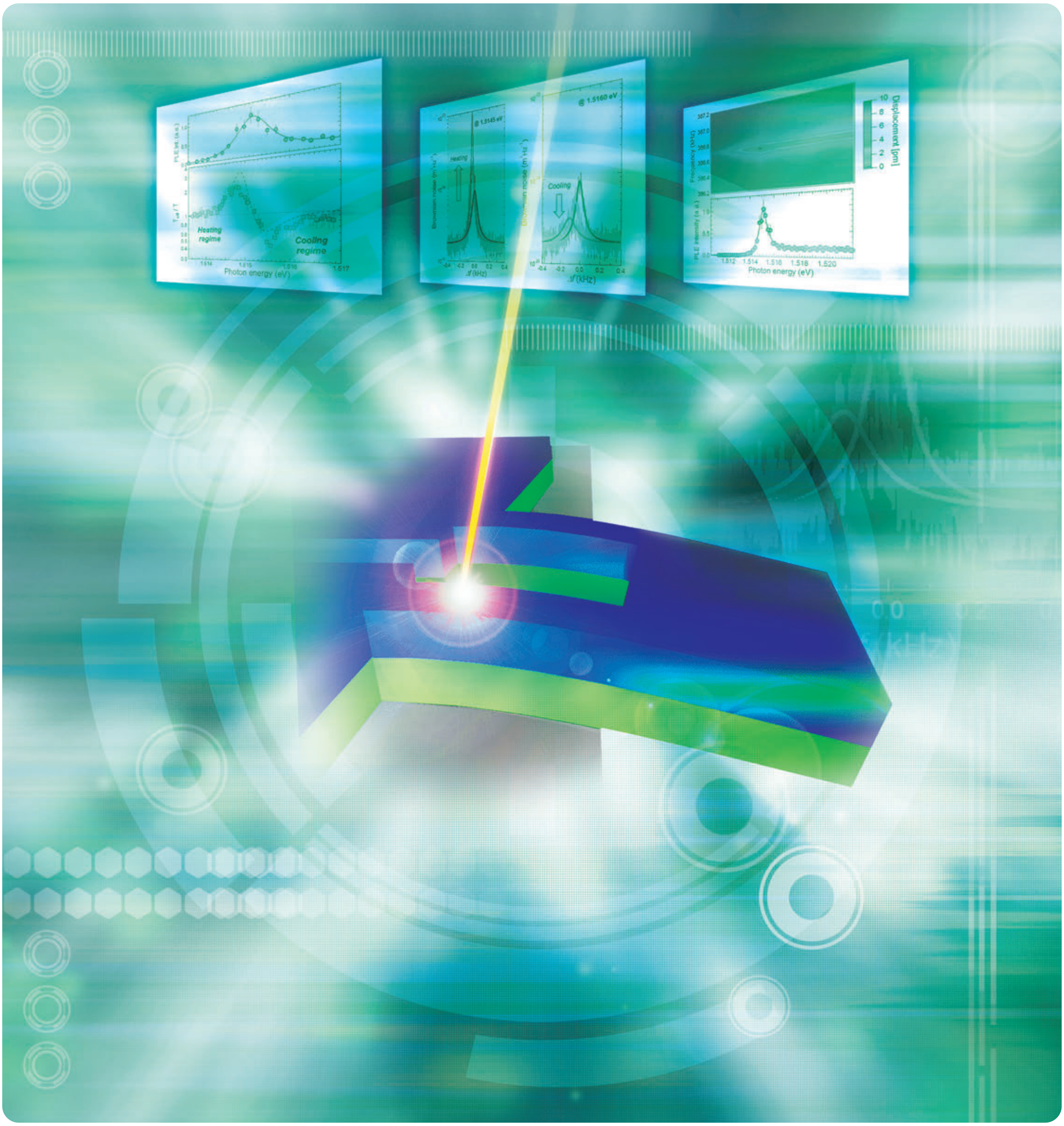
# Research Activities in NTT Basic Research Laboratories

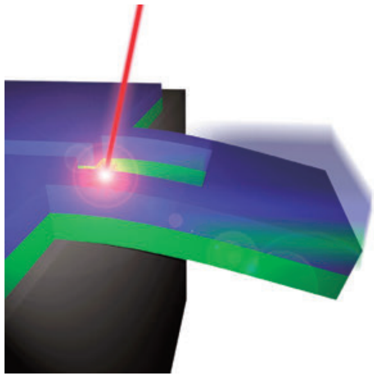
Fiscal 2015

VOL. 26



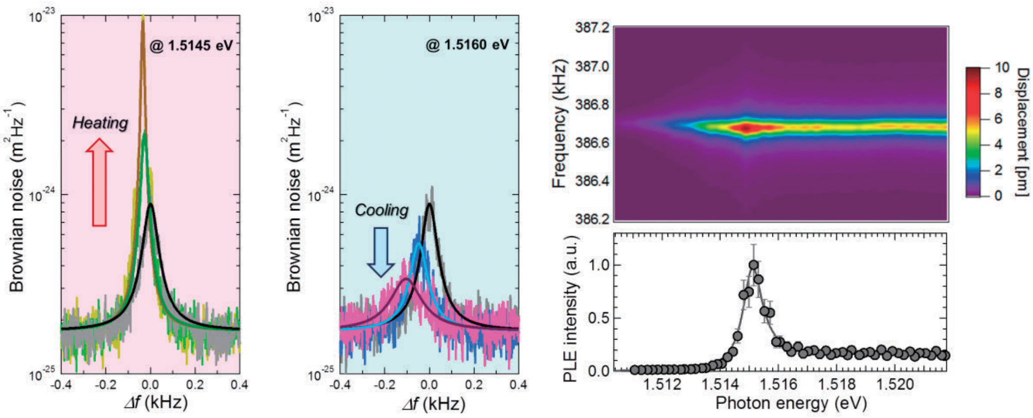

NTT Basic Research Laboratories,
Nippon Telegraph and Telephone Corporation
http://www.brl.ntt.co.jp/

# Cover: Optomechanics Using Excitonic Transitions



Schematic image in the middle of the cover.

Electron-hole pairs are generated by laser irradiation in the AlGaAs/GaAs cantilever. Electrons and holes are spacially separated via the built-in electric field, leading to the piezoelectric compressive stress in the GaAs (the green colored lower layer). This stress causes bending. Thus, the cantilever can be driven via this opto-piezoelectric effect. Because the driving efficiency depends on the degree of optical absorption, high-sensitivity spectroscopy is realized by monitoring the displacement of the cantilever. The optically induced stress acts on the cantilever in a time delay with respect to the optical excitation. Therefore, the continuous laser irradiation results in a feedback effect on the mechanical oscillation. This enables us to reduce the thermal noise in the cantilever as well as to amplify its vibration.




Graphs on the cover (top left graphs on the cover are shown on page 34).

Top middle graph: Amplification (left) and de-amplification (right) of the thermal vibration by continuous laser illumination. Detuning the photon energy from the exiciton resonance energy (1.5152 eV) causes a positive or negative feedback effect. Top right graph: Photon-energy dependence of the frequency response under modulated illumination (top) and the photoluminescence excitation (PLE) spectrum (bottom). The driving efficiency is maximized at the exciton resonance energy, where the PLE intensity is the maximum.

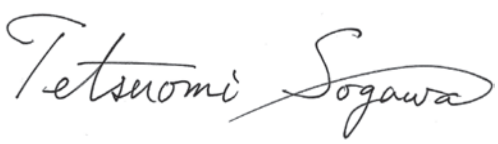
# Message from the Director

We at NTT Basic Research Laboratories (BRL) are extremely grateful for your interest and support with respect to our research activities. BRL's missions are to promote progress in science and innovations in leading-edge technology to advance NTT's business. To achieve these missions, researchers in fields including physics, chemistry, biology, mathematics, electronics, informatics, and medicine, conduct basic research on materials science, physical science and optical science.

Since our management principle is based on an "open door" policy, we are collaborating with many universities and research institutes in Japan, US, Europe, and Asia as well as other NTT laboratories. NTT-BRL regularly organizes international conferences related to quantum physics and nanotechnology at NTT Atsugi R&D Center and also holds a "Science Plaza" to enhance public understanding of our activities and to ensure a frank exchange of opinions. Moreover, one of our missions is the education of young researchers and we sponsor the biennial "BRL School", which boasts distinguished researchers as lecturers. In November 2015, thirty Ph.D. students and young researchers from universities and institutes in 11 countries participated in the BRL School.

These activities enable us to realize our missions with respect to the promotion of advances in science and the development of groundbreaking technology for NTT's business. Your continued support will be greatly appreciated.

July, 2016



Tetsuomi Sogawa
Director
NTT Basic Research Laboratories

# Table of Contents

# Organogram

As of March 31, 2016

**Director**
Tetsuomi Sogawa, Dr.

**Quantum and Nano Device Research**
Senior Distinguished Researcher
Hiroshi Yamaguchi, Dr.

**Biomedical・Exercise Physiology Research**
Senior Distinguished Researcher
Shingo Tsukada, Dr.

**Research Planning Section**
Executive Manager
Hideki Gotoh, Dr.

**Nanophotonics Center**
Project Manager
Masaya Notomi, Dr.

**Materials Science Laboratory**
Executive Manager
Hideki Yamamoto, Dr.

**Physical Science Laboratory**
Executive Manager
Akira Fujiwara, Dr.

**Optical Science Laboratory**
Executive Manager
Hideki Gotoh, Dr.

# Member List

As of March 31, 2016
(*/ left in the middle of the year)

## NTT Basic Research Laboratories

**Director** **Dr. Tetsuomi Sogawa**

### Quantum and Nano Device Research

Senior Distinguished Researcher **Dr. Hiroshi Yamaguchi**

### Biomedical Exercise Physiology Research

Senior Distinguished Researcher **Dr. Shingo Tsukada**

### Research Planning Section

| | |
|---|---|
| Senior Research Scientist, Supervisor | **Dr. Hideki Gotoh** |
| | **Dr. Hideki Yamamoto*** |
| Senior Research Scientist, Supervisor | Dr. Yoshitaka Taniyasu |
| Senior Research Scientist, Supervisor | Dr. Shiro Saito |
| Senior Research Scientist | Dr. Masumi Yamaguchi |

### NTT Research Professor

| | |
|---|---|
| **Prof. Yasuhiro Tokura** | University of Tsukuba |
| **Prof. Hiroki Hibino** | Kwansei Gakuin University |

## Materials Science Laboratory

Executive Manager **Dr. Hideki Yamamoto**
Dr. Yuko Ueno
Dr. Kazuaki Furukawa*

### Thin-Film Materials Research Group

**Dr. Kazuhide Kumakura (Group Leader)**

Dr. Hisashi Sato
Dr. Kota Tateno
Dr. Kazuyuki Hirama
Dr. Junichi Nishinaka
Dr. Tetsuya Akasaka
Dr. Masanobu Hiroki
Dr. Kazuaki Ebata

### Low-Dimensional Nanomaterials Research Group

**Dr. Hideki Yamamoto (Group Leader)**

Dr. Satoru Suzuki
Dr. Ken-ichi Sasaki
Dr. Yoshiharu Krockenberger
Dr. Yoshiaki Sekine
Dr. Shengnan Wang
Dr. Adel Najar*
Dr. Ai Ikeda
Dr. Hiroo Omi
Dr. Koji Onomitsu
Dr. Shin-ichi Karimoto
Dr. Makoto Takamura
Dr. Yui Ogawa
Dr. Manabu Ohtomo

### Molecular and Bio Science Research Group

**Dr. Hiroshi Nakashima (Group Leader)**

Dr. Koji Sumitomo
Dr. Yuko Ueno
Dr. Nahoko Kasai
Dr. Aya Tanaka
Dr. Azusa Oshima
Dr. Shingo Tsukada
Dr. Kazuaki Furukawa
Dr. Yoshiaki Kashimura
Dr. Toichiro Goto
Dr. Tetsuhiko Teshima

## Physical Science Laboratory

Executive Manager **Dr. Akira Fujiwara**
Dr. Takeshi Ota
Dr. Toshiaki Hayashi*
Takeshi Karasawa

### Nanodevices Research Group

**Dr. Akira Fujiwara (Group Leader)**

Toru Yamaguchi
Dr. Katsuhiko Nishiguchi
Dr. Jinichiro Noborisaka
Dr. Kensaku Chida
Dr. Toshiaki Hayashi
Hirotaka Tanaka
Dr. Gento Yamahata
Dr. Nicolas Clement

### Hybrid Nanostructure Physics Research Group

**Dr. Hiroshi Yamaguchi (Group Leader)**

Dr. Imran Mahboob
Dr. Kosuke Kakuyanagi
Dr. Daiki Hatanaka
Dr. Ryuichi Ohta
Dr. Hajime Okamoto
Dr. Yuichiro Matsuzaki
Dr. Hiraku Toida

### Quantum Solid State Physics Research Group

**Dr. Koji Muraki (Group Leader)**

Dr. Kiyoshi Kanisawa
Dr. Hiroyuki Tamura
Dr. Takeshi Ota
Dr. Keiko Takase
Dr. Takafumi Akiho
Dr. Francois Couedo
Dr. Satoshi Sasaki
Dr. Kyoichi Suzuki
Dr. Norio Kumada
Dr. Hiroshi Irie
Dr. Trevor David Rhone*

## Optical Science Laboratory

| | |
|---|---|
| Executive Manager | **Dr. Hideki Gotoh** |
| | Dr. Makoto Yamashita |
| | Kazuhiro Igeta |

### Quantum Optical State Control Research Group

**Dr. Kaoru Shimizu (Group Leader)**

Dr. Hiroki Takesue
Dr. Tetsuya Mukai
Dr. Kensuke Inaba
Dr. Takahiro Inagaki
Dr. Makoto Yamashita
Dr. Fumiaki Morikoshi
Dr. Nobuyuki Matsuda
Dr. Kazuto Noda

### Theoretical Quantum Physics Research Group

**Dr. William John Munro (Group Leader)**

Dr. Kiyoshi Tamaki
Dr. George Knee*
Dr. Stefan Bäuml
Dr. Koji Azuma
Dr. Fabian Furrer

### Quantum Optical Physics Research Group

**Dr. Hideki Gotoh (Group Leader)**

Dr. Takehiko Tawara
Dr. Atsushi Ishizawa
Dr. Haruki Sanada
Dr. Hiroki Mashiko
Dr. Hiromitsu Imai
Dr. Katsuya Oguri
Dr. Guoqiang Zhang
Dr. Keiko Kato
Dr. Kenichi Hitachi
Dr. Yoji Kunihashi

### Photonic Nano-Structure Research Group

**Dr. Masaya Notomi (Group Leader)**

Dr. Akihiko Shinya
Dr. Eiichi Kuramochi
Dr. Hideaki Taniyama
Dr. Masato Takiguchi
Dr. Kenta Takata
Dr. Feng Tian
Dr. Shota Kita
Dr. Atsushi Yokoo
Dr. Hisashi Sumikura
Dr. Kengo Nozaki
Dr. Masaaki Ono
Dr. Devin Smith
Dr. Sylvain Sergent

## Nanophotonics Center

Project Manager **Dr. Masaya Notomi**

### Photonic Nano-Structure Research Group

Dr. Akihiko Shinya
Dr. Eiichi Kuramochi
Dr. Hideaki Taniyama
Dr. Masato Takiguchi
Dr. Kenta Takata
Dr. Takehiko Tawara
Dr. Kota Tateno
Dr. Atsushi Yokoo
Dr. Hisashi Sumikura
Dr. Kengo Nozaki
Dr. Masaaki Ono
Dr. Hiroo Omi
Dr. Nobuyuki Matsuda
Dr. Guoqiang Zhang

### Nanostructured Device Research Group

Dr. Shinji Matuo
Dr. Takaaki Kakitsuka
Dr. Koji Takeda
Dr. Kota Okazaki
Ryo Nakao
Dr. Tai Tsuchizawa
Dr. Koichi Hasebe
Hidetaka Nishi
Tatsurou Hiraki
Takuro Fujii

# Senior Distinguished Researchers

**Masaya NOTOMI** received his B.E., M.E. and Ph.D. degrees in applied physics from The University of Tokyo, Japan in 1986, 1988, and 1997, respectively. He joined NTT Optoelectronics Laboratories, Nippon Telegraph and Telephone Corporation in 1988 and moved to NTT Basic Research Laboratories in 1999. Since then, his research interest has been to control the optical properties of materials and devices by using artificial nanostructures, and engaged in research on quantum wires/dots and photonic crystal structures. In 1996-1997, he was a visiting researcher of Linköping University, Sweden. He was a guest associate professor of Applied Electronics in 2003-2009 and is currently a guest professor of Physics in Tokyo Institute of Technology. He was appointed as Senior Distinguished Scientist of NTT since 2010. He is currently a director of NTT Nanophotonics Center and a group leader of Photonic Nanostructure Research Group.

He received IEEE/LEOS Distinguished Lecturer Award in 2006, Japan Society for the Promotion of Science (JSPS) prize in 2009, Japan Academy Medal in 2009, The Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology (Prize for Science and Technology, Research Category) in 2010, and IEEE Fellow grade in 2013. He served as a member of National University Corporation Evaluation Committee in the Japanese government. He is a research director of JST CREST program from 2015. He is also a member of the Japan Society of Applied Physics, APS, IEEE, and OSA.

**Hiroshi YAMAGUCHI** received his B.E., M.S. in physics and Ph.D. degrees in engineering from Osaka University in 1984, 1986, and 1993, respectively. He joined NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corporation in 1986 and has been engaged in the study of compound semiconductor surfaces using electron diffraction and scanning tunneling microscopy. His current interests are micro/nanomechanical devices using semiconductor heterostructures. He was a visiting research fellow in Imperial College, University of London, U.K. during 1995-1996 and a visiting research staff in Paul Drude Institute, Germany in 2003. He is a guest professor in Tohoku University from 2006 and a director of the Japanese Society of Applied Physics (JSAP) in 2008 and 2009. He served as more than 40 committee members of academic societies and international conferences. He was appointed as Senior Distinguished Scientist of NTT since 2011. He is currently an executive manager of Quantum and Nano Device Research and a group leader of Hybrid Nano-Structure Physics Research Group.

He received the Paper Awards of Japan Society of Applied Physics in 1989, 2004, and 2010, MNC2008 Outstanding Paper Award in 2009, SSDM2009 Paper Award in 2010, Inoue Prize for Science in 2012, and Commendation for Science and Technology by MEXT in 2013. He was made a Fellowship of Institute of Physics (IOP) in 2011 and JSAP in 2013. He is a member of JSAP, the Physical Society of Japan, Institute of Physics (IOP), American Physical Society (APS), and IEEE.

**Koji MURAKI** received his B.S., M.S., and Ph.D. degrees in applied physics from The University of Tokyo, Japan, in 1989, 1991, and 1994, respectively. He joined NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corporation in 1994. Since then, he has been engaged in the growth of high-mobility heterostructures and the study of highly correlated electronic states realized in such structures. He was a guest researcher at Max-Planck Institute, Stuttgart, Germany during 2001-2002. He served as a program committee/chair of international conferences on High Magnetic Fields in Semiconductor Physics (HMF) and Electronic Properties of Two-Dimensional Systems (EP2DS). He was a leader of physics research and epitaxy group of ERATO Nuclear Spin Electronics Project, Japan Science and Technology, during 2008-2015. He was appointed as Distinguished Scientist of NTT in 2009 and Senior Distinguished Scientist of NTT in 2013. He is currently a group leader of Quantum Solid State Physics Research Group. He is a member of the Physical Society of Japan and Japan Society of Applied Physics.

**Shingo TSUKADA** received his M.D. degrees from Toyama Medical and Pharmaceutical University, Japan and his medical license in 1990. He received the Ph.D. degrees in medicine from Tsukuba University, Japan in 2003 respectively. He was a visiting researcher at University of California at San Diego, U.S.A. during 2003-2005. He joined NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corporation in 2010 as a Research Specialist, and from 2013 as a Senior Research Scientist. Since then, he has been engaged in the study of mechanism and activity control of signal transduction of brain cell. His current interests are the detection of biomedical signals using novel wearable-type and implant-type bioelectrodes based on the composites of conductive polymers with various fibers and textiles. He was appointed as Senior Distinguished Scientist of NTT in 2014. He is currently a member of Molecular and Bio Science Research Group. He is a member of Society for Neuroscience, The Physiological Society of Japan, The Japan Society of Applied Physics, the japan Neuroscience Society, the Japanese Circulation Society, and the Japanese Orthopaedic Association.

**Akira FUJIWARA** received his B.S., M.S., and Ph.D. degrees in applied physics from The University of Tokyo, Japan in 1989, 1991, and 1994, respectively. He joined NTT LSI Laboratories, Nippon Telegraph and Telephone Corporation in 1994 and moved to NTT Basic Research Laboratories in 1996. Since 1994, he has been engaged in research on silicon nanostructures and their application to single-electron devices. He was a guest researcher at the National Institute of Standards and Technology (NIST), Gaithersburg, MD, USA during 2003-2004. He was a director of the Japanese Society of Applied Physics in 2010 and 2011 and a visiting professor of Hokkaido University in 2013. He was appointed as Distinguished Scientist of NTT in 2007 and Senior Distinguished Scientist of NTT in 2015. He is currently a senior manager of Physical Science Laboratory and a group leader of Nanodevices Research Group.

He received the SSDM Young Researcher Award in 1998, SSDM Paper Award in 1999, and Japanese Journal of Applied Physics (JJAP) Paper Awards in 2003, 2006, and 2013. He was awarded the Young Scientist Award from the Minister of MEXT (Ministry of Education, Culture, Sports, Science, and Technology) in 2006. He was supported by the funding program for Next Generation World-Leading Researchers (NEXT Program), JSPS in 2011-2014. He is a member of the Japan Society of Applied Physics and a senior member of the IEEE.

# Distinguished Researchers

**Norio KUMADA** received his B.S., M.S., and Ph.D. degrees in physics from Tohoku University, Japan, in 1998, 2000, and 2003, respectively. He joined NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corporation in 2003. Since then, he has been engaged in the study of highly correlated electronic states in semiconductor heterostructures. He was a visiting researcher at CEA Saclay during 2013-2014. He was appointed as Distinguished Scientist of NTT in 2010. He is currently a member of Quantum Solid State Physics Research Group.
He received the Young Scientist Award of the Physical Society of Japan in 2008, and the Young Scientists' Prize from the Minister of Education, Culture, Sports, Science and Technology in 2012. He is a member of the Physical Society of Japan.

**Katsuhiko NISHIGUCHI** received his B.E., M.E., and Ph.D. in electrical engineering from Tokyo Institute of Technology, Japan in 1998, 2000, and 2002, respectively. He joined NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corporation in 2002. Since then, he has been engaged in the research on physics and technology of Si nanometer-scale devices for LSI applications with low power consumption and new functions. He was an invited researcher at the National Center for Scientific Research (CNRS), France during September 2008 and also a guest researcher at Delft University of Technology, Delft, the Netherlands during 2012-2013. He was appointed as Distinguished Scientist of NTT in 2011. He is currently a member of Nanodevices Research Group.
He received IUPAP Young Author Best Paper Award at the International Conference on Physics of Semiconductors 2000, Graduate Student Award Silver at the Materials Research Society 2000 Fall Meeting, Young Scientist Award at the Japan Society of Applied Physics Spring Meeting in 2000, JSAP Outstanding Paper Award 2013, and The Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology of Japan (the Young Scientists' Prize) in 2013. He is a member of the Japan Society of Applied Physics.

**Shiro SAITO** received his B.S., M.S., and Dr. Eng. degrees in applied physics from The University of Tokyo, Japan, in 1995, 1997, and 2000, respectively. He joined NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corporation in 2000. Since then, he has been engaged in quantum information processing using superconducting circuits. He was a guest researcher at Delft University of Technology, Delft, the Netherlands during 2005-2006. He is a guest associate professor in Tokyo University of Science from 2012. He was appointed as Distinguished Scientist of NTT in 2012. He is currently a member of Hybrid Nano-Structure Physics Research Group.

He received the Young Scientist Presentation Award at the Japan Society of Applied Physics (JSAP) Spring Meeting in 2004. He is a member of the Physical Society of Japan and the Japan Society of Applied Physics.

**Hiroki TAKESUE** received his B.E., M.E., and Ph.D. degrees in engineering science from Osaka University, Japan, in 1994, 1996, and 2002, respectively. He joined NTT Access Network Systems Laboratories, Nippon Telegraph and Telephone Corporation in 1996 and moved to NTT Basic Research Laboratories in 2003. Since then, he has been engaged in research on quantum communications and novel computation schemes based on nonlinear optics. He was appointed as Distinguished Scientist of NTT in 2013. He is currently a member of Quantum Optical State Control Research Group.

He received several awards including the ITU-T Kaleidoscope Conference 2nd Best Paper Award (2nd place) in 2008 and The Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology of Japan (the Young Scientists' Prize) in 2010. He was a Visiting Scholar at Stanford University, Stanford, CA from 2003 to 2004, and a guest researcher at the National Institute of Standards and Technology (NIST), Boulder, CO in 2014. He is a member of IEEE and the Japan Society of Applied Physics.

**Imran MAHBOOB** received a combined B.Sc. and M.Sc. degree in Theoretical Physics from The University of Sheffield, U.K., in 2001 and Ph.D. degree in Physics studying the electronic properties of nitride semiconductors from The University of Warwick, U.K., in 2004, respectively. He joined NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corporation in 2005 as a Research Associate, from 2008 as a Research Specialist, and from 2012 as a Senior Research Scientist. His current interests are developing electromechanical resonators for digital signal processing applications and to study their non-linear dynamics. He was appointed as Distinguished Scientist of NTT in 2013. He is currently a member of Hybrid Nano-Structure Physics Research Group.

He received the Clarke Prize in Physics from the University of Sheffield in 2001 and the Young Scientist Award at the 2003 Physics of Semiconductors and Interfaces conference. He is a member of the American Physical Society.

**Haruki SANADA** received his B.E., M.E., and Ph.D. degrees in electrical engineering from Tohoku University, Japan, in 2001, 2002, and 2005 respectively. He joined NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corporation in 2005. His research interests are optical and spin properties of low-dimensional semiconductor nanostructures, and their application to solid-state quantum information processing. He is a visiting researcher at Chalmers University of Technology, Sweden in 2015. He was appointed as Distinguished Scientist of NTT in 2014. He is currently a member of Quantum Optical Physics Research Group.

He received the Young Scientist Presentation Award at the Japan Society of Applied Physics (JSAP) Autumn Meeting in 2004, the SSDM Paper Award in 2010, and the RIEC Award from Tohoku University in 2014. He is a member of the Japan Society of Applied Physics.

**Yoshiharu KROCKENBERGER** received his diploma in physics from The University of Technology of Munich, Germany, studying tunneling spectroscopy on superconductors. Working at the Max Planck Institute for Solid State Research in Stuttgart, Germany, on transition metal oxides with strong electron correlations he received his PhD degree from The University of Technology of Darmstadt, Germany in 2006. At the end of 2006 he joined the Correlated Electron Research Center at The Institute for Advanced Industrial Science and Technology in Tsukuba, Japan as a research scientist. In 2008, he moved to RIKEN in Wako, Japan where he was engaged as a research scientist at the Cross-Correlated Materials Research group. He joined NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corporation in 2010. His interests are development of novel superconducting materials and competing order parameters in strongly-correlated electronic systems. He was appointed as Distinguished Scientist of NTT in 2013. He is currently a member of Low-Dimensional Nanomaterials Research Group.

He received the Young Scientist Award for an Excellent Article from Superconductivity Division of Japan Society of Applied Physics in 2012. In 2016, the Society for Non-Traditional Technology awarded his contributions to research in superconductivity. He is a member of American Physical Society, Materials Research Society, and The Japan Society of Applied Physics.

**Kazuhide KUMAKURA** received his B.E., M.E., and Ph.D. degrees in engineering from Hokkaido University, Japan, in 1993, 1995, and 1998, respectively. He joined NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corporation in 1998. His current interests are high-power, high-speed optoelectronic devices using nitride semiconductors. He was a visiting researcher at Paul-Drude-Institute, Germany during 2007-2008. He was appointed as Distinguished Scientist of NTT in 2015. He is currently a group leader of Thin-Film Materials Research Group.

He received the Young Scientist Presentation Award at the Japan Society of Applied Physics Spring Meeting in 2000. He is a member of the Japan Society of Applied Physics.

**William J. MUNRO** received his B.Sc in Chemistry, M.Sc and D.Phil degrees in Physics from the University of Waikato, NZ in 1989, 1991, and 1995 respectively. He was a research fellow at the University of Queensland, Australia from 1997-2000 and then a staff scientist at Hewlett Packard Laboratories in Bristol (2000-2010). He joined NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corporation in 2010 as a research specialist and from 2014 as a Senior Research Scientist. Since then, he has researched several areas of Quantum Physics ranging from foundational issues of quantum theory through to quantum information processing and its practical realization.

He is currently a visiting professor at the National Institute of Informatics in Japan (2006 - 2015), the University of Leeds in the UK (2009 - 2015) and the University of Queensland in Australia (2012 - 2015). He was appointed as Distinguished Scientist of NTT in 2015 and is currently the group leader of the theoretical quantum physics research group.

He was made a fellow of the Institute of Physics (UK) in 2009, the American Physical Society (APS) in 2013 and the Optical Society of America (OSA) in 2014. He is also a member of The International Society for Optical Engineering (SPIE).

# Advisory Board Members

| Name | Affiliation |
|---|---|
| Prof. Gerhard Abstreiter | Walter Schottky Institute,Technische Universität München, Germany |
| Prof. John Clarke | University of California, Berkeley, U.S.A. |
| Prof. Evelyn Hu | Harvard University, U.S.A. |
| Prof. Mats Jonson | University of Gothenburg, Sweden |
| Prof. Sir Peter Knight | Imperial College London, U.K. |
| Prof. Anthony J. Leggett | University of Illinois at Urbana-Champaign, U.S.A. |
| Prof. Allan H. MacDonald | The University of Texas at Austin, U.S.A. |
| Prof. Andreas Offenhäusser | Forschungszentrum Jülich, Germany |
| Prof. Halina Rubinsztein-Dunlop | The University of Queensland, Australia |
| Prof. Klaus von Klitzing | Max Planck Institute for Solid State Research, Germany |

# Overseas Trainees

| Name | Affiliation | Period |
|---|---|---|
| Hadrien Duprez | École Polytechnique de Montréal, Canada | May 2014 - Apr. 2015 |
| Sophia Chan | University of Edinburgh, U.K. | June 2014 - June 2015 |
| Aleksandra Krajewska | University of Edinburgh, U.K. | July 2014 - June 2015 |
| Todt Clemens | Technical University Dresden, Germany | Sep. 2014 - Aug. 2015 |
| Aleix Llenas | Polytechnic University of Catalonia Barcelona Tech, Spain | Sep. 2014 - Aug. 2015 |
| Dorota Kowalczyk | Gdansk University of Technology, Poland | Sep. 2014 - Aug. 2015 |
| Silviu Dinulescu | University Politehnica of Bucharest, Romania | Sep. 2014 - Aug. 2015 |
| Akie Watanabe | The University of British Columbia, Canada | Jan. 2015 - Aug. 2015 |
| Mats Powlowski | Corcodia University, Canada | Jan. 2015 - July 2015 |
| Joo Whan Yoo | McGill University, Canada | May 2015 - Mar. 2016 |
| Ziyan Xu | The University of British Columbia, Canada | May 2015 - Dec. 2015 |
| Andrew David Browning | The University of British Columbia, Canada | May 2015 - |
| Samarth Desai | Padue University, U.S.A. | May 2015 - July 2015 |
| Samuele Grandi | Imperial College London, U.K. | July 2015 - Oct. 2015 |
| Nathaniel Walmsley | University of Bath, U.K. | July 2015 - Dec. 2015 |
| Victoria Hamilton | University of Bath, U.K. | July 2015 - Dec. 2015 |
| Corentin Deprez | ESPCI ParisTech (École supérieure de physique et de chimie industrielles de la ville de Paris), France | July 2015 - Dec. 2015 |

| | | |
|---|---|---|
| Marius Villiers | ESPCI ParisTech (École supérieure de physique et de chimie industrielles de la ville de Paris), France | July 2015 - Dec. 2015 |
| Tom Darras | ESPCI ParisTech (École supérieure de physique et de chimie industrielles de la ville de Paris), France | July 2015 - Dec. 2015 |
| Mathieu Durand | ESPCI ParisTech (École supérieure de physique et de chimie industrielles de la ville de Paris), France | July 2015 - Dec. 2015 |
| Isabel Gonzalvez | University of Edinburgh, U.K. | Sep. 2015 - |
| Monika Theresa Schied | Ulm University, Germany | Sep. 2015 - |
| Veronika Zagar | University of Ljubljana, Slovenia | Sep. 2015 - |
| Carla Maria Palomares Garcia | Carlos III University of Madrid, Spain | Sep. 2015 - |
| Giacomo Mariani | Politecnico di Milano, Italy | Sep. 2015 - |
| Dominika Urszula Gnatek | Jagiellonian University, Poland | Sep. 2015 - |
| Jun Ki Kim | Geogia Institute of Technology, U.S.A. | Sep. 2015 - |
| Javier Cambiasso | Imperial College London, U.K. | Jan. 2016 - |

# Domestic Trainees

| Name | Affiliation | Period |
|---|---|---|
| Masafumi Horio | The University of Tokyo | Apr. 2015 - Mar. 2016 |
| Ahmad Yoshinari | Tokyo University of Science | Apr. 2015 - Mar. 2016 |
| Takuya Ohrai | Tokyo University of Science | Apr. 2015 - Mar. 2016 |
| Toru Tanaka | Waseda University | Apr. 2015 - Mar. 2016 |
| Suguru Endo | Keio University | Apr. 2015 - Mar. 2016 |
| Yamato Ashikawa | Tohoku University | Apr. 2015 - Mar. 2016 |
| Rento Osugi | Tohoku University | Apr. 2015 - Mar. 2016 |
| Takahiro Gotoh | Tokyo Denki University | Apr. 2015 - Mar. 2016 |
| Kazutaka Hara | Tokyo Denki University | Apr. 2015 - Mar. 2016 |
| Yu Shimojo | Tokyo Denki University | Apr. 2015 - Mar. 2016 |
| Yuya Hasegawa | Tokyo Denki University | Apr. 2015 - Mar. 2016 |
| Masato Tsunekawa | Tokyo Institute of Technology | Apr. 2015 - Mar. 2016 |
| Takuya Ikuta | Osaka University | Apr. 2015 - Dec. 2015 |
| Hisashi Chiba | Tokyo Institute of Technology | Apr. 2014 - Mar. 2015 |
| Ryo Sawaishi | Tohoku Institute of Technology | May 2015 - Dec. 2015 |
| Daisuke Yoshizumi | Tokushima University | Aug. 2015 - Sep. 2015 |
| Takahiro Tominaga | Hokkaido University | Aug. 2015 - Sep. 2015 |
| Tatsuya Ogawa | Hirosaki University | Aug. 2015 - Sep. 2015 |
| Naoki Kanazawa | Toyohashi University of Technology | Sep. 2015 - Mar. 2016 |
| Akiyoshi Naka | Nagaoka University of Technology | Oct. 2015 - Feb. 2016 |
| Gento Nakamura | The University of Electro-Communications | Oct. 2015 - Mar. 2016 |
| Junpei Yamaguchi | Hokkaido University | Nov. 2015 - Mar. 2016 |
| Yuki Hamada | The University of Tokyo | Nov. 2015 - Dec. 2015 |
| Shuntaro Ishii | The University of Tokyo | Dec. 2015 - Mar. 2016 |
| Shun Saito | Toyohashi University of Technology | Jan. 2016 - Feb. 2016 |
| Thomas Tiong | Toyohashi University of Technology | Jan. 2016 - Feb. 2016 |
| Xinwei Liu | Tokyo Institute of Technology | Jan. 2016 - Mar. 2016 |

# Ⅰ. Research Topics

# Overview of Research in Laboratories

## Materials Science Laboratory

**Hideki Yamamoto**

The aim of the Materials Science Laboratory is to contribute to progress in materials science and to revolutionize information communication technology by creating novel materials and functions through materials design at the atomic and molecular levels.

The laboratory consists of three research groups investigating a wide range of materials e.g., typical compound semiconductors including GaAs and GaN, two-dimensional materials such as graphene, high-$T_c$ oxide superconductors, and biological molecules. We are conducting innovative materials research based on advanced thin-film growth technologies along with high-precision and high-resolution measurements of structures and properties.

This year, we succeeded in growing high-quality N-polar GaN, metastable *c*-BN, and as-grown superconducting thin films. We also applied controlled strain to graphene, which provides way of realizing "graphene strain engineering". Moreover, we successfully measured mental and physical bio-signals in various use scenarios including medical, rehabilitation, sports, worker safety control and extreme situations by using a functional sensing fabric "hitoe®", which we developed in collaboration with Toray Industries, Inc.

## Physical Science Laboratory

**Akira Fujiwara**

The aim of the Physical Science Laboratory is to develop semiconductor- and superconductor-based devices and/or hybrid-type devices, which will have a revolutionary impact on future ICT society. Utilizing the high-quality crystal growth techniques and nanolithography techniques that we have developed, research groups in our laboratory are exploring novel properties that can lead to nanodevices for ultimate electronics and novel information processing devices based on new degrees of freedom such as single electrons, mechanical oscillations, quantum coherent states, electron correlation, and spins.

This year we succeeded in realizing optomechanical system using excitonic transitions in semiconductor heterostructures and an electron beam splitter at a graphene *p*-*n* junction in the quantum Hall regime. We also demonstrated experimentally the operation of a $MoS_2$/$SiO_2$/Si tunnel diode, thermal-noise suppression by feedback control of single electrons in Si nanotransistors, and gate-controlled semimetal-topological insulator transition in InAs/GaSb heterostructures. We show theoretically that the spin coherence time of an NV center in diamond can be significantly improved by coupling it to a superconducting flux qubit.

## Optical Science Laboratory

**Hideki Gotoh**

The aims of the Optical Science Laboratory are to develop innovative core technologies for optical communications and optical signal processing, and to make fundamental scientific progress.

The groups in our laboratory are working to achieve quantum state control and quantum information processing by using very weak light, to discover intriguing phenomena by using very intense short pulse light, to control optical properties by using photonic crystals and ultrasonic techniques, and to characterize the unique properties of semiconductor nanostructures such as quantum dots and nanowires.

This year, one of our achievements in quantum information processing has been the demonstration of a new scheme for manipulating the color of single phonons, which are the main carriers of information. Moreover, we have proposed an uncrackable quantum cryptography technique for use over double the previous distance and developed a new quantum cryptography scheme that can ensure security without us having to monitor the error rate of a photon transmission. In the spintronics field, we have achieved spin transportation over 100 μm in semiconductor nanostructures, which will be applied to spin functional devices in the near future.

## Nanophotonics Center

**Masaya Notomi**

The Nanophotonics Center (NPC) was established in April 2012, and is now composed of several groups involved in nanophotonics research and based in NTT's Basic Research Laboratories and Device Integration Laboratories. Our aim is to develop a full-fledged large-scale photonic integration technology by which we will be able to densely integrate a large number of nano-scale photonic devices with various functions in a single chip. Furthermore, we are targeting a huge reduction in energy consumption for photonic information processing by taking advantage of nanophotonics technology.

This year, we broke the power consumption record for photonic memories by one order of magnitude by using novel photonic crystal nanocavities, and demonstrated laser oscillation with a semiconductor nanowire on a silicon photonic crystal. In addition, we demonstrated thresholdless laser oscillation by using a special photonic crystal nanocavity, and realized distributed feedback membrane lasers on a silicon substrate with spot-size converters.

# Ion-Irradiation Effect in Ion-beam-assisted MBE Growth of *c*-BN Films

Kazuyuki Hirama, Yoshitaka Taniyasu, Hideki Yamamoto, and Kazuhide Kumakura
Materials Science Laboratory

Cubic boron nitride (*c*-BN) with $sp^3$-bonding has a large bandgap energy of 6.25 eV, which may further expand the potential of nitride-based semiconductor devices. However, conventional growth methods for group-III nitrides, such as MOVPE, have been unsuccessful in the epitaxial growth of *c*-BN films because *c*-BN is a metastable phase in ambient atmosphere and a thermodynamically stable $sp^2$-bonded BN phase is easily formed. Recently, we achieved the epitaxial growth of *c*-BN films by the ion-beam-assisted molecular beam epitaxy (MBE) method, in which boron atoms are supplied by electron-beam evaporation with a simultaneous irradiation of $N_2^+$ and $Ar^+$ [1]. Here we establish the growth phase diagram for *c*-BN thin-film growth and show that the flux intensity ratio of $Ar^+$ to boron ($F_{Ar+}/F_B$) is a key to controlling the crystal structures of BN films.

BN films were grown on diamond(001) substrates by electron-beam evaporation of boron with a simultaneous supply of nitrogen radical ($N^*$) and $Ar^+$. Instead of $N_2^+$, $N^*$ was used a nitrogen source to investigate the proper ion-irradiation condition of $Ar^+$ for *c*-BN growth. The V/III ratio, defined as the flux intensity ratio of $N^*$ to boron ($F_{N*}/F_B$), was set at values > 1. The growth temperature ($T_g$) was 920°C.

Figure 1 shows FT-IR absorption spectra of BN films with and without $Ar^+$ irradiation. Without $Ar^+$ irradiation, absorption peaks attributed to BN $sp^2$-bonding were observed at around 780 and 1380 $cm^{-1}$. On the other hand, with $Ar^+$ irradiation ($F_{Ar+}/F_B$>1), only an FT-IR absorption peak attributed to BN $sp^3$-bonding was observed at around 1070 $cm^{-1}$. Other peaks originating from BN $sp^2$-bonding were not observed. From a cross-sectional TEM image and the selective-area electron diffraction (SAED) pattern, we confirmed that the *c*-BN(001) film was epitaxially grown on the diamond(001) substrate from the initial growth stage (Fig. 2). Accordingly, the $Ar^+$ irradiation is a prerequisite for the selective formation of the $sp^3$-bonded *c*-BN.

Next, we focused on the effect of $F_{Ar+}$ on the structure of BN films. We carried out regrowth of BN films on *c*-BN(001) film templates on diamond substrates; $F_{Ar+}$ and $F_B$ were systematically varied. Figure 3 shows the growth phase diagram plotted as functions of $F_{Ar+}$ and $F_B$. The *c*-BN(001) films are epitaxially grown at $F_{Ar+}/F_B$ larger than 1, while $sp^2$-bonded turbostratic BN (*t*-BN) films are grown at $F_{Ar+}/F_B$ smaller than 1 even on the *c*-BN(001) templates. Thus, $F_{Ar+}/F_B$ larger than 1 is necessary for epitaxial growth of *c*-BN films, in addition to V/III larger than 1 and $T_g$ above 750°C [1].

This work was supported by KAKENHI.

[1] K. Hirama et al., Appl. Phys. Lett. **104**, 092113 (2014).

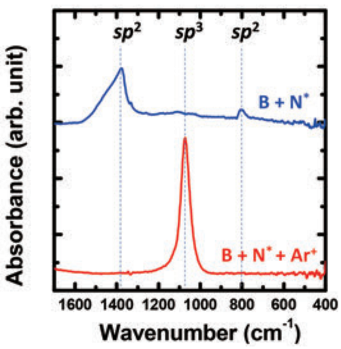



Fig. 1. FT-IR spectra of BN films grown with and without $Ar^+$ irradiation.

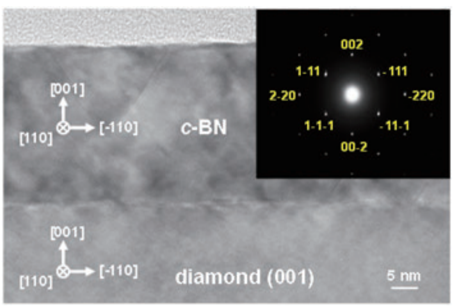



Fig. 2. Cross-sectional TEM image and SAED pattern of epitaxial *c*-BN(001) film.

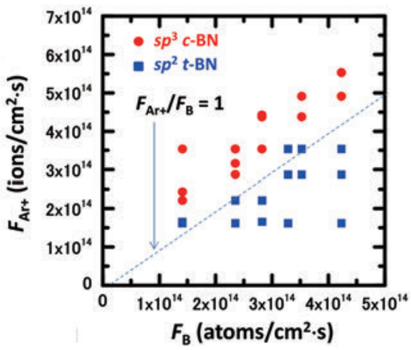



Fig. 3. Growth phase diagram for BN as functions of $F_{Ar+}$ and $F_B$.

# N-Face GaN ($000\bar{1}$) Films with Hillock-free Smooth Surfaces Grown by Group-III-source Flow-rate Modulation Epitaxy

Chia-Hung Lin, Tetsuya Akasaka, and Hideki Yamamoto
Materials Science Laboratory



Low incorporation efficiency of nitrogen atoms has been a problem in the growth of nitride semiconductors, such as InN and InGaN, with the conventional group-III-face (0001) surface. Improvement of the crystal quality is expected by using N-face ($000\bar{1}$) surface, since one can avoid re-evaporation of nitrogen compared with the group-III-face (0001) surface. However, a serious problem in N-face ($000\bar{1}$) nitride films has been a high density of hillocks on the film surface. Here, we report that N-face GaN ($000\bar{1}$) films with hillock-free smooth surfaces can be grown by group-III-source flow-rate modulation epitaxy (FME), wherein the flow-rates of group-III sources are sequentially modulated under a constant supply of $NH_3$ [1].

In the group-III-source FME, NH3 was continuously supplied, while the group-III source (trimethylgallium or triethylgallium) was supplied at a higher (21 μmol/min) or lower (10 μmol/min) flow rate alternately. The durations of the higher and lower flow-rate periods for one cycle were 1 and t s, respectively. The t value was varied from 0 to 10 s. Neither deposition nor etching of GaN occurs during the period of the lower flow rate t. Totally, 900 cycles were repeated, resulting in the total film thickness of approximately 450 nm.

Figure 1 shows optical micrographs of N-face GaN ($000\bar{1}$) films. Hillocks are observed in the samples grown by conventional continuous growth (t = 0). On the other hand, there are no hillocks on the surface prepared by group-III-source FME (t = 10 s). Hillock-free surfaces are achieved over almost the whole sample area ($10 \times 5$ mm$^2$) for t longer than 5 s. As shown in Fig. 2, the hillock density on the surface decreases drastically with increasing t. We have confirmed by cross-sectional transmission electron microscopy that there is a screw-type dislocation or micro-pipe at around the center of a hillock. This indicates that a hillock develops by spiral growth originating from a screw-type dislocation or micro-pipe. The reason for the decrease in hillock density by group-III-source FME is considered to be the enhancement of the surface migration of Ga atoms under low surface supersaturation during the lower Ga supply period t. The spiral growth rate of GaN rapidly decreases with decreasing surface supersaturation, while the step-flow growth rate decreases linearly. Therefore, under low surface supersaturation, the spiral growth rate can be lower than the step-flow growth one so that hillock formation is suppressed.

[1] C. H. Lin, T. Akasaka, and H. Yamamoto, Jpn. J. Appl. Phys. **55**, 04EJ01 (2016).

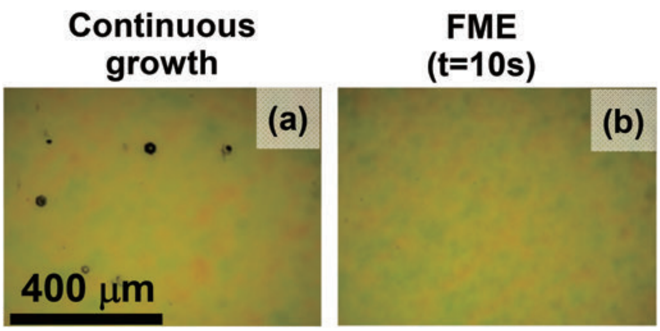



Fig. 1. Optical micrographs of the surfaces of N-face GaN ($000\bar{1}$) films grown by (a) conventional continuous growth (t = 0) and (b) group-III-source FME (t = 10 s).

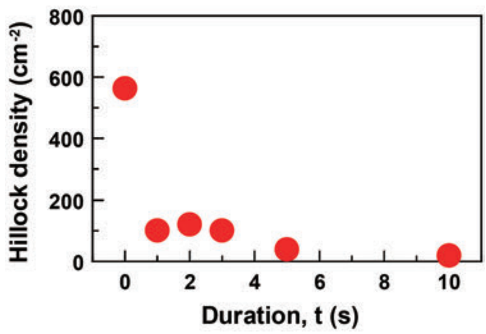



Fig. 2. Hillock density on N-face GaN ($000\bar{1}$) film surfaces plotted as a function of t.

# Determination of Intrinsic Lifetime of Edge Magnetoplasmons

Ken-ichi Sasaki[1], Shuichi Murakami[2], and Yasuhiro Tokura[3,4]
[1]Materials Science Laboratory, [2]Tokyo Institute of Technology, [3]Optical Science Laboratory,
[4]University of Tsukuba

Many types of intriguing phenomena can emerge at the edge of a material that are invisible or hiding in the interior for some reason. Edge magnetoplasmon is such an example; it is a gapless collective excitation that appears at the edge of a two-dimensional electron gas (2DEG) under the application of an external magnetic field [1]. The properties unique to the edge magnetoplasmons, such as the localization length and dispersion relation, were calculated by Volkov and Mikhailov [2]. They succeeded in solving an integral equation of the electric potential using the Wiener-Hopf method. Meanwhile, an internal magnetic field, which is coupled to the potential through Maxwell equations, is neglected, and this simplification prevents the lifetime of the edge magnetoplasmon from being determined and also obscures the magnetic configurations of the excitations. The fact that the localization length and dispersion relation are dependent on the lifetime makes it difficult to analyze experimental results.

In Ref. [3], we determine the intrinsic lifetime of the edge magnetoplasmon. Our analyses are based on two observations. The first is that there is a purely relaxational state with a very long lifetime in the interior of a 2DEG. The second is that the state acquires a non-zero real part of the frequency through localization and starts to propagate. By showing that the properties of the localized state are consistent with those of the edge magnetoplasmons, we identified the purely relaxational state as the bulk counterpart of the edge magnetoplasmons and determined the lifetime of the edge magnetoplasmons (Fig. 1). Our results show that the internal magnetic field normal to the layer is strongly suppressed in the interior, which partly justifies the assumption used in the past and may lead us to a more complete description of the edge magnetoplasmons.

[1] H. Yan, et al., Nano Lett. **12**, 3766 (2012).
[2] V. A. Volkov and S. A. Mikhailov, Sov. Phys. JETP **67**, 1639 (1988).
[3] K. Sasaki, S. Murakami, Y. Tokura, and H. Yamamoto, Phys. Rev. B **93**, 125402 (2016).

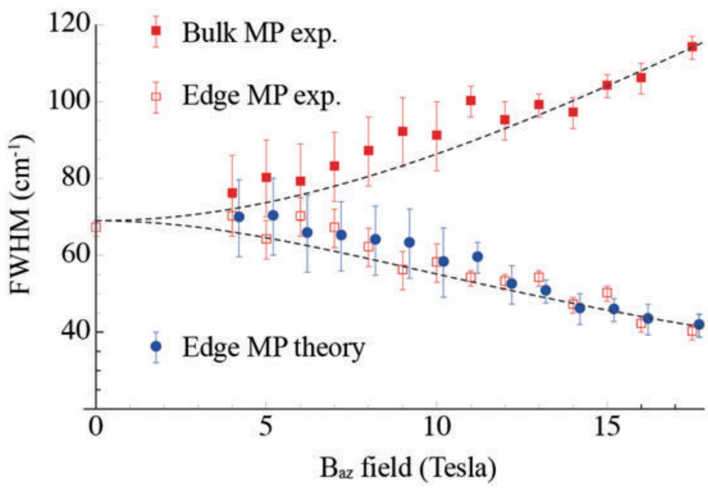



Fig. 1. Our result on the lifetime of edge magnetoplasmons is applied to a recent experiment reported in Ref. [1]. The close agreement between the circle and open square plots supports the validity of our result.

# Applying Strain into Graphene - toward Strain Engineering of Graphene

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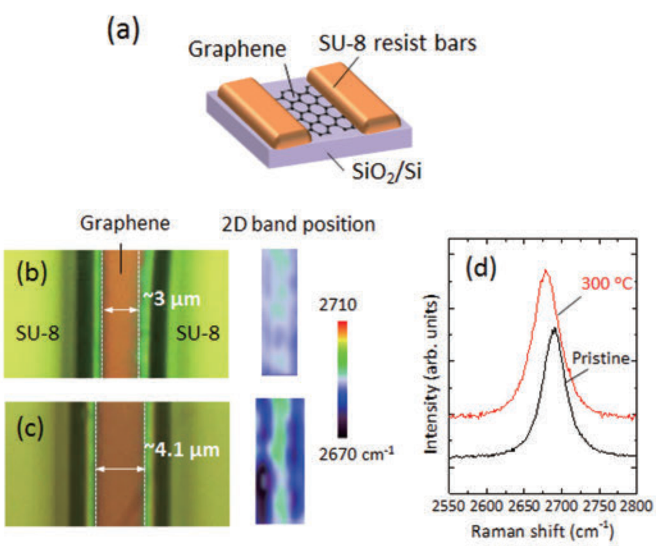
[1]Materials Science Laboratory, [2]Kwansei Gakuin University

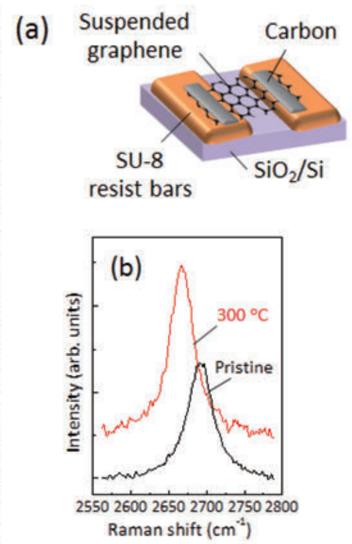
The strain engineering of graphene is expected to make breakthroughs for graphene-based electronics. Graphene's high Young's modulus of 1 TPa and high elastic strain limit of 15% allow us to widely tune its electronic properties. However, applying strain under control is still challenging in experiments.

We thus investigated the strain in graphene induced by thermal shrinkage of SU-8 resist to establish a method for applying a strain with high controllability [1]. The SU-8 resist significantly shrinks ~10-20% when annealed at over 300°C, which is caused by dissociation of oxygen or hydrogen in SU-8. We studied two types of samples: grounded graphene (GG) [Fig. 1(a)], where two resist bars were deposited on graphene that had been transferred onto the substrate, and suspended graphene (SG) [Fig. 2(a)], where graphene was suspended between two bars of resist deposited on the substrate. In both samples, tensile strain is induced in graphene by shrinking the resist, where the resist pulls the graphene.

We first show results for GG samples. When we annealed a GG sample, the gap between the bars expanded [Fig. 1(b), (c)] and 2D peak position shifted to lower frequencies [Fig. 1(d)]. These results indicate that the tensile strain was applied into graphene by shrinking the SU-8. From the 2D peak position maps [Fig. 1(c)], we also found that the applicable area of the shrinkage-induced strain is limited to near the resist (1-2 μm from it), which suggests that designing the resist deposition will allow us to locally control the strain in GG samples. Meanwhile, for SG samples, a larger tensile strain is induced. After annealing an SG sample, the 2D peak largely shifted to lower frequencies [Fig. 2(b)] and the amount of strain was three times larger than that for GG samples. We can conclude that a larger strain was induced because of the lack of adhesion between the graphene and substrate. We found that the configuration of SG will take full advantage of the large shrinkage of SU-8 for inducing a large strain, while GG allow us to induce a local strain. Our findings provide an avenue to the spatial control of graphene's mechanical, and consequently its electronic properties.

[1] M. Takamura et al., Proc. 15th IEEE Int. Conf. on Nanotechnology, Rome, Italy, **33** (2015).




(Left) Fig. 1. (a) A schematic of GG sample. Optical microscopy images and the corresponding Raman 2D peak position maps (b) before and (c) after annealing at 300°C. (d) Raman spectra before and after annealing.
(Right) Fig. 2. (a) A schematic of SG sample. (b) Raman spectra before and after annealing.

# Er-Sc Silicate as an Optical Gain Material in Telecommunications Band

Adel Najar[1], Hiroo Omi[1,3], and Takehiko Tawara[2,3]
[1]Materials Science Laboratory, [2]Optical Science Laboratory, [3]NTT Nanophotonics Center

Photonic interconnects requires the development of new efficient and reliable on-chip optical device elements, including light sources, modulators, amplifiers, buffers, switches, and detectors. The realization of a silicon-based light source is considered to be one of the most challenging tasks. One of the possible solutions for the realization of silicon based light source is to use the emission from Er-silicates. Er silicates ($Er_2SiO_5$ and $Er_2Si_2O_7$) have been attracting considerable attention as Er based materials for small size and high optical gain light source in silicon photonics integration, because they contain a higher Er density of $10^{22}$ $cm^{-3}$ than Er doped Si-based materials. However, such a high concentration of Er results in up-conversion due to closely neighboring Er ions which limits the Er luminescence. Therefore, it is necessary to characterize and control the distance between Er ions in such Er silicates. An effective strategy for reducing this up-conversion is to incorporate yttrium (Y) cations into the structure, where they substitute Er ions in the silicate lattice and prevent neighboring Er ions from causing up-conversion due to the similar ionic radius between Y and Er. Scandium ions ($Sc^{3+}$), on the other hand, are small (ionic radius = 0.75 Å) than erbium ($Er^{3+}$) (ionic radius = 0.881 Å). Generally, this can result in enhancing the crystal field strength for Er doped silicates and oxides. In fact, $Sc^{3+}$ ions in Er doped Sc silicate single crystals would increase the Stark-splitting of the thermally populated erbium ground state as well as that of other electronic energy levels of the silicates and thereby reduce re-absorption losses. In this work, we successfully synthesized a polycrystalline Er-Sc silicate and discilicate compounds in which Er and Sc are homogeneously distributed using RF-sputtering with multilayer $Er_2O_3$, $Sc_2O_3$, and $SiO_2$ deposited on $SiO_2$/Si (100) substrate and thermal annealing at high temperature [Fig. 1(Left)]. Photoluminescence (PL) measurements show the presence of $Er_xSc_{2-x}SiO_5$ with an emission peak at 1528 nm for annealing from 900 to 1100°C, and $Er_xSc_{2-x}Si_2O_7$ with an emission peak at 1537 nm for higher annealing temperature. The PL intensity of the $Er_xSc_{2-x}Si_2O_7$ phase is five times stronger than that of the $Er_xSc_{2-x}SiO_5$ phase at 1250°C. From PL excitation and PL spectra of $Er_xSc_{2-x}Si_2O_7$ thin film [Fig. 1(Middle), (Right)], we determined the energy levels of $Er^{3+}$ ions in the silicates. Temperature-dependent PL of the $Er_xSc_{2-x}Si_2O_7$ phase exhibits a variation of the full-width at half-maximum (FWHM) from 1.1 to 2.3 nm. The narrow FWHM is due to the small ionic radii of $Sc^{3+}$, which enhance the crystal field strength affecting the optical properties of $Er^{3+}$ ions located at the well-defined lattice sites of Sc silicate.

[1] A. Najar, H. Omi, and T. Tawara, Opt. Express **23**, 7021 (2015).

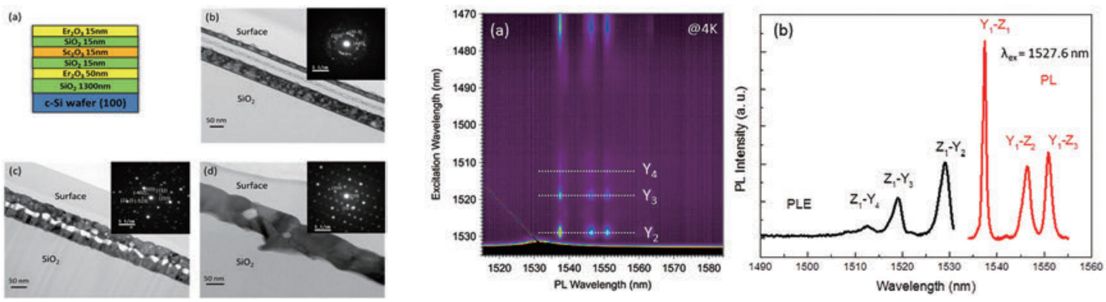



Fig. 1. (Left) Fabricated structures, (Middle) PLE color plot measured at 4 K obtained from the sample annealed at 1250°C. (Right) PLE and PL spectra at 4K.

# As-grown Superconducting $Pr_2CuO_4$ Thin Films

Yoshiharu Krockenberger[1], Masafumi Horio[1,2], Ai Ikeda[1], Hiroshi Irie[3],
Atsushi Fujimori[2], and Hideki Yamamoto[1]
[1]Materials Science Laboratory, [2]The University of Tokyo, [3]Physical Science Laboratory

The synthesis of electron doped cuprate superconductors, i.e. cuprates with square-planar coordinated copper, is entangled to a delicate problem arising from imperfection on the oxygen sub-lattice of the crystal. In particular, superconductivity in electron doped cuprates is known to appear only after an elaborate annealing process. While we have shown earlier that a proper tuning of the annealing process allows the induction of superconductivity even in the undoped cuprate [1], the thought of circumventing the annealing procedure by optimizing the growth conditions is tempting. Using molecular beam epitaxy, we have grown $Pr_2CuO_4$ (PCO) thin films coherently onto (110) $GdScO_3$ substrates (Fig. 1) as a negligible lattice mismatch is to be expected. For coherently grown PCO thin films one may raise the synthesis temperature well beyond the point usually considered to result in disorder of the material. More importantly, it is now possible to further ease the oxidation power during the growth. We systematically varied the growth temperature, the oxidizing potential, and the substrate material in order to elucidate the very best combination possible. The results are circled in Fig. 1. Ultimately, PCO thin films grown at such conditions are superconducting and this is shown in Fig. 2 where we plot the temperature dependency of the resistivity of a PCO thin film coherently grown onto (110) $GdScO_3$. At high temperatures, the PCO is metallic as the resistivity value monotonically decreases and superconductivity sets in at 27 K. In Fig. 2, we also show the resistivity response when a magnetic field is applied perpendicular to the $CuO_2$ planes of PCO [2].

In summary, we have shown that superconducting PCO thin films can be synthesized *in situ* and such a method is important if one needs to avoid surface contaminations as is the case for angle resolved photoemission spectroscopy.

[1] Y. Krockenberger *et al.* , Sci. Rep. **3**, 2235 (2013).
[2] Y. Krockenberger, M. Horio, H. Irie, A. Fujimori, and H. Yamamoto, Appl. Phys. Express **8**, 053101 (2015).

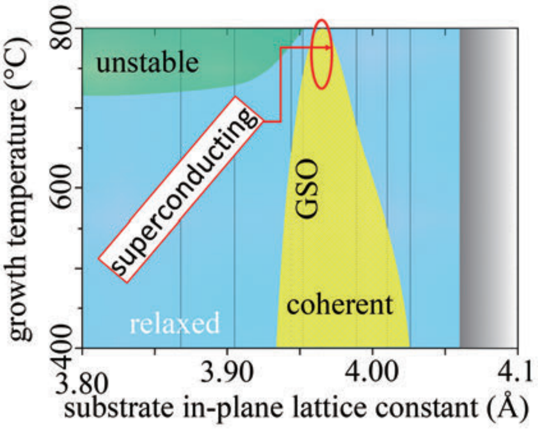



Fig. 1. Synthesis conditions for coherently grown PCO thin films.

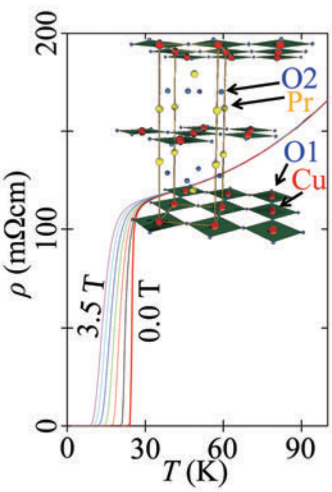



Fig. 2. Resistivity vs temperature of a coherently grown PCO thin film without annealing.

# On-chip FRET Graphene Oxide Aptasensor: Enhanced Sensitivity by Using Aptamer with Double-stranded DNA Spacer

Yuko Ueno and Kazuaki Furukawa
Materials Science Laboratory

Graphene and graphene oxide (GO) behave as efficient acceptors for energy transfer between a graphene/GO surface and molecules located close to it. By combining the energy transfer reaction with a biomolecule reaction, we can visualize an invisible biological response to a measurable physical quantity such as fluorescence.

We have successfully demonstrated a unique type of fluorescence biosensor, namely a graphene/GO aptasensor, for selective and highly sensitive protein detection. We realized this sensor by modifying the graphene/GO surface with a pyrene-aptamer-dye probe that we developed (biomolecular interface). These three components of the probe work as a linker to the GO surface, a protein recognition part, and a fluorescence detection tag, respectively [1]. The system allows us to perform molecular detection on a solid surface, which is a powerful tool for realizing an on-chip sensor, and especially for forming a multichannel configuration and for micropatterning probes [2]. The on-chip sensor allows us to evaluate the sensor response quantitatively by using one of the channels/patterns as an internal standard.

The most attractive feature of aptamers is that they can be flexibly designed without loss of activity. We designed biomolecular probes for highly sensitive protein detection by modifying an aptamer with (i) a single-stranded DNA spacer between the aptamer sequence and the dye [3] and (ii) a double-stranded DNA spacer between the aptamer sequence and the graphene/GO [Fig. 1(Left)] [4]. The spacer controls the distance between the dye and the graphene/GO, which is crucial for the energy transfer reaction (FRET, fluorescence resonance energy transfer). We improved the sensitivity of an on-chip GO aptasensor by using a longer spacer for probes (i) and (ii) [Fig. 1(Right)]. By using the best probe design, we achieved a detection limit of ~1 nM for thrombin, which is in the *in vivo* concentration range during blood clotting [3].

[1] K. Furukawa et al., J. Mater. Chem. B, **1**, 1119 (2013).
[2] Y. Ueno et al., Anal. Chim. Acta, **866**, 1 (2015): Featured on cover.
[3] Y. Ueno et al., Chem. Commun., **49**, 10346 (2013): Featured on cover.
[4] Y. Ueno et al., Anal. Sci., **31**, 875 (2015): Hot Article Award.

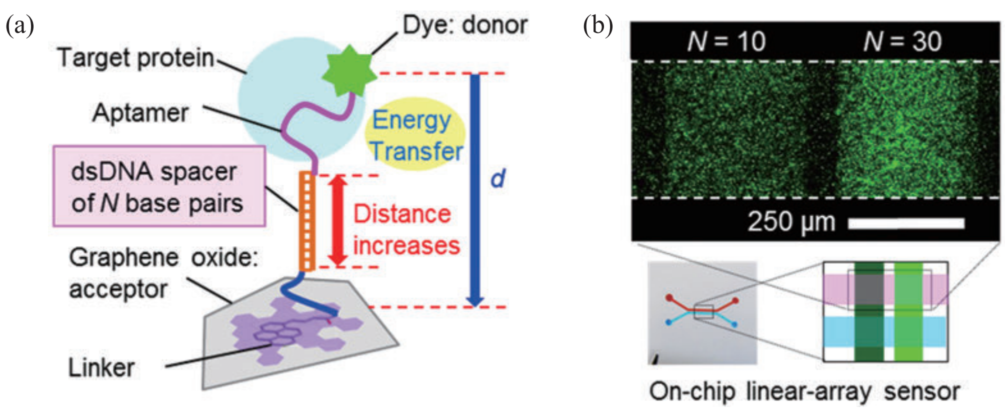



Fig. 1. (a) Molecular design of the probe (ii) for enhancing sensitivity of the aptasensor. (b) Quantitative comparison of enhancement effect depending of the spacer length.

# Time-lapse Imaging of a Single Neuron During the Early Stages of Apoptosis Using Scanning Ion Conductance Microscopy

Aya Tanaka, Koji Sumitomo, and Hiroshi Nakashima
Materials Science Laboratory

It is known that neural morphologies change dynamically during neural network formation. Since the morphological changes are strongly associated with neural functions, it is important to obtain the morphological details of individual neurons. Here, we use scanning ion conductance microscopy (SICM) to describe the series of neural morphological changes that occurs during the early stages of apoptosis, which is well defined as programmed cell death and one of key events in neural network formation [1].

Neurons were prepared from the cortex of a Wistar Rat (18-day embryo) and cultivated on a glass substrate for 8 to 10 days *in vitro*. Apoptosis was induced by adding staurosporine (STS), whose function is to activate caspase-3, to the culture solution during the SICM observation. Images of apoptotic neurons were obtained every 20 min.

The SICM images show the formation of a spherical shape on the cell surface after the neurons had been exposed to STS for 180 min [Fig. 1(a), white arrows]. This morphological change is similar to blebbing, which is the formation of a bulge in a plasma membrane, caused by decoupling from an underlying cytoskeleton. We performed time-course imaging experiments for five different neurons and thus estimated their volume change over time as a ratio of volume to initial volume, $v/v_0$ [Fig. 1(b)]. The graph shows that the neural volume decreases from 80 to 120 min after exposure to STS, which is known as an apoptotic volume decrease. These results indicate that apoptosis induces a reduction in cellular volume and subsequent membrane blebbing.

This is the first report to use SICM to describe the series of morphological changes ranging from an apoptotic volume decrease to membrane blebbing that occurs during the early stages of apoptosis. In future work, we expect to reveal the relationship between the apoptotic morphological changes and biological events using the simultaneous observation of morphology and conventional live cell imaging equipment such as a fluorescence microscope.

[1] A. Tanaka, R. Tanaka, N. Kasai, S. Tsukada, T. Okajima, and K. Sumitomo, J. Struct. Biol. **191**, 32 (2015).

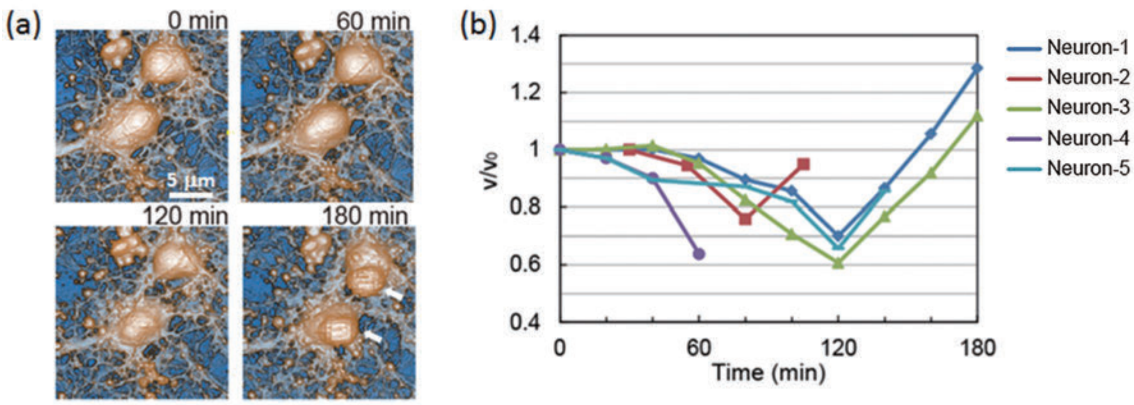



Fig. 1. Morphological changes in apoptotic neurons induced by STS. (a) Time-lapse SICM images of apoptotic neurons induced by STS. White arrows indicate membrane blebs. (b) Time-course graph of volume change of 5 neurons. The vertical axis is the ratio of volume to the initial volume. $v$ is the neuron volume at each time point, and $v_0$ is the volume at 0 min.

# Si and Au Nanopillar Arrays as Scaffolds for Neuronal Growth

Nahoko Kasai and Koji Sumitomo
Materials Science Laboratory

Neuronal *in vitro* cultivation has been widely used with the aim of elucidating neuronal signaling mechanisms and for applications in the neuro-engineering field. Our group has cultivated neurons on various substrates to create interfacial devices for neuronal guidance and thus realize artificial synapses. Neuronal guidance using nano-scale structures has also attracted attention thanks to recent advancements in nanotechnology. In this study, we examined neuronal guidance using nanopillar arrays made of amorphous silicon (a-Si) and gold (Au) as scaffolds for neuronal growth [1].

Nanopillars 100 and 500 nm in diameter were fabricated on quartz substrates using electron-beam lithography, and rat cortical neurons were cultivated on them for 7 days. The samples were then fixed and observed by using scanning electron microscopy and confocal laser scanning microscopy after the treatment.

Neurons cause neurites to lengthen on an a-Si pillar as shown in Fig. 1. The neurites behaved differently in terms of width; they were wider on 500-nm-diameter pillars than on 100-nm-diameter pillars. This implies that the adhesion of neurites to pillars promotes skeletal protein expression, and thus neurite width is dependent on adhesion area size.

Then we examined neurons on different pillar materials as shown in Fig. 2. Neurons grew randomly on Au pillars while they became longer along with the patterns on a-Si pillars [Fig. 2(A)]. A quantitative analysis demonstrated that there was a higher ratio of neurite tips on the a-Si pillars than on the Au pillars [Fig. 2(B)]. This low affinity of neurons for Au corresponds to neuronal cross-sections results obtained using FIB/SEM, which showed less attachment of soma to the Au substrate [2]. These results demonstrate the possibility of neuronal guidance using nanopillars made of appropriate materials.

This work was supported by JSPS/MEXT KAKENHI Grant Number 15H03541.

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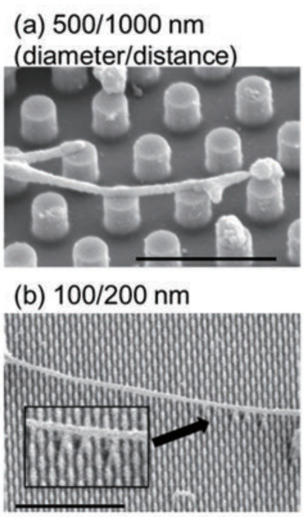


Fig. 1. Neurites grown on different patterned a-Si pillars. Scale: 2 μm.

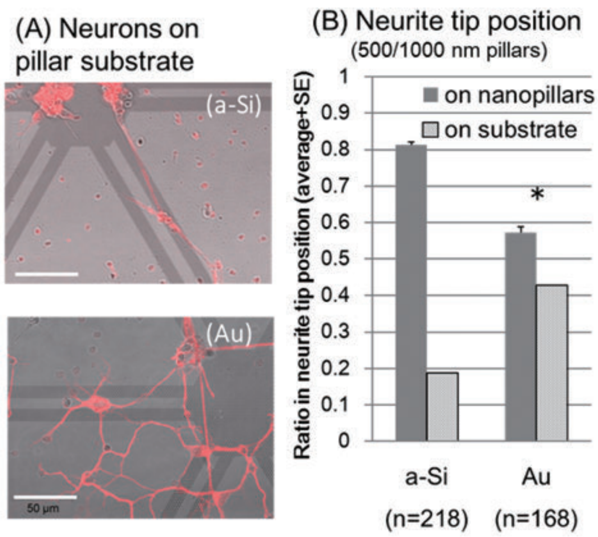


Fig. 2. Neurons grown on a-Si or Au pillar substrate (A) and neurite tip position on different pillar materials (B). Scale: 50 μm.

# Observing Semiconducting Band-gap Alignment in $MoS_2$ Layers Using a $MoS_2/SiO_2/Si$ Heterojunction Tunnel Diode

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The performance of Si transistors, the main fundamental devices in logic circuits, increases with miniaturization. When their size reaches from a few to ten nanometers, they gain new functionalities, such as single-electron manipulation [1], high-sensitivity charge detection [2], and photo emission [3]. However, even as miniaturization proceeds, it is essentially impossible to change the fundamental characteristics of Si material. On the other hand, graphene and other two-dimensional layered materials have been actively studied due to their remarkable characteristics, such as high carrier mobility and transparency. However, such materials still face technological difficulties for their applications. Therefore, we have been studying new devices that integrate Si and two-dimensional layered material in order to combine their remarkable characteristics. In this work, we demonstrate a tunnel diode composed of Si and $MoS_2$ [4].

The tunnel diode is based on a Si transistor, except that its gate terminal is replaced with multiple-layer $MoS_2$ film as shown in Fig. 1. This $MoS_2$ film is formed on the Si channel by means of an exfoliation method using a bulk $MoS_2$. The Si channel and $MoS_2$ film have *p*-type and *n*-type transistor characteristics, respectively. Since there is a gate oxide $SiO_2$ between the Si channel and $MoS_2$ film, a *p*/insulator/*n* heterostructure is constructed (Fig. 2). Since the $SiO_2$ is thin (6 nm), tunnel current flows between the Si and $MoS_2$ when voltage is applied between them as shown in Figs. 2 and 3. Multiple current peaks indicating negative differential resistance (NDR) are clearly observed at room temperature. The mechanism of NDR is the same as that in a tunnel or Esaki diode composed of heavily doped *p*-*n* junctions, though current tunnels through the $SiO_2$ layer in our device. The appearance of the four NDR peaks originates from the fact that the $MoS_2$ film has four areas of different thickness and that the bandgap of layered $MoS_2$ varies with its thickness. From voltages giving NDR peaks, we can evaluate the energy-band alignment of the heterostructure in our device. Using the heterostructure even for other two-dimensional layered materials, we can obtain information about their energy-band structure in a simple system under various conditions, e.g., low temperature and magnetic field. The heterostructure is also promising for new functional devices.

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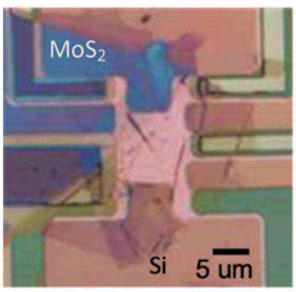


Fig. 1. Photograph of the fabricated device.

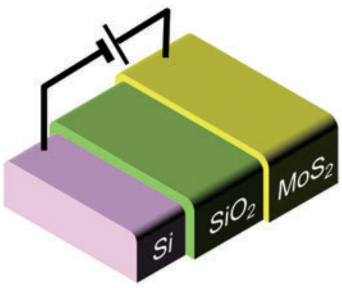


Fig. 2. Schematic view of the device.

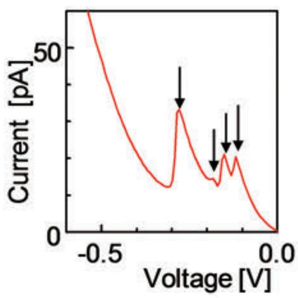


Fig. 3. Current characteristics.

Physical Science Laboratory

# High-speed Single-hole Transfer in a Si Tunable-barrier Pump

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Physical Science Laboratory

A single-electron (SE) pump can transfer SEs in synchronization with a clock signal. It is expected to be used for low-power-consumption devices, current standards, and single-photon sources. In particular, high-accuracy and high-speed operation is necessary for the current standard, but there is so far no device that has a performance suitable for practical use (gigahertz operation with an error rate of less than $10^{-8}$). A tunable-barrier pump is a promising device, with which we can achieve gigahertz SE pumping [1]. One factor determining its accuracy is the effective mass of charge carriers. We expect an accuracy improvement by using a hole (electric charge *e*), which has a heavy effective mass. However, there is no report on high-speed single-hole (SH) transfer. Here, we report the achievement of high-speed SH transfer using a Si tunable-barrier pump [2].

Figure 1(a) shows a schematic of the device. It has a double-layer gate structure on a Si wire. S and D are heavily doped to form *p*-type leads. We apply negative voltage $V_{UG}$ to the upper gate (UG) to generate holes in the Si wire and apply positive voltages to the two lower gates (G1, G2) to form hole potential barriers. As a result, there is an SH island in the Si wire between G1 and G2. In addition, we apply a high-frequency signal with frequency *f* to G1 to transfer SHs from S to D [Fig. 1(b)]. When the barrier under G1 is low, holes are loaded to the island. Since the island potential rises when the barrier is raised because of a capacitive coupling, the loaded holes escape to S. However, when the rise rate of the barrier is much larger than the escape rate, holes are captured by the island at a non-equilibrium state. The captured holes are ejected to D. Since our device has a very small island, SH addition energy $E_{add}$ is much larger than the energy of thermal fluctuations. In this case, a rate of SH escape from the island with two holes can be much larger than that from the island with one hole, leading to capture of an SH in the island. When the number of transferred holes is *n*, the current is *nef*. The *n* can be tuned by changing the island potential by applying $V_{UG}$.

Figure 1(c) shows a measurement result for the current at 1 GHz (red circles). We observe a current plateau with decreasing $V_{UG}$. A fit using a theoretical model of the non-equilibrium hole capture agrees well with the data (blue curve), indicating non-equilibrium hole transfer. From the fit, the transfer error rate is estimated to be about $10^{-3}$ at 17 K. A theory predicts that a transfer accuracy of $10^{-8}$ can be achieved at 9 K. These results pave the way for accurate manipulation of SHs and its application to metrological standards.

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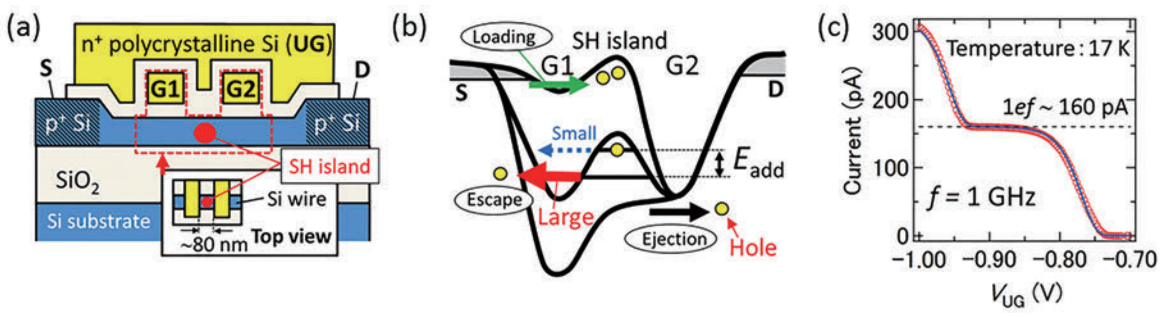


Fig. 1. (a) Schematic of the device. (b) Hole potential diagram and SH transfer mechanism. (c) Measurement data for the high-speed SH transfer and a fit.

# Thermal-noise Suppression in Nano-scale Si Field-effect Transistors by Feedback Control of Single Electrons

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Hirotaka Tanaka, and Akira Fujiwara
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Feedback control is a way to put target objects in desired conditions by controlling outputs based on measurement outcomes. For example, an air conditioner keeps a room temperature at a pleasant temperature by changing its output power based on the outcome of temperature measurements. The function cannot be achieved without proper measurement of the target object, the room temperature.

In this study, we performed feedback control on single electrons (SEs) using nano-scale Si field-effect transistors, which can detect SEs. Our device has an SE-resolution charge detector, an SE box, and an electron reservoir (Fig. 1). We can monitor the number $n$ of SEs in the SE box by measuring current $I_d$ through the charge detector. $I_d$ fluctuates among discrete values with 5-nA intervals [Fig. 2(a)]. This fluctuation corresponds to the fluctuation of $n$ caused by thermal motion of SEs between the SE box and electron reservoir [1]. Based on the measurement outcome of $n$, we changed the voltage $V_{res}$ applied to the electron reservoir to fix $n$ as a value (here, we define the value as $n = 0$): we changed $V_{res}$ to -310 mV when $n > 0$, -470 mV when $n < 0$, and -390 mV when $n = 0$. The feedback control modifies the rate at which an SE enters to the SE box: when $n > 0$ ($n < 0$), the rate is decreased (increased) to reduce (increase) possibility of an increase in $n$. As a result, we achieved about a 60% reduction in the thermal fluctuation of $n$; variance σ of $n$ is reduced from 1.5 to 0.5 [Fig. 2(b)] [2]. Feedback control of SEs can be used to correct errors at the SE level for achieving current standards with SE pumps, and to realize Maxwell's demon in electrical devices [3].

This work was partially supported by the Funding Program for Next Generation World-Leading Researchers of JSPS.

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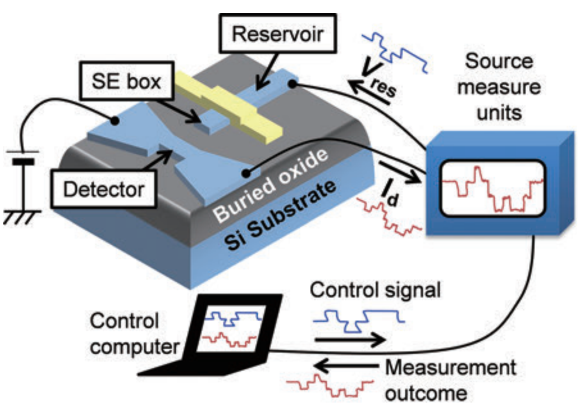


Fig. 1. Schematics of feedback control of SEs. Number $n$ of SEs in the SE box is monitored with current $I_d$ through the detector (red line). Voltage $V_{res}$ applied to the electron reservoir was modulated based on the $n$ measurement outcome (blue line).

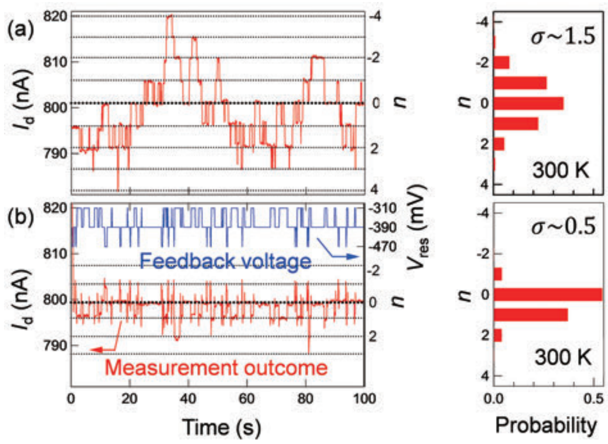


Fig. 2. Thermal-noise suppression with feedback control. (a) Thermal fluctuation of $n$ monitored with $I_d$ without feedback control. (b) Suppressed thermal fluctuation with feedback control. $V_{res}$ (blue line) was modulated based on $I_d$ (red line).

# Optomechanics Using Excitonic Transitions in Semiconductor Heterostructures

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Optical control of micromechanical resonators has been widely demonstrated via cavity-enhanced radiation pressure or photothermal backaction [1]. Such cavity optomechanics allow highly tunable manipulation of a single mechanical resonator, including vibration amplification and damping (i.e., mode cooling). However, it cannot be straightforwardly extended to integrated mechanical systems because it needs delicate cavity operation, including tapered-fiber access and coupling adjustment. Thus, an alternative cavity-free approach is highly demanded in order to practically apply the optical control capability to integrated micromechanical systems. Here, we present excitonic optomechanics implemented in a compound semiconductor microcantilever. By using opto-piezoelectric stress induced via excitonic transitions, cavity-free control of a micromechanical resonator is achieved [2].

We used the AlGaAs/GaAs heterostructured cantilever shown in Fig. 1(a). In this system, the optically excited electrons and holes are separated via the built-in electric field [Fig. 1(b)]. This causes piezoelectric (compressive) stress along the longitudinal direction in the GaAs layer, which leads to downward bending of the cantilever [Fig. 1(a)]. This effect depends on the optical absorption and on strain via the deformation potential. Therefore, strain-dependent opto-piezoelectric stress appears around the exciton resonance, where the per-strain change in the optical absorption is maximized. Since this stress acts on the cantilever in a time delay with respect to the optical excitation, it causes a self-feedback effect on the mechanical vibration, where the sign and gain of the self-feedback depend on the slope of the absorption spectrum [Fig. 1(c)]. We achieved both vibration amplification and mode cooling (damping) by detuning the photon energy from the exciton resonance [Fig. 1(d), (e)].

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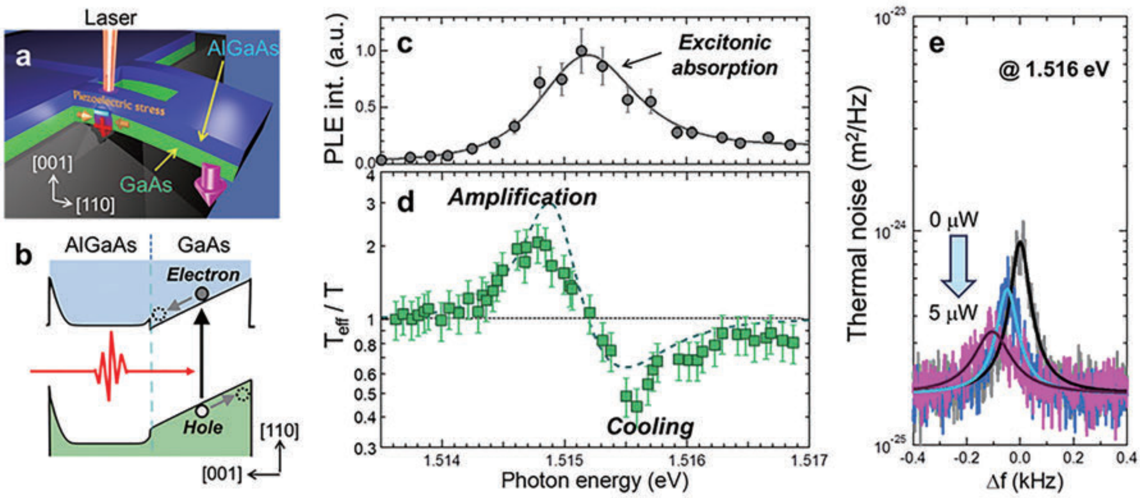


Fig. 1. (a) Schematic drawing of the cantilever and opto-piezoelectric effect. (b) Calculated energy-band diagram, in which the separation of photoexcited electrons and holes is schematically drawn. (c) Photoluminescence excitation (PLE) spectrum in the vicinity of the exciton resonance. (d) Photon-energy dependence of mode temperature ($T_{eff}$) normalized by the sample temperature $T$ = 9.2 K for the laser power of 1.19 μW. The broken line is a theoretical fit, which depends on the slope of the PLE spectrum. (e) Laser-power dependence of the thermal displacement noise power spectrum at 1.516 eV.

# Optical Control of Mechanical Mode Coupling at Room Temperature

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The ability to manipulate mechanical vibrations and their transportation in multiple mechanical modes are of great interest for practical applications of mechanical systems, such as to mechanical logic circuits and acoustic metamaterials. For this purpose, tunable intermodal coupling, which is induced by the modulation of tension at the modes' frequency difference, is highly desired at room temperature. If the coupling rates of different mechanical modes exceed the damping rate of each mode, called the strong coupling regime, we can quickly transfer the vibrations from one mode to another and thereby achieve fast switching of mechanical resonators [1]. Such a demonstration has so far been reported in GaAs mechanical resonators at cryogenic temperatures using piezoelectric stress modulation. However, it is difficult to extend it to room temperature, because the coupling rate achieved by the piezoelectric effect is too small to overcome the mechanical damping rate at room temperature. In this work, we demonstrate strong and tunable coupling of two mechanical modes at room temperature by using laser-induced photothermal stress modulation [2].

Figure 1(a) shows a microscope image of two mechanical resonators connected to each other. Figure 1(b) shows symmetric and anti-symmetric modes calculated by the finite element method. These resonators were fabricated on a GaAs wafer containing AlAs/GaAs superlattices. Applying a laser whose wavelength is 780 nm causes photothermal expansion in the GaAs layer, which provides the internal stress in a mechanical resonator. The internal stress generates the coupling of the symmetric and anti-symmetric modes, when the laser is modulated to the difference frequency of the two modes. Figure 1(c) shows the mechanical spectrum of the anti-symmetric mode at various frequencies of the amplitude-modulated laser, and Fig. 1(d) shows the modulation-amplitude dependence of the spectrum. When the modulation frequency is close to the differential frequencies of the two modes, we can clearly observe the mode splitting, where the amount of the split corresponds to the coupling rate. As shown in Fig. 1(d), the coupling rate can be controlled by changing the modulation amplitude. The maximum coupling rate is 2.57 kHz. It exceeds the damping rates of both modes at room temperature (2.14 and 1.59 kHz), which indicates that the strong coupling of two mechanical modes is achieved at room temperature.

This work was supported by KAKENHI.

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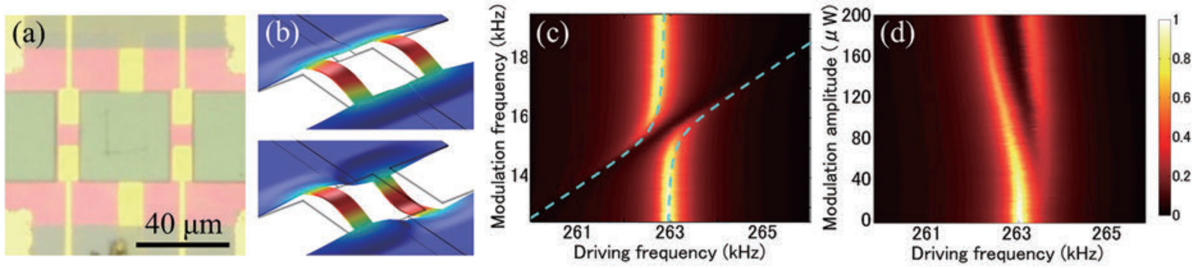


Fig. 1. (a) Microscope image of two mechanical resonators. (b) Schematic image of the symmetric and anti-symmetric modes calculated by the finite element method. (c) Modulation-frequency dependence and (d) modulation-amplitude dependence of anti-symmetric mode. Blue dotted lines show calculated peak frequencies.

# Improving the Coherence Time of a Quantum System by Coupling it to a Short-lived System

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[3]NII, [4]NICT, [5] Optical Science Laboratory

A single nitrogen-vacancy (NV) center is a promising candidate to realize quantum information processing [1]. However, it is known that low frequency magnetic field noise decreases the coherence time of the NV center [2].

We theoretically show that coupling an NV center with a short-lived superconducting flux qubit (FQ) improves the coherence time of that NV center [3]. The NV center has two excited states. One of them is called a bright state coupled with the FQ while the other one is called a dark state decoupled from the FQ. Since these two excited states are degenerate without the FQ, low frequency magnetic field noise can cause stochastic transitions between them, and this decreases the coherence time of the NV center. However, if the NV center is coupled with the FQ, these two excited states are energetically separated due to the coupling. There is an energy gap between the bright state and dark state, and so the transition between them by the low frequency magnetic field noise is suppressed. This improves the coherence time of the dark state. From numerical simulations, we have confirmed that a flux qubit with a coherence time of 10 μs can improve the coherence time of the NV center from 100 μs to nearly 1 ms via the coupling (Fig. 1). Our proposal opens a new way to use a quantum hybrid system for the realization of robust quantum information processing.

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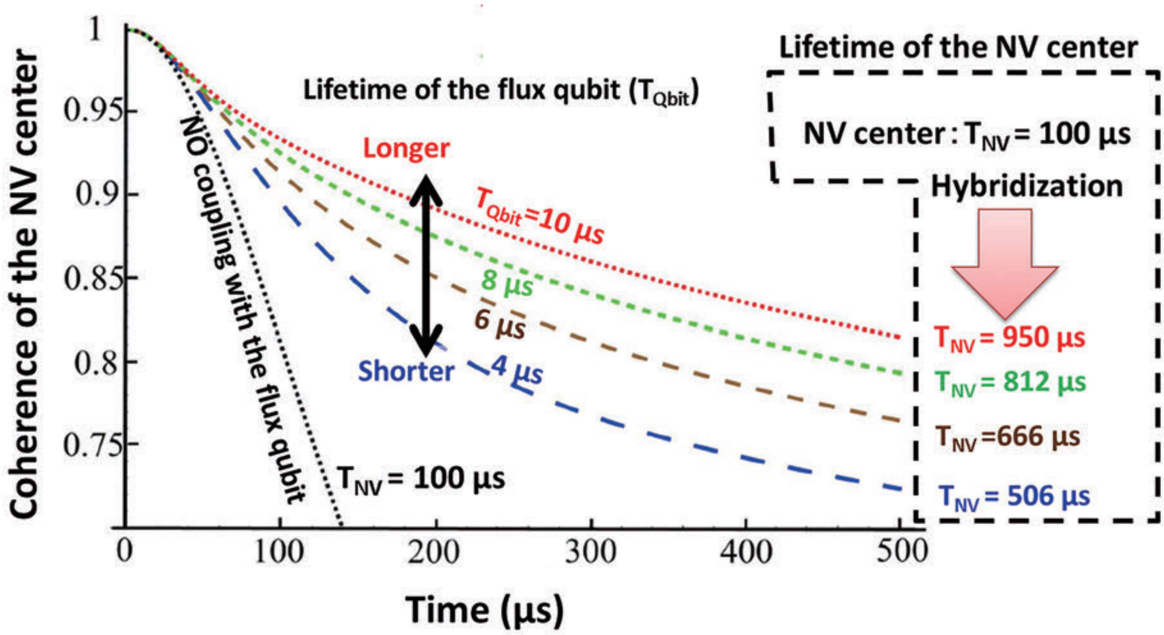


Fig. 1. Numerical simulation of the decoherence behavior of the NV center with and without coupling to the FQ. Here, the horizontal axis denotes the time and the vertical axis denotes the coherence of the NV center.

# Observation of Quantum Zeno Effect in Superconducting Flux Qubit

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Shiro Saito[1], and Kouichi Semba[1,3]
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It is known that an ideal quantum measurement stochastically projects a quantum state into an energy eigenstate. As the distance between the target state and eigenstate becomes smaller, the probability of projecting it into the eigenstate increases. If the quantum state is modified even slightly from the initial eigenstate due to a time evolution, the probability of projecting it into the eigenstate approaches unity. This means that frequent quantum measurements can freeze a specific time evolution of a quantum system where the holding time of the state depends on the measurement period. This phenomenon is both academically interesting and useful for many applications such as the estimation of quantum measurements and the realization of a decoherence free subspace.

A superconducting flux qubit is composed of a superconducting loop circuit with Josephson junctions. By applying a characteristic bias field, we can manipulate this circuit as a quantum two-level system with an energy of several GHz. We implement Rabi oscillations by applying a resonant microwave to the superconducting qubit, and attempt to freeze the Rabi oscillations by applying periodic measurement pulses. To induce the projection, we use a Josephson bifurcation readout, which is a quantum non-demolition measurement.

Fig. 1 (a) shows the probability of detecting excited flux qubit in the time domain with a resonant microwave pulse. Without projections, we can clearly observe Rabi oscillations between the excited and ground states. On the other hand, with the projections, the Rabi oscillation is suppressed, and the qubit remains in the excited state. Fig. 1 (b) shows the probability of detecting excited flux qubit when we change the measurement period. As the measurement period decreases, the holding time increases. These results are well explained by a model of the quantum Zeno effect. This is the first demonstration to observe the quantum Zeno effect on a superconducting qubit by using periodic quantum measurements [1].

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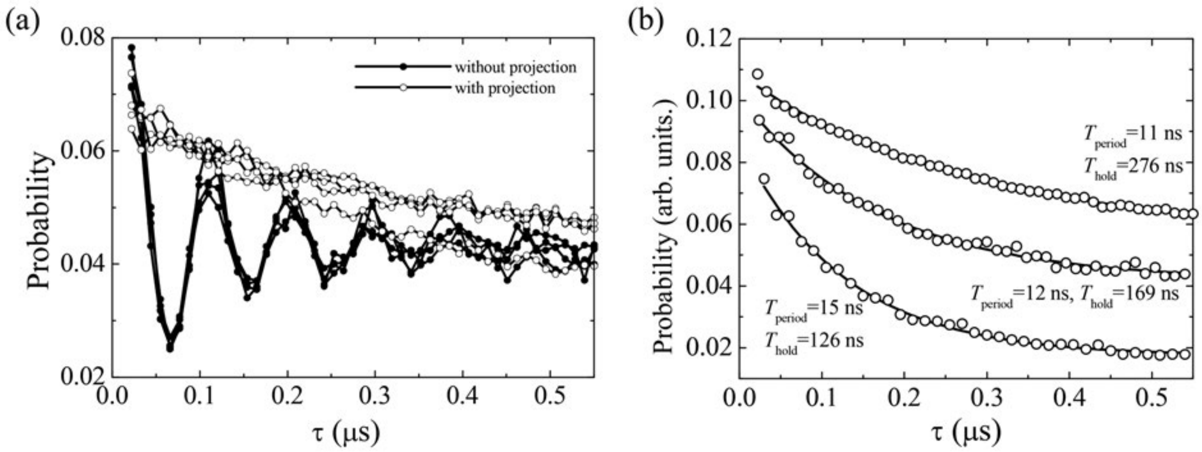


Fig. 1. (a) Time evolution of qubit with and without measurement pulse. (b) Holding time of quantum state with different measurement periods.

# Electron Paramagnetic Resonance Using a SQUID Magnetometer Directly Coupled to an Electron Spin Ensemble

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[1]Physical Science Laboratory, [2]Optical Science Laboratory, [3]NII

Magnetic resonance is a widely-used tool from analyzing material properties to medical applications, for instance with electron paramagnetic resonance (EPR) or nuclear magnetic resonance. However, conventional EPR spectrometers require a large number of spins (~$10^{13}$) for the detection and do not have high spatial resolution (~0.1 mm). To expand the field of applications including quantum information processing, highly sensitive EPR spectrometers are necessary.

Here, we demonstrate the detection of electron spin polarization and EPR spectroscopy using a SQUID magnetometer directly coupled to an electron spin ensemble [1]. Our experimental setup is shown in Figs. 1(a) and (b) where the magnetization from the sample is detected by measuring the critical current of the SQUID. To begin, we measure the electron spin polarization as a function of the in-plane magnetic field and temperature. By increasing the in-plane magnetic field, we observe an increase of electron spin polarization ratio due to the reduction of the thermal fluctuations [Fig. 1(c)]. Figure 1 (d) shows the EPR spectrum of a type Ib diamond crystal containing nitrogen impurities. We confirm a linear increase of resonance frequency. Furthermore, ~93 MHz shifted peaks are observed due to hyperfine splitting of $^{14}N$.

The minimum detectable number of spins for our method is ~$10^6$. This number is much smaller than the conventional EPR spectrometer and can be improved for three orders of magnitude by replacing the SQUID with a superconducting flux qubit. Further we estimate the sensing volume at ~$10^{-10}$ $cm^3$ [~0.1 pL]. This is two order of magnitude smaller than the reported value in the literature [2].

This work was supported by the Commissioned Research of NICT, in part by an MEXT Grant-in-Aid for Scientific Research on Innovative Areas, and in part by KAKENHI grant.

Present address: *Chinese Academy of Sciences

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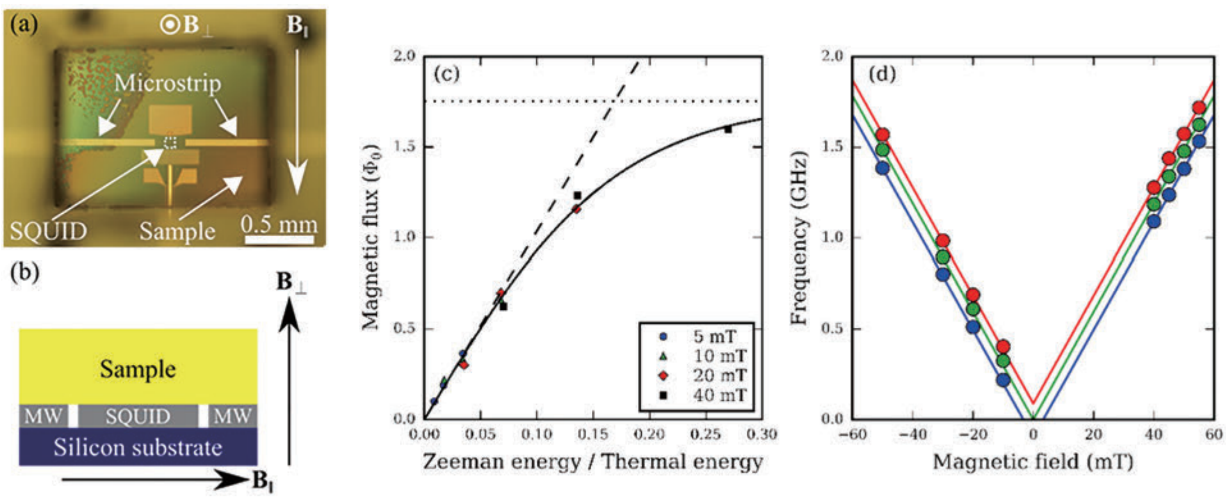


Fig. 1. (a) Optical microscope image of the sample. (b) Cross sectional view of the experimental setup. (c) Magnetization as a function of the in-plane magnetic field and the temperature. (d) Results of EPR spectroscopy.

# Shot Noise Generated by Graphene *p-n* Junctions in the Quantum Hall Effect Regime

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[1]Physical Science Laboratory, [2]Materials Science Laboratory, [3]CEA Saclay

In graphene, owing to the linear and gapless band structure, a unique *p-n* junction, where *n*-type and *p*-type regions adjoin each other without a gap in between, is formed. In the quantum Hall effect regime under high magnetic field, counter-circulating electron and hole edge modes mix in the *p-n* junction [Fig. 1(a)]. In this work, we investigate the mode mixing process by shot noise measurements and suggest that the *p-n* junction can serve as an electronic beam splitter [1].

We used graphene grown on SiC. A *p-n* junction is formed by applying a gate bias to the top gate covering half of the graphene. The current injected to the *p-n* junction is distributed to electron and hole modes by the mode mixing and then partitioned at the exit of the *p-n* junction. We measured the shot noise generated by this mode mixing and the subsequent partitioning process. We demonstrate the crucial role of the *p-n* junction length on the mode mixing process [Fig. 1(b)]. For longer *p-n* junctions, the shot noise is reduced by the energy relaxation. On the other hand, for *p-n* junctions with the length shorter than the relaxation length (15 µm), the energy loss to the environment is negligible and the noise is consistent with a quasielastic mode mixing. This suggests that a graphene *p-n* junction can serve as an electronic beam splitter. Since the beam splitter is an important element of quantum optics, our results encourage using graphene for such applications.

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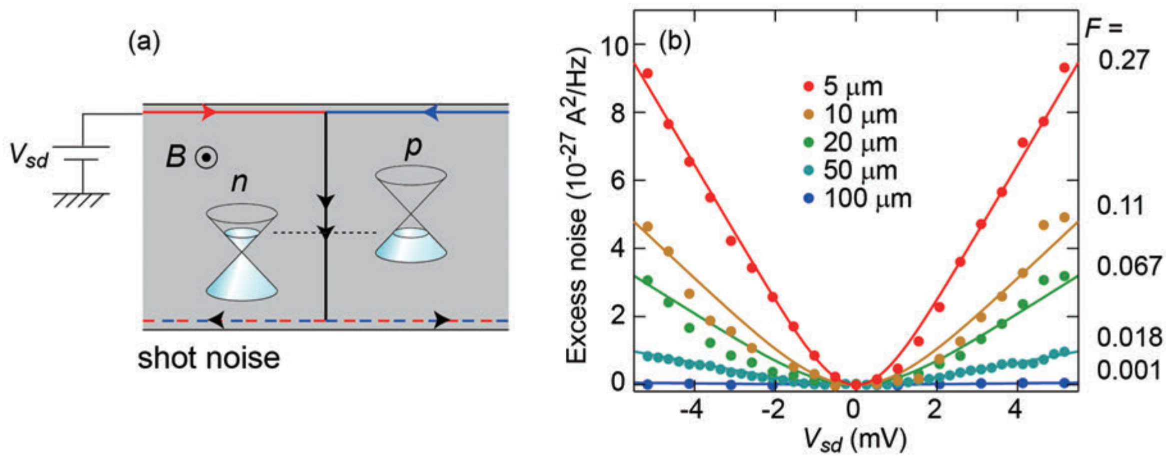


Fig. 1. (a) Counter-circulating electron and hole edge modes in a bipolar graphene quantum Hall effect regime. (b) Shot noise as a function of the source-drain bias for the samples with different *p-n* junction length.

# Gate-controlled Semimetal - Topological Insulator Transition in an InAs/GaSb Heterostructure

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Topological insulators (TIs) are new states of matter that cannot be classified into any existing categories of materials. The insulating state in TIs cannot continue to the normal insulating state outside, and it is therefore necessary to break the insulating states. As a result, a conductive channel arises at the boundary of a TI. Electron scattering in this topologically protected conductive channel is restricted. Particularly, for two-dimensional (2D) TIs, dissipationless transport is expected. Therefore, TIs are promising for low power consumption electric devices.

Thus far we have succeeded in artificially realizing a 2D TI arising from the heterojunction between InAs and GaSb, which both are commonly used in III-V semiconductors [1]. Recently, we have further achieved *in-situ* semimetal-TI transition by applying a gate voltage between the gates on both the substrate and surface sides of an InAs/GaSb heterostructure [2]. This adds new functionality to TIs, which would enhance their device application.

Figure 1 shows the energy band profile of the InAs/GaSb heterostructure with front (surface side) and back (substrate side) gates. Due to the hybridization between the conduction band of InAs and valence band of GaSb through the heterointerface, the topologically nontrivial different energy gap opens. The energy overlap between the conduction and valence bands can be controlled by applying a gate voltage on both sides. When the overlap is large enough the system becomes semimetallic as a result of the anisotropy of the GaSb valence band [Fig. 2(a)]. By increasing the back gate voltage, the overlap becomes smaller and the band structure becomes that of a TI [Fig. 2(b)].

This work was supported by JSPS KAKENHI Grant No. 26287068.

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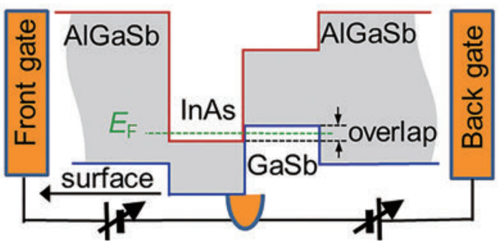


Fig. 1. Energy band profile of the InAs/GaSb heterostructure with front (surface side) and back (substrate side) gates.

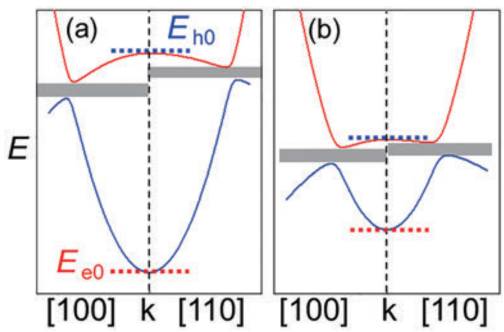


Fig. 2. Schematic illustrations of dispersion relations for (a: semimetallic) large energy band overlap case and (b: TI) small overlap case .

# Probing the Extended-state Width of Disorder-broadened Landau Levels in Epitaxial Graphene

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Graphene is theoretically predicted to have a zero-energy Landau level, the energy width of which depends on the types of disorder; the energy width is ideally nearly zero in the presence of typical hopping disorder such as ripples, owing to protected chiral symmetry associated with graphene sublattice-symmetry. Previously, we developed transport energy-spectroscopy techniques relaying on densities of interface states involved in epitaxial graphene device [1]. Using the technique, here we report temperature dependences of the energy widths of the extended states of the zero-energy and first excited Landau levels, from which we can also deduce exponents corresponding to the critical exponents used in the quantum Hall plateau-plateau transition. The energy widths obtained from the spectroscopy technique are also compared with the energy widths deduced from the activation gap measurements [2].

Figure 1(a) shows longitudinal resistance as a function of gate voltage ($V_g$) and magnetic field ($B$). Due to the presence of the interface states in gate insulator or in SiC underneath the graphene (Fig. 1(b)), trajectories of the longitudinal-resistance peaks become parabolic, reflecting the unequally-spaced graphene Landau levels. Such a $V_g$-$B$ relation enables us to deduce the energy width $\Delta E_N$ of the extended states of the $N$th Landau level. Figure 1(c) and (d) show temperature ($T$) dependences of $\Delta E_0$ and $\Delta E_1$. These show that $\Delta E_0$ and $\Delta E_1$ have similar magnitudes and are proportional to $T^\eta$ with $\eta = 0.30$ - $0.31$ for $\Delta E_0$ and $\eta = 0.32$ - $0.35$ for $\Delta E_1$. These values are comparable to the critical components previously deduced from the plateau-plateau transition in quantum Hall regimes. Moreover, we deduced the energy widths independently using activation gap measurements. The energy width for $N = 1$ Landau level show a good agreement between two different types of measurement methods, while the energy width for the $N = 0$ Landau level obtained from activation gap measurement is larger by 30 meV than that deduced from the transport energy-spectroscopy.

Using these two different measurement techniques systematically, we demonstrate that our device include random disorder rather than typical hopping disorder such as ripples.

This work was partly supported by KAKENHI.

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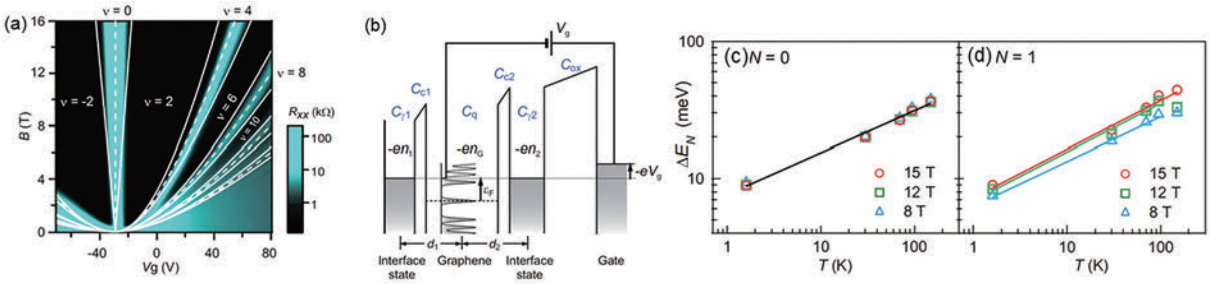


Fig. 1. (a) Longitudinal resistance as a function of gate voltage ($V_g$) and magnetic field ($B$). (b) Energy diagram of graphene with interface states. Temperature dependence of $\Delta E_N$ for the $N = 0$ Landau level (c) and $N = 1$ Landau level (d).

# Coherent Raman Beat Analysis of the Hyperfine Sublevel Coherence Properties of $^{167}Er^{3+}$ Ions Doped in an $Y_2SiO_5$ Crystal

Kaoru Shimizu and Daisuke Hashimoto
Optical Science Laboratory

A metastable $\Lambda$-type three-level system of atoms and ions provides us with a medium with which to demonstrate electromagnetically induced transparency (EIT) and coherent population trapping (CPT). EIT and CPT media have attracted a lot of attention in the field of quantum optics, where they are expected to be used for devices capable of converting quantum information between light and matter. An ensemble of $Pr^{3+}$ ions doped sparsely in a host crystal $Y_2SiO_5$ cooled to a cryogenic temperature (< 4 K) has been studied intensively for demonstrating EIT and CPT. Recently, a $\Lambda$-type three-level system was also identified for $^{167}Er^{3+}$ ions doped in an $Y_2SiO_5$ crystal, which had an optical transition at a telecom wavelength and a set of hyperfine sublevels in ground and excited states [1]. Although the measured population life time $t_1$ of the sublevels is approximately 100 ms at 1.5 K, the phase dissipation time $t_2$ of the sublevel coherence has not yet been examined. To examine the feasibility of an $Er^{3+}$:$Y_2SiO_5$ crystal as a solid state medium for EIT and CPT, we must clarify the $t_2$ value.

At first glance, Raman echoes or optically detected spin echoes appear suitable for measuring the $t_2$ value provided that the optical coherence time $T_2$ or the sublevel population life time $t_1$ is long enough. However, an $Er^{3+}$:$Y_2SiO_5$ crystal cannot satisfy the conditions for the above echo techniques. This is because an $Er^{3+}$ ion is a Kramers ion and has a half-integer electronic spin, which results in a large average magnetic moment and makes the quantum state being sensitive to the fluctuating local magnetic field. In contrast, coherent Raman beat (CRB) spectroscopy is insensitive to the $T_2$ and $t_1$ values and worth employing if we can cope with inhomogeneous dephasing in the signal.

By comparing carefully with the effects of sublevel inhomogeneous broadening $\Delta_{sub}$ on the various Raman signals (Fig. 1) that are obtained with different $Er^{3+}$ ion dopant concentrations, we can estimate the $t_2$ value even when $t_2 > 1/\Delta_{sub}$ [2]. The ground-state $t_2$ values of the $\Lambda$-type three-level system identified in the $^{167}Er^{3+}$ ions are approximately 12 and 50 μs at 2.3 K when the dopant concentrations are 0.005 (Fig. 2) and 0.001 at%, respectively. These $t_2$ values are long enough to realize EIT and CPT with an $Er^{3+}$:$Y_2SiO_5$ crystal at a wavelength of 1.5 μm.

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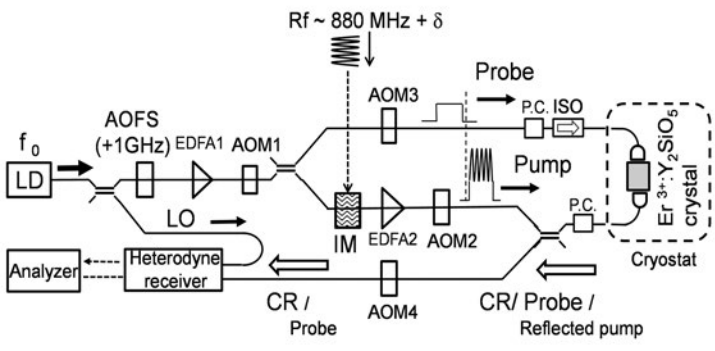


Fig. 1. Experimental configuration of the CRB spectroscopy.

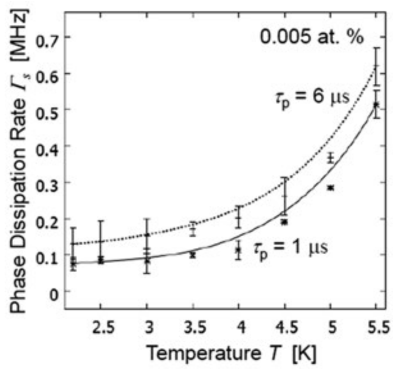


Fig. 2. Sublevel phase relaxation rate $1/t_2$.

# Deterministic Wavelength Conversion of Single Photons Using Cross-phase Modulation

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Optical Science Laboratory

Wavelength (frequency, color) is an important physical parameter of light. Wavelength conversion of single photons is crucial for quantum networking, which requires an interface for photon wavelength. We have developed a lossless scheme for the wavelength conversion of photons using a nonlinear-optical effect called cross-phase modulation (XPM) [1].

The experimental scheme is illustrated in Fig. 1(a). XPM enables us to control the phase of light (signal pulses) via a change in the refractive index of a medium induced by another light (control pulses). An instantaneous frequency shift is added to the signal pulses when the phase shift is dynamic. Since XPM always occurs regardless of the intensity of the control pulses, by using single photons as the signal pulses we can convert the wavelength of the photons without a photon loss.

Wavelength conversion using XPM has been widely demonstrated for classical optical pulses; however, it has not yet been demonstrated for single photons. This is because it was difficult to add a wavelength shift to single photons while mitigating noise photons induced by the control pulses via other optical processes. We solved this problem by using a photonic crystal fiber (PCF) whose dispersion property was properly designed for the experiment. As a result, we were able to successfully convert the wavelength of telecommunication-band single photons with a wavelength shift as large as 3 nm (0.4 THz in frequency). The amount of the wavelength shift can be easily tuned by adjusting the intensity of the control pulses. Photon loss due to the conversion was not observed.

Using the scheme, we further controlled the quantum correlation of pairs of photons. The demonstrations include the modulations of non-classical frequency correlation [Fig. 1(b)], inter-packet interference, and entanglement between distant photons. These results demonstrate our scheme's applicability to a wide range of quantum information science and technologies, including computation [2] and metrology.

This work was supported by KAKENHI.

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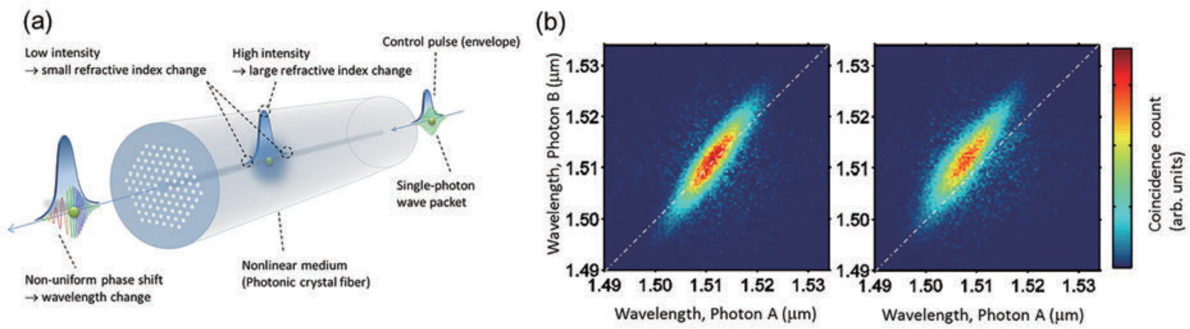


Fig. 1. (a) The illustration of the scheme. (b) Reshaping the non-classical frequency correlation between photons. In the experiment, first, photon pairs were created via an optical process called parametric down conversion (left). Then the wavelength of "photon A" was blue shifted with our scheme. As a result, the overall spectral correlation was also blue shifted (right).

# An Entanglement Analogue in Light Cones

Fumiaki Morikoshi
Optical Science Laboratory

In relativistic spacetime, the notion of light cones is essential and nothing can travel faster than light. Thus, the path of a particle stays inside the light cone. (In what follows, we take the unit of $c = 1$). In this work, we drew an analogy between the structure of light cones and entanglement in quantum theory.

There are two parts in a light cone, the future cone and the past cone, as shown in Fig. 1. The cross sections at $t = \pm 1$ become unit spheres in three dimensions (In Fig. 1, the cross sections of the light cone in 2+1 dimensions become unit circles in two dimensions). Each unit sphere can be identified with the Bloch sphere of a qubit in quantum information theory. Thus, we introduce two imaginary qubits, one for the future and the other for the past. Considering world lines of particles with constant speeds, the directions of the particles in four dimensions can be represented by points on or inside the Bloch sphere. In other words, the directions of particles with the light speed correspond to the points on the surface of the sphere, and the directions of particles travelling slower than light correspond to the points inside the sphere.

This correspondence can be seen as the one between world lines of particles and entangled states of two imaginary qubits representing the cross sections of the light cones in the future and the past. According to this analogy, particles with the light speed correspond to product states, stationary particles maximally entangled states, and particles slower than light partially entangled states. Furthermore, by quantifying the amount of entanglement with concurrence, we can show an intriguing relation between the concurrence $E$ and the particle's speed $v$ [1],

$$E = \sqrt{1 - v^2}$$

This relation allows us to interpret the factor frequently appearing in relativity, $\sqrt{1 - v^2}$, in terms of the notion of entanglement in quantum information theory.

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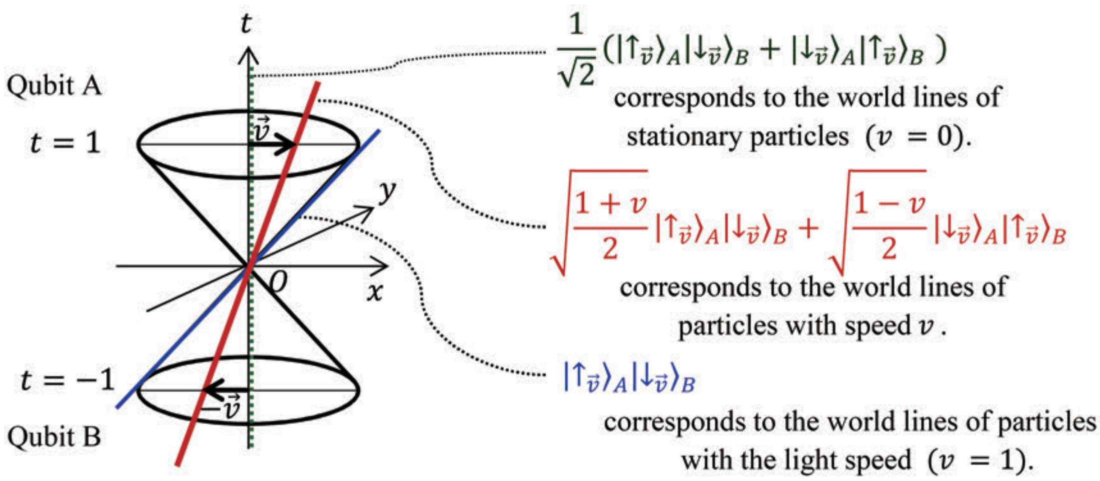


Fig. 1. Correspondence between world lines and entanglement in a light cone (2+1 dimensions).

# All-photonic Intercity Quantum Key Distribution

Koji Azuma, Kiyoshi Tamaki, and William J. Munro
Optical Science Laboratory

Quantum key distribution (QKD), a technique for ultimately secure communication based on the law of physics, usually relies on the transmission of photons over optical fibres. In fact, based on the direct transmission of photons between a sender and a receiver, conventional QKD schemes are already commercially available for 100-km communication distances and testbed networks like the 'Tokyo QKD network' are running in Japan. Therefore, with the conventional schemes, intracity QKD links (over about 100 km) are available even at present. However, owing to the photon loss in the optical fibre, about 400 km is considered to be the maximum distance of the conventional schemes. Thus, to connect QKD networks in different cities above 400 km distant, it was thought that we needed 'quantum repeaters', rather than the conventional schemes based on the direct transmission. Quantum repeaters enable us to perform QKD over any communication distance efficiently, but, they necessitate many intermediate nodes connected with optical fibres, each of which needs challenging components such as matter quantum memories and quantum error correction. These requisites are necessary to achieve an extremely high goal such as intercontinental QKD connections. But, they may be too demanding to connect different major cities below 1,000 km separation.

In this research [1], we have proposed an 'all-photonic intercity QKD' protocol (Fig. 1) that doubles the achievable distance of the QKD without decreasing its efficiency, using only linear optical devices, that is, without matter quantum memories and quantum error correction required in quantum repeaters. This scheme could outperform quantum repeaters based on atomic ensembles for communication distances below 800 km, and it expands the communication range from 400 km of conventional schemes to 800 km (Fig. 2). In addition, since the proposed scheme does not use matter quantum memories similarly to all-photonic quantum repeaters [2], (a) it displays the communication speed in the same order of the repetition rate of optical devices, irrespective of the communication distance, (b) it does not need a still challenging interface between matter and photons and (c) it could work at room temperature in principle. Therefore, our scheme could work as cost-effective backbone links to connect metropolises within a radius of 800 km. If our scheme is combined with the all-photonic quantum repeater protocol, it is made seamless to realize the high-speed and cost-effective 'all-photonic' QKD network based only on optical devices on a global scale.

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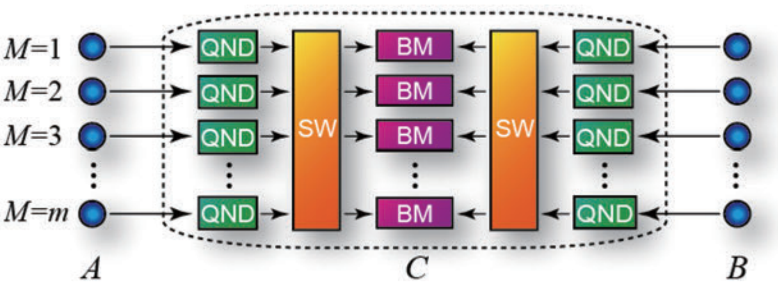


Fig. 1. All-photonic intercity QKD. The middle point *C* performs quantum nondemolition measurement (QND) on optical pulses sent by communicators *AB*. Optical switches (SW) then make only surviving photons paired, which are subjected to the Bell measurement (BM).

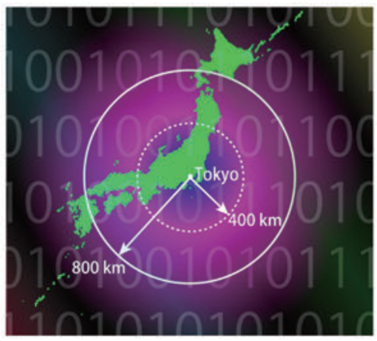


Fig. 2. Communication range expanded by our scheme.

# Finite-key Security Analysis of Quantum Key Distribution with Imperfect Light Sources

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Nobuyuki Imoto[1], and Kiyoshi Tamaki[4]
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[3]University of Geneva, [4]Optical Science Laboratory

Sending confidential information such as a password over a communication channel needs to be encrypted. Among the many encryption methods, the one-time pad is the only encryption scheme rigorously proven to be secure. This crypt requires a key, which is a random bit string, and if its information is kept from an eavesdropper the one-time pad is secure. Therefore, secure distribution of the key is critical, and so key distribution (QKD) has attracted much attention as a means to accomplish this. For the secure distribution, a QKD system has to satisfy requirements imposed by a security proof. Unfortunately, most of the requirements in existing security proofs are hard to meet in practice. Therefore, to guarantee the implementation security, that is the security of a real-life QKD system, we need to construct security proofs with relaxed requirements.

In previous work [1], we modified the security proofs to accommodate the effect of imperfect phase modulation (PM) in the asymptotic limit of a large number of the pulses. In this current work, we have generalized it to the one with a finite number of pulses [2]. Figure 1 shows one of our results where the horizontal (vertical) axes represents the fiber distance (the secret key generated per pulse). The solid (dashed) lines correspond to the case of the perfect (imperfect of 8.42°) PM. Moreover, the colors represent the number of pulses, and each line, form right to left, corresponds to the asymptotic limit, $10^{12}$, $10^{11}$, $10^{10,}$ $10^{9}$, respectively. The small differences between the solid and dashed lines mean that the effect of the imperfect PM is negligible. As the clock rate of most of the QKD system is more than 1 GHz, our results show the feasibility of secure key distribution with current QKD systems. These results constitute an important step towards guaranteeing implementation security for QKD systems.

Our work is in part supported by NICT.

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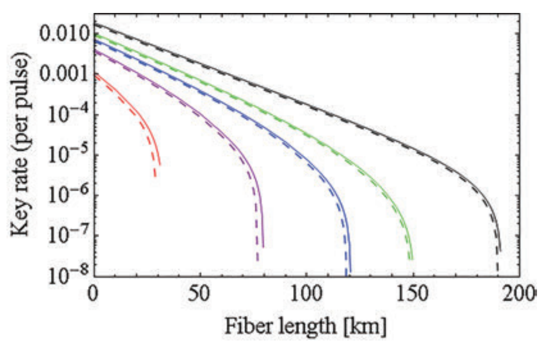


Fig. 1. Communication distance vs Key generation rate per pulse.

# Extraction of Phonon Decay Rate in *p*-type Silicon Under Fano Resonance

Keiko Kato, Katsuya Oguri, Haruki Sanada, Takehiko Tawara,
Tetsuomi Sogawa, and Hideki Gotoh
Optical Science Laboratory

It is of primary importance to understand phonon dynamics in Si, not only for basic physics but also for obtaining ultrafast responses in semiconductor devices. Raman measurement is one of the experimental methods for determining phonon decay rates. However, in doped Si, especially *p*-type Si, an asymmetric lineshape appears due to Fano resonance, which makes it difficult to evaluate them [1]. In the present study, we performed time-resolved measurements to determine phonon decay rates free from the interaction with a continuum state in Fano resonance [2].

Time-resolved reflectivity measurements were performed with a sub-10-fs laser pulse, whose wavelength was centered on 780 nm. Figure 1(a) shows the time-resolved reflectivity of *p*-type Si. The *p*-type Si exhibits an asymmetric lineshape in the Raman measurement due to Fano resonance [inset in Fig. 1(a)]. The decay rate ($\Gamma_{cp}$) obtained from the time-resolved reflectivity is plotted as a function of temperature in Fig. 1(b), along with the Raman linewidths ($\Gamma_{Raman}$). The temperature dependence of $\Gamma_{Raman}$ can be explained with the anharmonic decay model [3], but that of $\Gamma_{cp}$ cannot be. The different temperature dependences between $\Gamma_{Raman}$ and $\Gamma_{cp}$ could be explained by how the Fano resonance modifies the frequency- and time-domain spectra, respectively. The frequency-domain spectrum (i.e., Raman spectrum), on one hand, is broadened due to Fano resonance [1]. As a result, $\Gamma_{Raman}$ in the *p*-type Si deviates from the anharmonic decay model. The time-resolved response, on the other hand, is given by the summation of exponential decaying and deltalike responses, originating from the discrete (i.e., phonon) and continuum states, respectively [4]. The short decay time of the continuum state enables us to extract the exponentially phonon decay without any distortion. As a result, the temperature dependence of $\Gamma_{cp}$ of the *p*-type Si reveals that the anharmonic decay model is dominant in *p*-type Si even under Fano resonance. We have shown that time-resolved measurements can extract discrete-state dynamics free from the interaction with the continuum state even under Fano resonance.

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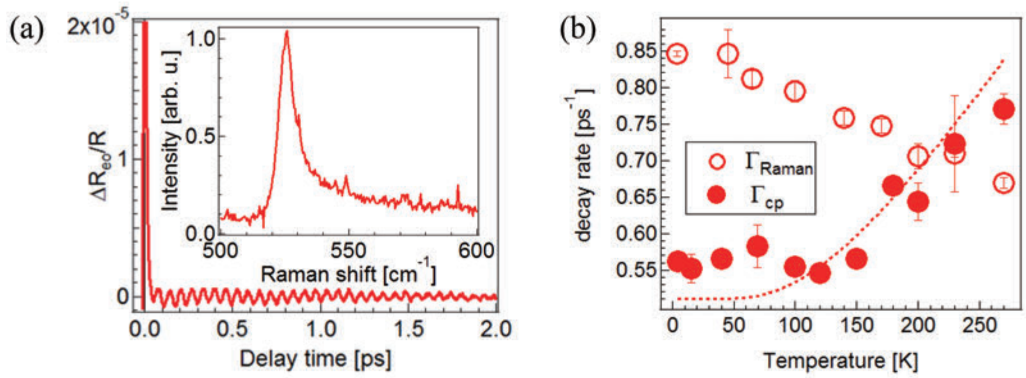


Fig. 1. (a) Time-resolved reflectivity of *p*-type Si. The inset shows the Raman spectra of *p*-type Si. (b) Temperature dependence of the phonon decay rate. The solid and open symbols correspond to $\Gamma_{cp}$ and $\Gamma_{Raman}$, respectively. Dotted lines are the fits with the anharmonic decay models.

Optical Science Laboratory

# Frequency Stabilization of an Er-doped Fiber Laser with a Collinear *2f*-to-*3f* Self-referencing Interferometer

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Techniques for stabilizing the carrier-envelope offset (CEO) frequency of an optical frequency comb are prerequisites for precision spectroscopy. To stabilize an optical frequency comb, we need to generate a supercontinuum (SC) light, which broadens its spectrum. A 2*f*-to-3*f* self-referencing interferometer (SRI) is used for stabilizing the CEO frequency of an optical frequency comb that has only a 2/3-octave bandwidth of SC light. To stabilize such an optical frequency comb, we constructed a collinear 2*f*-to-3*f* SRI with a dual-pitch (DP-) periodically poled lithium niobate (PPLN) ridge waveguide [1].

The DP-PPLN ridge waveguide has two different pitch sizes ($\Lambda_1$ and $\Lambda_2$) to satisfy the quasi-phase matching conditions for generating second- and third-harmonic lights with a wavelength of 600 nm [Fig. 1(a)]. In the first part, second-harmonic light with a wavelength of 900 nm is generated from the SC component at around 1800 nm. In the second part, sum frequency light with a wavelength of 600 nm is generated from the SC component at 1800 nm and 900-nm second-harmonic light. In addition, in the second part, second-harmonic light with a wavelength of 615 nm is involved. If 615-nm second-harmonic light and 600-nm third-harmonic light spectrally overlap, a CEO beat signal is obtained. Figure 1(b) shows a CEO beat signal. The SNR of the CEO beat is 52 dB at the resolution bandwidth of 100 kHz. This is the highest SNR ever reported in a 2*f*-to-3*f* SRI.

Then, to evaluate the instability of the CEO frequency, we measured Allan deviations for both in-loop and out-of-loop interferometers, where the former was used for stabilizing an Er-doped fiber laser and the latter was used for monitoring the actual instability. The results showed that both the in-loop and out-of-loop Allan deviations are $7\times10^{-15}$ (= 1.4 Hz) at gate time of 1 s [Fig. 1(c)]. Furthermore, we measured the Allan deviations after we intentionally placed a small pump on the breadboard near the interferometer. We found that despite the pump vibration, both the in-loop and out-of-loop Allan deviations remained almost the same values. These results confirmed that our collinear 2*f*-to-3*f* SRI allows us to stabilize a CEO frequency regardless of environmental perturbation.

This work was supported by KAKENHI.

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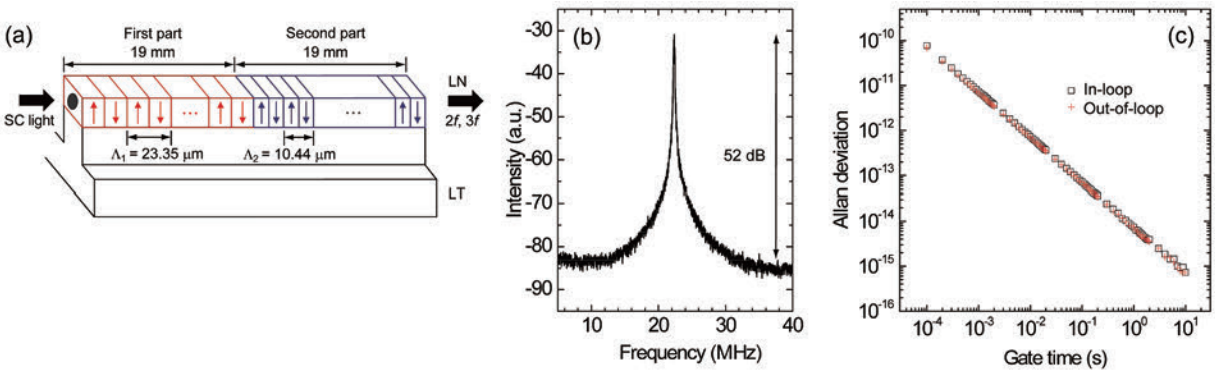


Fig. 1. (a) DP-PPLN ridge waveguide. (b) CEO beat signal. (c) Allan deviations of CEO frequencies.

# Long-distance Transport of Electron Spins in Persistent Spin Helix State

Yoji Kunihashi[1], Haruki Sanada[1], Hideki Gotoh[1], and Koji Onomitsu[2]
[1]Optical Science Laboratory, [2]Materials Science Laboratory

Future information processing techniques using electron spins in non-magnetic semiconductors will require both the manipulation and transfer of spins without their coherence being lost. The effective magnetic field induced by a spin-orbit interaction (SOI) enables us to rotate the electron spins in the absence of an external magnetic field. However, the fluctuations in the effective magnetic field originating from the random scattering of electrons also cause undesirable spin decoherence, which limits the length scale of the spin transport. Here we report the electrical control of spin precession of drifting electrons in a robust spin structure, namely a persistent spin helix (PSH) where the Rashba and Dresselhaus SOIs are the same strength. We found that the PSH enhances the spatial coherence of drifting spins, resulting in a maximized spin decay length near the PSH condition. We also found that the spin precession period of drifting spins can be controlled by a gate-controlled SOI [1].

The sample consisted of a 25-nm-thick GaAs QW embedded in a HEMT structure. The wafer was processed into a cross-shaped channel with a top gate electrode (Fig. 1 inset). This structure allowed us to use in-plane voltages $V_x$ and $V_y$ to create drift motion, and a vertical gate voltage $V_g$ to tune the strengths of the SOIs. We measured the spatial spin distribution of drifting electrons using Kerr rotation microscopy at $T$ = 8 K. A circularly polarized pump light from a cw Ti:sapphire laser generated electron spins at a certain position and a linearly polarized light probed the Kerr rotation $\theta_K$, which was proportional to the spin density at the focused position. Figure 2(a) shows the $V_g$ dependence of the Kerr rotation angle $\theta_K$ scanned along the [1-10] direction for $V_x$ = 50 mV and $V_y$ = 0 mV. Even in the absence of an external magnetic field, we observed a spin precession resulting from the effective magnetic field induced by the SOIs. By varying the gate voltage, the spatial frequency of the drifting spin precession was continuously modulated via the gate control of the Rashba SOI. We also estimated the gate voltage dependence of the spin decay length $l_S$ over which the spin density decays to $1/e$ of its initial value. In Fig. 2(b), $l_S$ is plotted as a function of the spin rotation length $L_{SO}$, which is inversely proportional to the SOI. We found that $l_S$ has its maximum value in the PSH condition, and this behavior was well reproduced by a simulation based on a spin drift-diffusion model. A comparison of the experimental and simulation results reveals that in the present sample the spin decay length is enhanced by suppressing the spin relaxation in the PSH condition.

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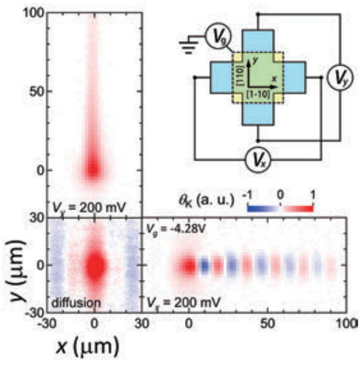



Fig. 1. Spatial distribution of diffusive and drifting spins in the PSH state. The inset shows a schematic image of the sample.

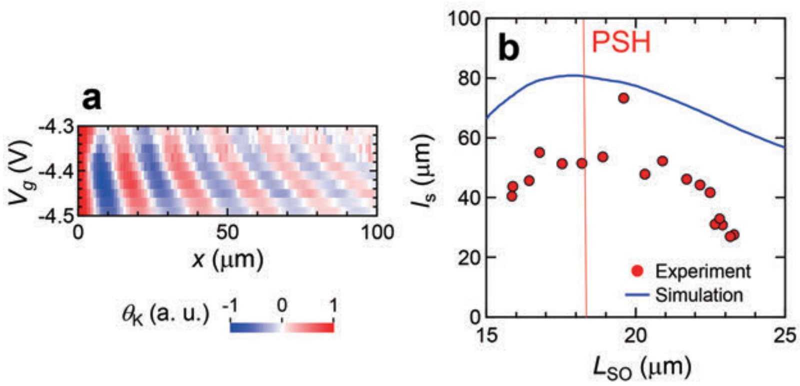



Fig. 2. (a) Gate voltage dependence of the spatial distribution of drifting spins in the [1-10] direction. (b) Spin decay length lS as a function of spin rotation length $L_{SO}$ in which an electron spin can rotate a full cycle.

# Thresholdless Oscillation in High-$\beta$ Buried Multiple-quantum-well Photonic Crystal Lasers

Masato Takiguchi[1,2], Hideaki Taniyama[1,2], Hisashi Sumikura[1,2],
Muhammad Danang Birowosuto[1,2], Eiichi Kuramochi[1,2], Akihiko Shinya[1,2],
Tomonari Sato[1,3], Koji Takeda[1,3], Shinji Matsuo[1,3], and Masaya Notomi[1,2]
[1]NTT Nanophotonics Center, [2]Optical Science Laboratory,
[3]NTT Device Technology Laboratories

A photonic crystal (PhC) cavity is promising for photonic network-on-chip architecture because its ultra-small mode volume and high quality factor will enable efficient and high-speed lasers and LEDs. To realize them, we study nano-emitters using buried multiple quantum wells (MQW) PhC cavities [Fig.1(a)]. Conventional QW-PhC have been extensively investigated, however they suffer from poor carrier confinement and surface non-radiative recombination. On the other hands, our buried MQW PhC cavities can exhibit distinctive spontaneous emission control [1] because of strong carrier confinement and low surface non-radiative recombination. Therefore spontaneous coupling factor ($\beta$) of our devices can be unity and theoretically-predicted thresholdless laser can be realised.

In this study, we have investigated the characteristics of high-$\beta$ buried MQW PhC lasers to clarify the thresholdless operation. To compare the nature of lasing operation for high and low $\beta$ values, we performed systematic measurements, such as L-L measurement and time resolved measurement, under a large and small detuning condition (2 nm and 15 nm detuning) as shown Fig. 1(b). From these results, we have unambiguously demonstrated high-$\beta$ lasing with a smoothed transition. In addition, we systematically investigated the dependence of $\beta$ on the detuning frequency, which was in good agreement with a numerical simulation based on the finite-difference time-domain method [Fig. 1(c)].

[1] M. Takiguchi et al., Appl. Phys. Lett. **103**, 091113 (2013).
[2] M. Takiguchi et al., Opt. Express **24**, 3441 (2016).

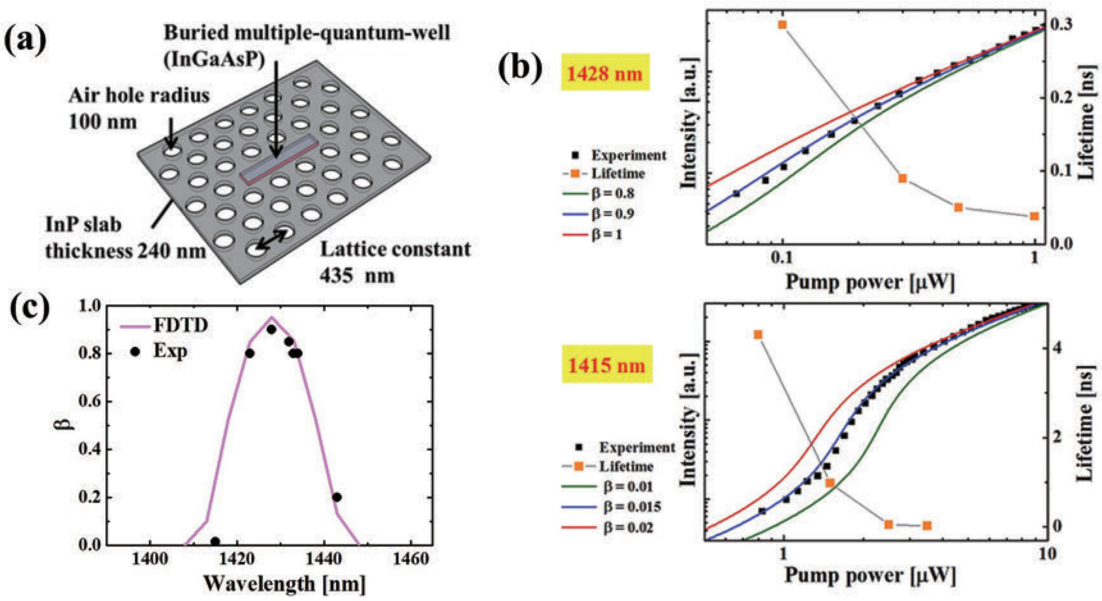



Fig. 1. (a) Schematic of L3 PhC cavity. (b) L-L curve. (c) Experimental and simulated $\beta$.

# Wavelength-scale All-optical Photonic Crystal Nanocavity Memory Operating at Nanowatt-level

Eiichi Kuramochi[1,2], Kengo Nozaki[1,2], Akihiko Shinya[1,2], Hideaki Taniyama[1,2], Koji Takeda[1,3], Tomonari Sato[1], Shinji Matsuo[1,3], and Masaya Notomi[1,2]
[1]NTT Nanophotonics Center, [2]Optical Science Laboratory,
[3]NTT Device Technology Laboratories

We are developing ultralow-power-consumption large-scale photonic integrated circuits on a chip using nanophotonic technologies. All-optical memory is one of the key devices. Since we need a considerably large memory, reducing power consumption is a crucial issue. We have realized an optical RAM with 30-nW operation using a wavelength-scale photonic crystal (PhC) nanocavity with a small buried heterostructure (BH) [1]. Here we describe a further one order of magnitude reduction of power consumption by employing a novel multi-hole-tuned three-missing-hole (L3) nanocavity with a BH placed at the cavity center [Fig. 1(a)] [2]. We used the same design as in [3], which enables large quality factor ($Q$) enhancement and multibit optical RAM operation [3]. In this study, a two-port filter design [Fig. 1(b)] was employed and $Q$ was enhanced to 45,000 and 210,000 with and without the InGaAsP BH, where the latter is the record high value among all InP-based nanocavities. Two multi-hole-tuned BH-L3 cavities (L3LM, L3M3) were operated as an all-optical bistable memory as shown in Fig. 1(c) and compared to the operation of mode-gap-confined BH nanocavity (MG1) reported before [1]. As shown in Fig. 1(d), L3M3 that had $Q$ comparable to MG1 decreased onset bias power to 10 nW thanks to the smaller mode volume ($V$) of the L3 nanocavity. Furthermore, L3M1 having much higher $Q$ (42,000) exhibited onset bias power of 2.3 nW, which is nearly 1/13 of MG1's, and the corresponding average number of photons in the cavity was only 0.1. Even at the 2.3-nW bias power, L3M1 operated with a very good "1"/"0" switching contrast [Fig. 1(e)]. This study paves the way for ultralow power consumption integrated photonic crystal devices and encourages the employment of multi-hole-tuned L-type nanocavities for fundamental and device studies.

[1] K. Nozaki et al., Nature Photon. **6**, 248 (2012).
[2] E. Kuramochi et al., Appl. Phys. Lett. **107**, 221101 (2015).
[3] E. Kuramochi et al., Nature Photon. **8**, 474 (2014).

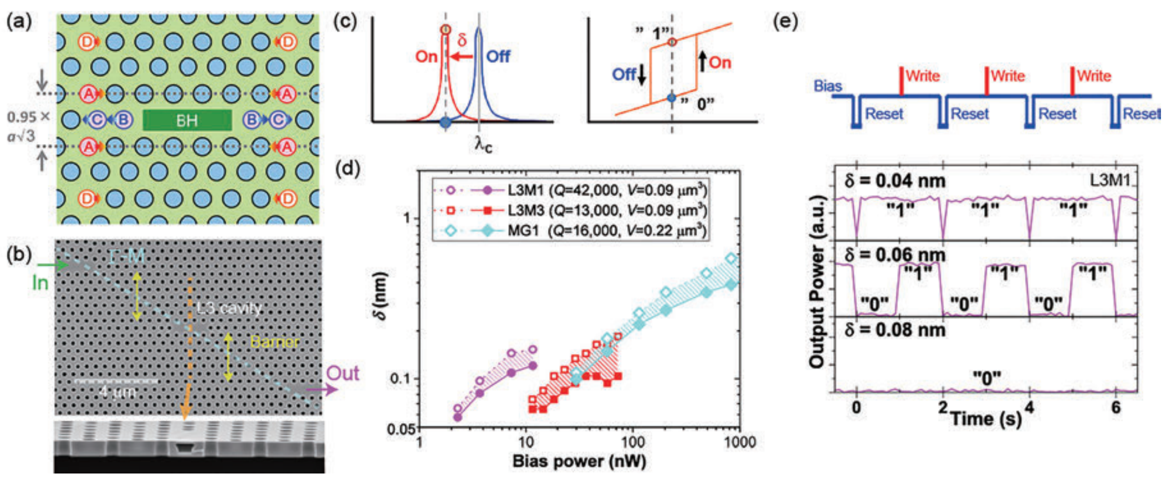



Fig. 1. (a) Design of systematically-tuned BH-L3. (Lattice constant ($a$): 426 nm. Shifts: 0.09$a$, 0.35$a$, 0.175$a$, and 0.045$a$ for A, B, C and D. BH is InGaAsP.) (b) SEM image of L3 optical memory. (c) Schematics of all-optical bistable memory operation. (d) Relation between detuning ($\delta$) and bias power for memory operation. (e) Input/output waveforms in memory operation at 2.3 nW bias power.

Optical Science Laboratory

# An All-optical Packet Switch Realized by Using the Ultralow-power Optical Bistability of a Nanocavity

Kengo Nozaki[1,2], Amedee Lacraz[2], Akihiko Shinya[1,2], Shinji Matsuo[1,3], Tomonari Sato[1,3], Koji Takeda[1,3], Eiichi Kuramochi[1,2], and Masaya Notomi[1,2]
[1]NTT Nanophotonics Center, [2]Optical Science Laboratory,
[3]NTT Device Technology Laboratories

A tiny semiconductor nanocavity allows a strong light-matter interaction with a low-power optical input, and is used for various functional nanophotonic devices. We achieved a buried heterostructure with which to form a nanocavity, as shown in Fig. 1(a), where an ultra-compact InGaAsP is buried in an InP photonic crystal (PhC). This nanocavity allowed us to strongly confine both photons and carriers, thus enabling us to realize bistable behavior even with nW-level optical power, as shown in Fig. 1(b). Thus bistable switching between “on” and “off” states can be obtained by combining a CW bias light and an optical pulse input, and thereby make it possible to realize an all-optical memory. As an extended application, in this research, we demonstrated that it can work as an all-optical packet switch [1].

For this demonstration, a write pulse (100 ps wide, 13 fJ), a CW bias light (0.8 μW), and a reset pulse (50 ns wide) were injected to switch the bistable states, and the optical packet data (10 Gbit/s, 1 ns long, NRZ signal) to be switched were also injected, as shown in Fig. 1(c). As a result, we confirmed that the bistable states were switched with the output bias light, and gate switching for the optical packet was successfully achieved, as shown in Fig. 1(d). Furthermore, we also investigated a 1×2-port configuration, as shown in Fig. 2(a). This realized output-port-selective switching for the optical packet via bistable memory switching as well as gate switching, as shown in Fig. 2(b). The ultralow-power all-optical packet switch that we achieved is promising in terms of realizing a chip-scale high-speed photonic routing circuit that does not need E-O/O-E signal conversion.

[1] K. Nozaki, A. Lacraz, A. Shinya, S. Matsuo, T. Sato, K. Takeda, E. Kuramochi, and M. Notomi, Opt. Express **23**, 30379 (2015).

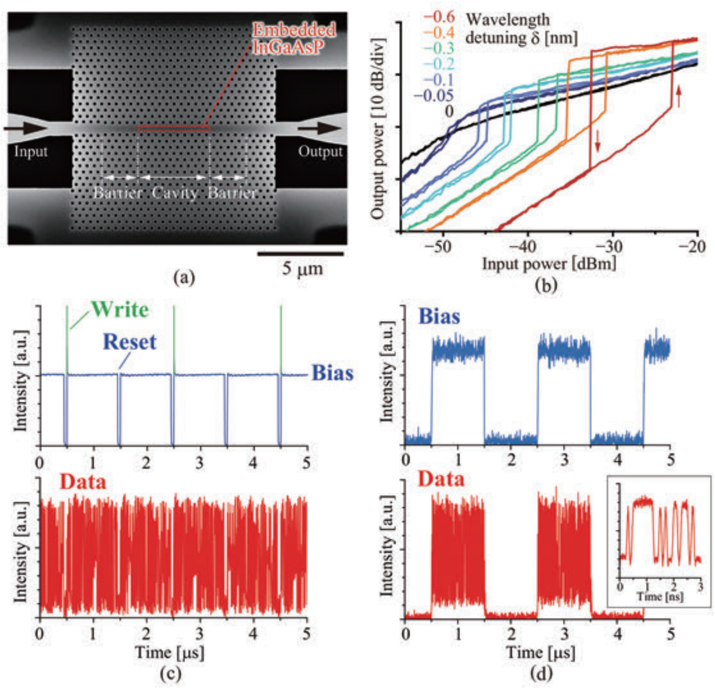



Fig. 1. (a) Photograph of photonic crystal nanocavity. (b) Hysteresis curves on optical input/output characteristic. (c) Input optical waveforms. (d) Output waveforms showing the gate switching of optical packet data.

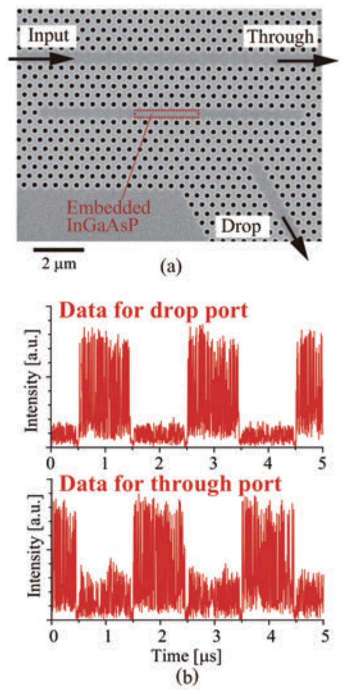



Fig. 2. (a) 1×2-port configuration of nanocavity. (b) Output waveforms showing the output-port-selective switching of optical packet data.

# Membrane Distributed-reflector Laser Integrated with $SiO_x$-based Spot-size Converter on Si Substrate


Hidetaka Nishi[1,2], Takuro Fujii[1,2], Koji Takeda[1,2], Koichi Hasebe[1,2],
Takaaki Kakitsuka[1,2], Tai Tsuchizawa[1,2], Tsuyoshi Yamamoto[2], and Shinji Matsuo[1,2]
[1]NTT Nanophotonics Center, [2]NTT Device Technology Laboratories


To meet requirements towards the new era of datacenter networks, we have proposed and realized membrane DFB lasers. Thanks to the strong optical confinement, the energy cost can be reduced to 171 fJ/bit for 25.8-Gbit/s NRZ modulation signal, which is the highest energy efficiency for DFB lasers to the best of our knowledge [1]. In addition, to obtain low-loss fiber coupling with Si high-refractive-index-difference (high-Δ) waveguides, we have also developed a spot-size converter (SSC) based on a low-Δ silicon-oxide ($SiO_x$) waveguide [2]. In this work, we achieved a further decrease of the energy cost by introducing a distributed-reflector (DR) laser structure and a reduction of fiber-coupling loss by integrating a $SiO_x$-based SSC.

Figures 1(a) and (b) show a schematic of the device structure and a top-view image of a fabricated device, respectively. The DR laser consists of a DFB section with uniform grating, a rear DBR section, and a front InP-wire waveguide. The DFB region has a $\kappa$ of 1500 $cm^{-1}$ and a buried heterostructure comprising InGaAsP-based six-QW layers (150-nm thick, 50-µm long, 0.8-µm wide) embedded with 250-nm-thick InP. Both the rear DBR section and output waveguide are made of InP. A compact cavity can be achieved by employing a DBR with high reflectivity. The output InP waveguide is tapered horizontally and connected with the low-Δ $SiO_x$ waveguide via the SSC.

Figure 1(c) shows current-versus-output-power (*I-L*) characteristics. The curve measured by a PD set in front of the $SiO_x$ waveguide facet shows a big kink with injection current between 5 and 6 mA. This is due to the reflection at the boundary between air and the $SiO_x$ waveguide. In contrast, the curve obtained by a high-NA fiber butt-coupled to the $SiO_x$-waveguide facet exhibits no kink thanks to the suppression of the reflection. The threshold current is 0.6 mA and the maximum output power is 0.7 mW. The fiber coupling loss is estimated to be 2.7 dB, which is 6-dB lower than our previous device. Then, we measured eye diagrams for 25.8-Gbps NRZ modulation. Figure 1(d) and (e) shows an diagram obtained with bias currents ($I_b$) of 5.0 and 2.5 mA, respectively. At $I_b$ = 2.5 mA, we achieved lower an energy cost of 132 fJ/bit.


[1] S. Matsuo et al., J. Lightwave Technol. **33**, 1217 (2015).
[2] T. Tsuchizawa et al., J. Sel. Top. Quantum Electron. **17**, 516 (2011).

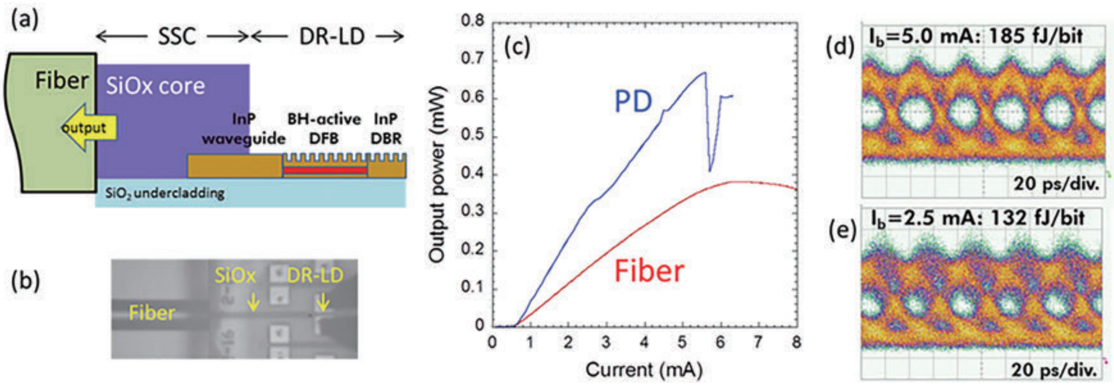




Fig. 1. (a) Schematic device structure. (b) Top-view image of a fabricated device. (c) *I-L* characteristics. (d) (e) Eye diagrams for 25.8-Gbps NRZ direct modulation with $I_b$ of 5.0 mA and 2.5 mA.

# Dislocation Reduction in MOVPE-grown GaAs/Ge Layers on Si Substrates by Thermal Cycle Annealing

Ryo Nakao[1,2], Masakazu Arai[1,2], Tsuyoshi Yamamoto[2], and Shinji Matsuo[1,2]
[1]NTT Nanophotonics Center, [2]NTT Device Technology Laboratories

Direct growth of III-V compound semiconductor has been desired for 30 years. Recently, incorporating a Ge buffer layer between Si and GaAs III-V compound semiconductor has been studied to improve the crystalline quality because Ge's lattice constant is very close to GaAs's [1]. Monogermane ($GeH_4$) is widely used as a material source for the Ge buffer layer. However, $GeH_4$ is explosive material. Thus, the Ge buffer layer cannot be grown in the same reactor used for GaAs epitaxial growth [2]. Instead of using $GeH_4$, we used metal-organic material iso-butyl germane (IBGe) as a Ge precursor. The Ge buffer layer and GaAs were grown in the same metal-organic vapor phase epitaxy (MOVPE) reactor. Figure 1(a) shows the cross-sectional transmission electron microscopy (TEM) image of a GaAs/Ge structure grown on Si substrate. At the boundary between the GaAs and Ge layer, dislocations can be seen. The dislocations penetrated the epitaxial layer surface. To reduce the dislocations, we performed thermal cycle annealing (TCA) after the GaAs and Ge layer growth [3]. As shown in Fig. 1(b), the dislocations at the GaAs/Ge boundary were significantly suppressed by TCA. Moreover, by employing TCA, the intensity of photoluminescence (PL) measured from InGaAs/GaAs multiple quantum wells (MQWs) grown on the GaAs epitaxial layer increased by a factor of three (Fig. 2). This is indicates that the crystalline quality was improved by TCA. On the other hand, the PL intensity was 11% smaller than that for MQWs on GaAs substrate. Further improvement of growth and annealing conditions will provide crystalline quality comparable to GaAs substrate. These results indicate that the MOVPE-grown GaAs/Ge layers are well-suited for integrating a light source onto Si substrate.

[1] A. Lee et al., Opt. Express **20**, 22181 (2012).
[2] M. E. Groenert et al., J. Appl. Phys. **93**, 362 (2003).
[3] R. Nakao et al., in Electronic Materials Symposium **34**, Th-2-3 (2015).

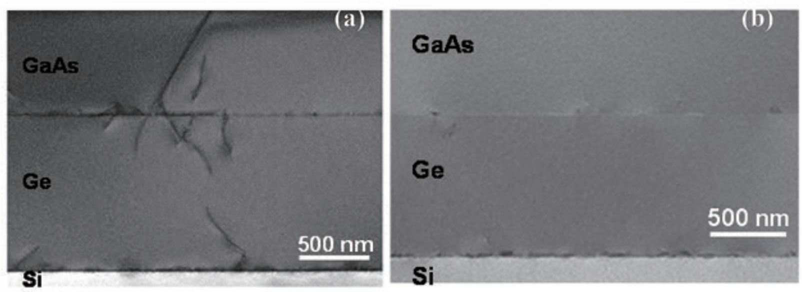



Fig. 1. Cross-sectional TEM images of (a) as-grown GaAs/Ge structure on Si substrate and (b) after TCA.

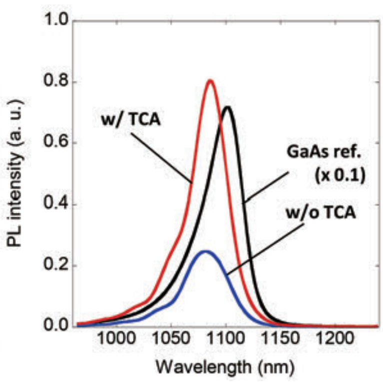


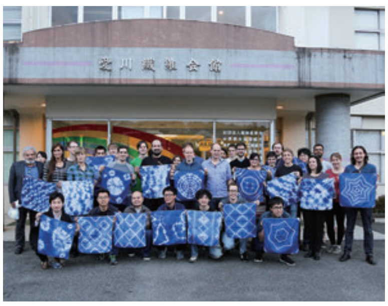

Fig. 2. PL spectra from MQWs.

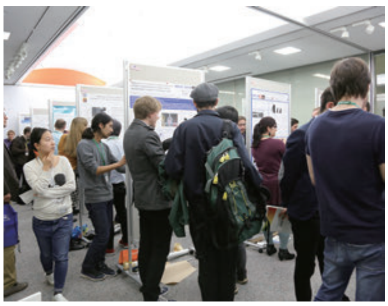
# Ⅱ. Data

# 7th NTT-BRL School

The seventh NTT Basic Research Laboratories (BRL) School was held on November 15-17th, 2015 at NTT Atsugi R&D Center. The aim of the school was to foster young researchers working in the material, nano and quantum science fields and to promote the international visibility of NTT BRL. This year the theme of the school was “Nano and Optics”, and was closely related to ongoing research within NTT BRL. Prestigious professors and researchers were invited to participate as lecturers. We accepted thirty (mainly PhD) students from eleven countries.

On the first day, Prof. Gerhard Abstreiter (Walter Schottky Institute, Technische Universität München) gave a lecture entitled “Physics and Technology of Semiconductor Hetero- Nano- and Quantum Structures”. His lectures covered topics ranging from basic semiconductor physics to fabrication technologies, and device applications for low-dimensional structures. In addition, the director of NTT BRL, Dr. Tetsuomi Sogawa, provided an introduction to NTT BRL and we conducted a laboratory tour to show our research facilities and to introduce recent research activities at NTT BRL. On the second day, Prof. Yasuhiko Arakawa (The University of Tokyo) gave a lecture entitled “Progress in Quantum Dot Photonics” and also introduced the “International Year of Light 2015” as the President of The International Commission for Optics (ICO). Dr. Masaya Notomi (Senior Distinguished Researcher) and Dr. William J. Munro (Distinguished Researcher) gave lectures entitled “Nanophotonics for Large-scale Integration” and “Quantum Fun with Photons”, respectively. After the lectures, the students went on an excursion to Aikawa City, which is close to the NTT Atsugi R&D Center and enjoyed the hands-on experience of learning indigo tie-dyeing, a traditional Japanese craft. On the third day, Prof. Tobias Kippenberg (École Polytechnique Fédérale de Lausanne) gave a lecture on “Cavity Optomechanics”. In the afternoon, the students attended the International Symposium on Nanoscale Transport and Technology (ISNTT) hosted by NTT BRL. As part of this event, the students gave poster presentations on their research. The students, lecturers, and NTT BRL researchers all had an excellent time exchanging information on current research topics in various fields. At a joint BRL School and ISNTT party, “Best Poster Prizes” were awarded to three students who gave noteworthy poster presentations. The students had the opportunity to discuss high-quality research and build human networks and friendships within this school. NTT BRL will continue to provide these occasions to support young researchers and to establish research collaborations in the fields of material, nano and quantum science.

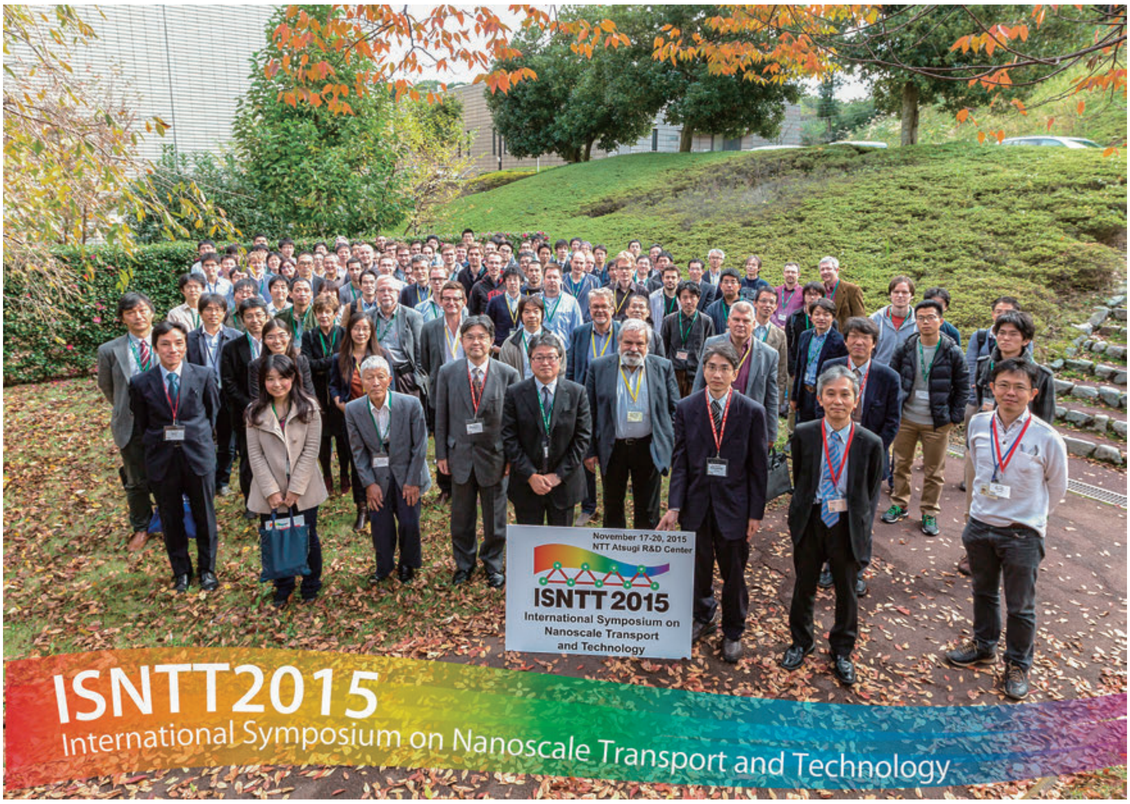


# ISNTT2015

The International Symposium on Nanoscale Transport and Technology (ISNTT2015) was held at NTT Atsugi R&D Center from November 17 to 20, 2015, and brought together 179 participants from 15 countries. The participants enjoyed oral and poster presentations at the symposium, exchanging their views and ideas on nanotechnology and quantum devices. Since 2009, NTT Basic Research Laboratories (BRL) has been holding ISNTT every two years to promote mutual exchanges between those working on different device and material technologies related to semiconductors, superconductors, and new materials, with the aim of creating new ideas and concepts with which to build new hybrid nanoscale and/or quantum systems.

ISNTT2015 was co-chaired by Drs. Akira Fujiwara, Hiroshi Yamaguchi, and Koji Muraki of NTT BRL. The symposium logo of ISNTT2015 represents the combination of nanostructures to create new functions. On the 17th, 18th, and 20th, respectively, the sessions started with keynote lectures entitled “Semiconductor Hetero-Nanowires on Si for Photonic and Electronic Applications” by Prof. Gerhard Abstreiter (Walter Schottky Institute, Technische Universität München), “Levitons: Clean Time-Resolved Electrons for Electron Quantum Optics” by Prof. Christian Glattli (CEA Sacley), and “Interaction between Sound and a Superconducting Qubit” by Prof. Per Delsing (Chalmers University of Technology). During the symposium we enjoyed 13 oral sessions with 46 oral presentations including 17 invited talks by world leading researchers, on such topics as nanophotonics, nanomechanics, quantum and spin-related electron transport, topological insulator, spintronics, single-electron devices, and semiconductor/superconductor quantum bit devices. On the 17th and 18th, two poster sessions were held and the first was a joint event with the 7th NTT-BRL School. 56 presentations were made at the poster sessions. The symposium offered many opportunities for interaction between senior and young researchers including 30 students. NTT BRL believes in the importance of providing such opportunities, and it is part of our open laboratory policy.

ISNTT2015
International Symposium on
Nanoscale Transport and Technology



# List of Visitors' Talks

| Date | Speaker (Affiliation) | Title |
|---|---|---|
| Apr. 20 | Prof. Masayuki Katsuragawa (The University of Electro-Communications, Japan) | Attractive natures in optical processes driven by a discrete coherent spectrum |
| May 12 | Dr. Erik Gauger (Heriot-Watt University, U.K.) | Superabsorption, dark-state protection and optical ratchets: Harnessing collective effects for enhanced light absorption with coupled nanostructures |
| June 5 | Prof. Toshinori Suzuki (Kyoto University, Japan) | Probing chemical reactions using ultrafast lasers in vacuum UV and hard X-ray regions |
| June 19 | Mr. Yuya Seki (Tokyo Institute of Technology, Japan) | Quantum annealing: the current problems and possible solutions |
| June29 | Prof. Takaharu Okajima (Hokkaido University, Japan) | Physics of the cell: measurement of mechanical properties of cells |
| July 3 | Mr. Ryan Hamerly (Stanford University, U.S.A.) | Theory of Coherent Ising Machine: Pulse-shape Dynamics in Synchronously Pumped Optical Parametric Oscillators |
| July 14 | Prof. John Clarke (University of California, Berkeley, U.S.A.) | The Flux Qubit Revisited: Enhanced T1 and T2 |
| July 23 | Dr. Richard J. E. Taylor (University of Sheffield, U.K.) | Coherently Coupled 2D Photonic Crystal Surface Emitting Laser Arrays |
| July 23 | Dr. Stefan Heun (The National Enterprise for nanoscience and nanoTechnology, Italy) | 2D Materials Research Activities at the NEST lab in Pisa, Italy |
| July 23 | Dr. Alberto Hernández-Mínguez (Paul Drude Institute for Solid State Electronics, Germany) | High-frequency surface acoustic waves on gated graphene |
| July 23 | Dr. Francois D. Parmentier (CEA Saclay, France) | Quantum Limit of Heat Flow Across a Single Electronic Channel |
| July 24 | Mr. Robinjeet Singh (Louisiana State University, U.S.A.) | Quantum Back-action Limited Optomechanical Cavity Using Microresonator: Towards Calibration of Quantum Noises for LIGO |
| July 28 | Dr. Koki Kamiya (Kanagawa Academy of Science and Technology, Japan) | Bottom-up reconstitution of artificial cellular system |

| | | |
|---|---|---|
| July 31 | Prof. Reinhold Koch<br>(Johannes Kepler University, Austria) | Radio-Frequency Scanning Tunneling Spectroscopy for Single-Molecule Spin Resonance |
| Aug. 3 | Dr. Toshiyuki Tashima<br>(Osaka University, Japan) | Extention, Fusion and Conversion of Multi-Photon Entangled State / Quantum Information Using Solid-State Paramagnetic Center |
| Aug. 3 | Dr. Andrey A. Shevyrin<br>(Rzhanov Institute of Semiconductor Physics, Russia) | Suspended nanostructures with two-dimensional electron gas: electron transport and electromechanical effects |
| Aug. 3 | Dr. Stefan Fölsch<br>(Paul Drude Institute for Solid State Electronics, Germany) | Controlling the charge state and conductance of a single molecule by electrostatic gating |
| Aug. 7 | Dr. Hans Hübl<br>(Walther-Meissner-Institute, Germany) | Hybrid Systems–Coupling spins, strings, and superconducting resonators |
| Aug. 7 | Dr. Aleksey Andreev<br>(Hitachi Cambridge Laboratory, U.K.) | Modelling of Si quantum bits and light emission in Si/Ge |
| Aug. 24 | Dr. Shungo Miyabe<br>(RIKEN, Japan) | Ultrafast probing of photoexcited molecular dynamics; an investigation towards molecular control |
| Sep. 25 | Prof. Shiro Tsukamoto<br>(Anan National College of Technology, Japan)<br>Prof. Hiroki Hibino<br>(Kwansei Gakuin University, Japan) | Recent progress on microscopy of graphene |
| Sep. 25 | Dr. JT Janssen (T. J. B. M. Janssen)<br>(National Physical Laboratory, U.K.) | Quantum Electrical Metrology with Graphene |
| Oct. 22 | Dr. Benjamin Piot<br>(Grenoble High Magnetic Field Laboratory, France) | Low dimensional electronic systems in high magnetic fields: Recent experiments |
| Oct. 22 | Prof. Dominik Zumbuhl<br>(University of Basel, Switzerland) | Breaking the mK barrier in Nanoelectronics |
| Dec. 16 | Dr. Michael J. Burek<br>(Harvard University, U.S.A.) | Free-standing nanomechanical and nanophotonic structures in single-crystal diamond |
| Dec. 18 | Dr. Michal Karpinski<br>(University of Oxford, U.K.) | Electro-optic spectral manipulation of pulsed quantum light |
| Feb. 4 | Dr. Tomoya Akatsuka<br>(RIKEN, Japan) | Development of optical lattice clocks and delivery of the clock frequency using an optical fiber link |
| Mar. 22 | Mr. Tomoki Ito<br>(Tohoku University, Japan) | Self assebly of light emitting Ge nanostrucutres on Si for Si photonics |

# List of Award Winners

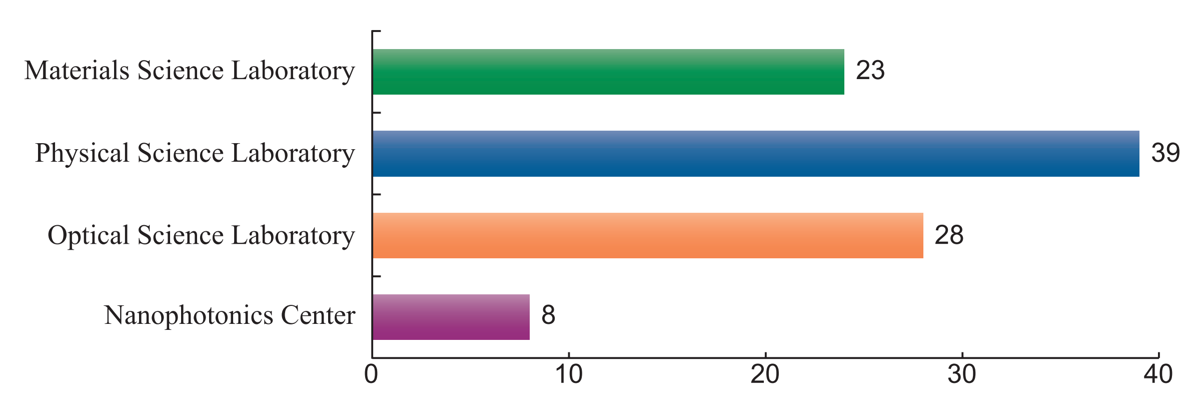
| Award | Award Winners | Title | Date |
|---|---|---|---|
| The 62nd JSAP Spring Meeting, 2015, Poster Award | T. Teshima<br>S. Tsukada<br>N. Kasai<br>S. Sasaki<br>A. Tanaka<br>H. Nakashima<br>K. Sumitomo | Conductive silk films for manipulation of adherent cells | Apr. 1, 2015 |
| 45th Senken Gousen Prize New Frontier Award | Nippon Telegraph and Telephone Corporation<br>Toray Industries | Development of functional fabric "hitoe®" | Apr. 24, 2015 |
| Analytical Sciences Hot Article Award | Y. Ueno<br>K. Furukawa<br>A. Tin<br>H. Hibino | On-chip FRET Graphene Oxide Aptasensor: Quantitative Evaluation of Enhanced Sensitivity by Aptamer with a Double-stranded DNA Spacer | Sep. 10, 2015 |
| JSAP<br>Young Scientist Award | D. Hatanaka | Mechanical random access memory in a phonon circuit | Sep. 13, 2015 |
| MNC 2014 Award for Most Impressive Presentation | D. Hatanaka<br>I. Mahboob<br>K. Onomitsu<br>H. Yamaguchi | All-Mechanical Bistable Memory In A Phonon Waveguide | Nov. 11, 2015 |
| MNC 2014 Award for Most Impressive Poster | K. Yamazaki<br>H. Yamaguchi | Renovation of Three-Dimensional Electron Beam Lithography System for Improvement of Positioning Accuracy and Reduction of Turnaround Time | Nov. 11, 2015 |
| The Surface Science Society of Japan Young Scientist Award | M. Ohtomo<br>Y. Sekine<br>H. Hibino<br>H. Yamamoto | Etching-free Transfer of Highly-aligned Bottom-up Graphene Nanoribbon Arrays on Au(788) Template | Feb. 8, 2016 |
| 20th Award on Superconductivity Science and Technology | H. Yamamoto<br>Y. Krockenberger<br>M. Naito | Discovery of Undoped Cuprate Superconductors and Research on its Physical Properties | Mar. 3, 2016 |
| JSAP Silicon Technology Division Incentive Award | J. Noborisaka | Electric tuning of direct-indirect optical transitions in silicon | Mar. 21, 2016 |
| Excellent Woman Researcher Award of The Electrochemical Society of Japan | N. Kasai | Nanobio-interfaces for detection and controlling of biological information | Mar. 30, 2016 |

# List of In-house Award Winners

| Award | Award Winners | Title | Date |
|---|---|---|---|
| NTT Science and Core Technology Laboratory Group Director's Award | K. Muraki<br>K. Suzuki<br>N. Kumada<br>K. Onomitsu | Realization of nontrivial electronic states using semiconductor heterostructures | Dec. 17, 2015 |
| NTT Science and Core Technology Laboratory Group Director's Award | K. Nozaki<br>E. Kuramochi<br>A. Shinya<br>S. Matsuo<br>M. Notomi | Development of ultralow-power many-bit optical random-access memory (RAM) based on photonic crystal | Dec. 17, 2015 |
| BRL Director's Award<br>Award for Achievements | N. Kumada<br>H. Hibino<br>K. Sasaki | Charge excitation and Relaxation Dynamics in Graphene | Mar. 25, 2016 |
| BRL Director's Award<br>Award for Achievements | K. Azuma<br>K. Tamaki<br>W. J. Munro | Proposals of Novel Concepts in Quantum Repeaters and Quantum Key Distribution | Mar. 25, 2016 |
| BRL Director's Award<br>Award for Excellent Papers | K. Hirama<br>Y. Taniyasu<br>S. Karimoto<br>Y. Krockenberger<br>H. Yamamoto | "Single-crystal cubic boron nitride thin films grown by ion-beam-assisted molecular beam epitaxy"<br>Applied Physics Letters **104**, 092113 (2014). | Mar. 25, 2016 |
| BRL Director's Award<br>Award for Excellent Papers | H. Okamoto<br>R. Ohta<br>K. Onomitsu<br>H. Gotoh<br>H. Yamaguchi | "Cavity-less on-chip optomechanics using excitonic transitions in semiconductor heterostructures"<br>Nature Communications **6**, 8478 (2015). | Mar. 25, 2016 |
| BRL Director's Award<br>Award for Best Paper for Environmental Contribution | K. Nozaki<br>A. Shinya<br>H. Taniyama<br>M. Notomi | "Sub-femtojoule all-optical switching using a photonic-crystal nanocavity"<br>Nature Photonics **4**, 477 (2010). | Mar. 25, 2016 |
| BRL Director's Award<br>Award for Performance | M. Yamaguchi<br>T. Kimura | Contribution to the Development of the Sports Brain Laboratory | Mar. 25, 2016 |
| BRL Director's Award<br>Award for Encouragement | A. Tanaka | Research for Functional and Structural Control of Neurons and Artificial Cells | Mar. 25, 2016 |
| BRL Director's Award<br>Award for Encouragement | Y. Matsuzaki | Development of a Theoretical Framework on a Superconducting Hybrid Quantum System | Mar. 25, 2016 |
| Special BRL Director's Award | H. Ueshima<br>H. Itou<br>M. Yamaguchi | Design & Establishment of a Secure Network Environment in the Basic Research Laboratories | Mar. 25, 2016 |

# Number of Papers

The number of papers published in international journals in fiscal 2015 is 98. Also the number of papers published in major journals are shown below.



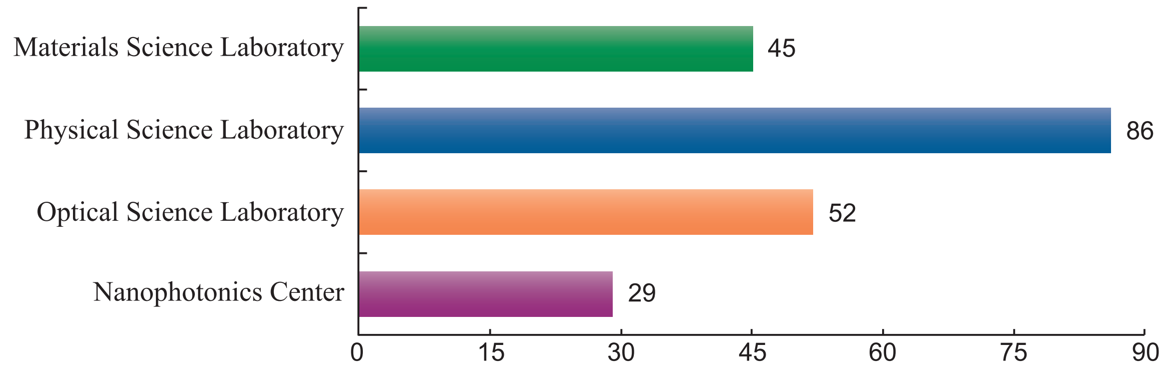

| Journals | IF2014 | Numbers |
|---|---|---|
| Physical Review A | 2.808 | 10 |
| Applied Physics Letters | 3.302 | 9 |
| Physical Review B | 3.736 | 7 |
| Japanese Journal of Applied Physics | 1.127 | 7 |
| Nature Communications | 11.470 | 6 |
| Physical Review Letters | 7.512 | 5 |
| New Journal of Physics | 3.558 | 5 |
| IEEE Journal of Selected Topics in Quantum Electronics | 2.828 | 4 |
| Applied Physics Express | 2.365 | 4 |
| Optics Express | 3.488 | 3 |
| Journal of Applied Physics | 2.183 | 3 |
| Physical Review Applied | — | 3 |
| Nano Letters | 13.592 | 2 |
| ACS Nano | 12.881 | 2 |
| Scientific Reports | 5.578 | 2 |
| Journal of Crystal Growth | 1.698 | 2 |
| Journal of Physical Society of Japan | 1.585 | 2 |
| AIP Advances | 1.524 | 2 |
| Science | 33.611 | 1 |
| Nature Photonics | 32.386 | 1 |
| Nature Physics | 20.147 | 1 |
| Chemistry of Materials | 8.354 | 1 |
| Nanotechnology | 3.821 | 1 |
| Science Advances | — | 1 |
| Optica | — | 1 |

***IF2014: Impact Factor 2014**

The average IF2014 for all research papers from NTT Basic Research laboratories is 4.847.

# Number of Presentations

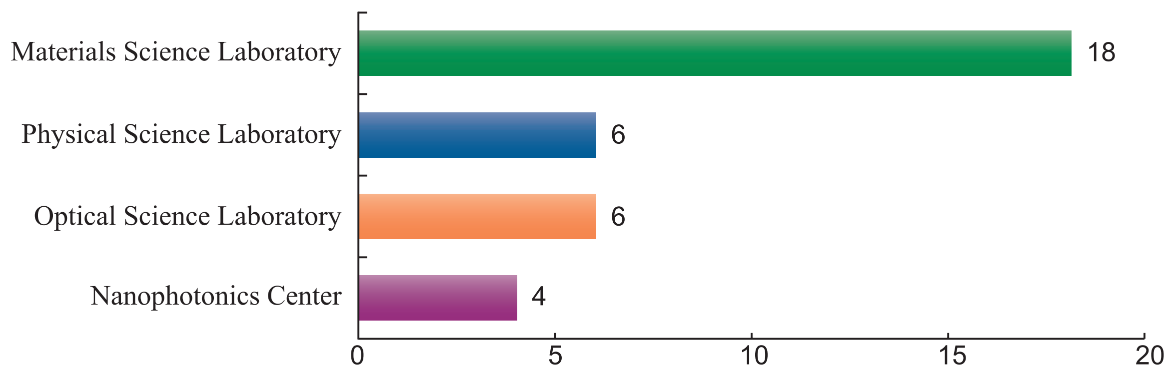
The number of presentations at international conferences in fiscal 2015 is 212. Also the number of presentations in major conferences are shown below.




| Conferences | Numbers |
|---|---|
| 21st International Conference on Electronic Properties of Two-Dimensional Systems / 17th International Conference on Modulated Semiconductor Structures (Joint Conference EP2DS-21/MSS17) | 26 |
| International Symposium on Nanoscale Transport and Technology (ISNTT2015) | 25 |
| The Conference on Lasers and Electro-Optics (CLEO/QELS 2015) | 13 |
| 2015 International Conference on Solid State Devices and Materials (SSDM 2015) | 8 |
| APS March Meeting 2016 | 7 |
| 5th International Conference on Quantum Cryptography (QCrypt2015) | 6 |
| 28th International Microprocesses and Nanotechnology Conference (MNC 2015) | 5 |
| International Workshop : Quantum Nanostructures and Electron-Nuclear Spin Interactions | 4 |
| Silicon Quantum Electronics Workshop 2015 | 4 |

# Number of Patents

The number of applied patents in fiscal 2015 is 34.



# Publication List


| | |
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| (1) | H. Ago, Y. Ohta, H. Hibino, D. Yoshimura, R. Takizawa, Y. Uchida, M. Tsuji, T. Okajima, H. Mitani, and S. Mizuno, "Growth Dynamics of Single-layer Graphene on Epitaxial Cu Surfaces", Chem. Mat. **27**, 5377-5385 (2015). |
| (2) | H. Akazawa and Y. Ueno, "Control of Surface Wettability of Hydroxyapatite Thin Films by Way of Crystal Imperfections", Appl. Phys. Express **8**, 107001 (2015). |
| (3) | R. Asaoka, H. Tsuchiura, M. Yamashita, and Y. Toga, "Dynamical Instability in the S=1 Bose-Hubbard Model", Phys. Rev. A **93**, 013628 (2016). |
| (4) | K. Azuma, K. Tamaki, and W. J. Munro, "All-photonic Intercity Quantum Key Distribution", Nat. Commun. **6**, 10171 (2015). |
| (5) | K. Azuma, K. Tamaki, and H. K. Lo, "All-photonic Quantum Repeaters", Nat. Commun. **6**, 6787 (2015). |
| (6) | H. Cai, Y. Matsuzaki, K. Kakuyanagi, H. Toida, X. Zhu, N. Mizuochi, K. Nemoto, K. Semba, W. J. Munro, S. Saito, and H. Yamaguchi, "Analysis of the Spectroscopy of a Hybrid System Composed of a Superconducting Flux Qubit and Diamond NV Centers", J. Phys.: Condes. Matter **27**, 345702 (2015). |
| (7) | P. A. Carles, K. Nishiguchi, and A. Fujiwara, "Deviation from the Law of Energy Equipartition in a Small Dynamic-random-access Memory", Jpn. J. Appl. Phys. **54**, 06FG03 (2015). |
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| (13) | T. Fujii, T. Sato, K. Takeda, K. Hasebe, T. Kakitsuka, and S. Matsuo, "Epitaxial Growth of InP to Bury Directly Bonded Thin Active Layer on $SiO_2$/Si Substrate for Fabricating Distributed Feedback Lasers on Silicon", IET Optoelectron. **9**, 151-157 (2015). |
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(86) H. Takesue, E. Diamanti, R. Thew, and Z. L. Yuan, "Introduction to the Issue on Quantum Communication and Cryptography", IEEE J. Sel. Top. Quantum Electron. **21**, 0200402 (2015).

(87) M. Takiguchi, H. Taniyama, H. Sumikura, M. D. Birowosuto, E. Kuramochi, A. Shinya, T. Sato, K. Takeda, S. Matsuo, and M. Notomi, "Systematic Study of Thresholdless Oscillation in High-beta Buried Multiple-quantum-well Photonic Crystal Nanocavity Lasers", Opt. Express **24**, 3441-3450 (2016).

(88) T. Tanaka, P. Knott, Y. Matsuzaki, S. Dooley, H. Yamaguchi, W. J. Munro, and S. Saito, "Proposed Robust Entanglement-based Magnetic Field Sensor Beyond the Standard Quantum Limit", Phys. Rev. Lett. **115**, 170801 (2015).

(89) A. Tanaka, R. Tanaka, N. Kasai, S. Tsukada, T. Okajima, and K. Sumitomo, "Time-lapse Imaging of Morphological Changes in a Single Neuron During the Early Stages of Apoptosis Using Scanning Ion Conductance Microscopy", J. Struct. Biol. **191**, 32-38 (2015).

(90) A. Tanaka, H. Nakashima, Y. Kashimura, and K. Sumitomo, "Electrostatically Induced Planar Lipid Membrane Formation on a Cationic Hydrogel Array by the Fusion of Small Negatively Charged Unilamellar Vesicles", Colloid Surf. A-Physicochem. Eng. Asp. **477**, 63-69 (2015).

(91) H. Toida, Y. Matsuzaki, K. Kakuyanagi, X. Zhu, W. J. Munro, K. Nemoto, H. Yamaguchi, and S. Saito, "Electron Paramagnetic Resonance Spectroscopy Using a Direct Current-SQUID Magnetometer Directly Coupled to an Electron Spin Ensemble", Appl. Phys. Lett. **108**, 052601 (2016).

(92) T. Uchida, M. Jo, A. Tsurumaki-Fukuchi, M. Arita, A. Fujiwara, and Y. Takahashi, "Fabrication and Evaluation of Series-triple Quantum Dots by Thermal Oxidation of Silicon Nanowire", AIP Adv. **5**, 117144 (2015).

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| (93) | Y. Ueno, K. Furukawa, A. Tin, and H. Hibino, "On-chip FRET Graphene Oxide Aptasensor: Quantitative Evaluation of Enhanced Sensitivity by Aptamer with a Double-stranded DNA Spacer", Anal. Sci. **31**, 875-879 (2015). |
| (94) | S. Wang, Y. Sekine, S. Suzuki, F. Maeda, and H. Hibino, "Photocurrent Generation of a Single-gate Graphene P-N Junction Fabricated by Interfacial Modification", Nanotechnology **26**, 385203 (2015). |
| (95) | K. Washio, R. Nakazawa, M. Hashisaka, K. Muraki, Y. Tokura, and T. Fujisawa, "Long-lived Binary Tunneling Spectrum in the Quantum Hall Tomonaga-Luttinger Liquid", Phys. Rev. B **93**, 075304 (2016). |
| (96) | K. Yamazaki and H. Yamaguchi, "Renovation of Three-dimensional Electron Beam Lithography for Improvement of Positioning Accuracy and Reduction of Turnaround Time", Jpn. J. Appl. Phys. **54**, 06FD02 (2015). |
| (97) | N. Zen, H. Shibata, Y. Mawatari, M. Koike, and M. Ohkubo, "Biomolecular Ion Detection Using High-temperature Superconducting $MgB_2$ Strips", Appl. Phys. Lett. **106**, 222601 (2015). |
| (98) | G. Zhang, C. Rainville, A. Salmon, M. Takiguchi, K. Tateno, and H. Gotoh, "Bridging the Gap between the Nanometer-scale Bottom-up and Micrometer-scale Top-down Approaches for Site-defined InP/InAs Nanowires", ACS Nano **9**, 10580-10589 (2015). |

# List of Invited Talks

## Ⅰ. Materials Science Laboratory

| | |
|---|---|
| (1) | H. Hibino, S. Wang, C. M. Orofeo, and S. Suzuki, "Synthesis and Functionalization of Two-Dimensional Materials: Graphene, Hexagonal Boron Nitride, and Transition Metal Dichalcogenides", The 22nd International Workshop on Active-Matrix Flatpanel Displays and Devices -TFT Technologies and FPD Materials- (AM-FPD '15), Kyoto, Japan (July 2015). |
| (2) | Y. Ueno and K. Furukawa, "On-Chip Graphene FRET Biosensor for Protein Detection", The Fifteenth International Symposium on Electroanalytical Chemistry (15th ISEAC), Changchun, China (Aug. 2015). |
| (3) | Y. Taniyasu, "Progress in AlN-Based Deep UV Emitters and Lasers", 2015 IEEE Photonics Conference (IPC), Reston, U.S.A. (Oct. 2015). |
| (4) | K. Furukawa, "Controlling Self-Spreading of Lipid Bilayer on Patterned Surface", Tethered Membrane 2015 Conference (TethMem 2015), Singapore, Singapore (Nov. 2015). |
| (5) | Y. Ueno, K. Furukawa, T. Teshima, M. Takamura, and H. Hibino, "Fabrication of Patterned Graphene Electrode by a Transfer Process Assisted by a Parylene Thin Film", The International Chemical Congress of Pacific Basin Societies 2015 (Pacifichem 2015), Honolulu, U.S.A. (Dec. 2015). |
| (6) | N. Kasai and K. Sumitomo, "Neuronal Guidance Using Nanopillars", 9th International Symposium on Nanomedicine (ISNM 2015), Tsu, Japan (Dec. 2015). |
| (7) | Y. Krockenberger, N. Breznay, N. Nair, H. Irie, R. McDonald, J. Analytis, and H. Yamamoto, "Snatching the Cuprates' Fermi Pockets", International USMM & CMSI Workshop: Frontiers of Materials and Correlated Electron Science-from Bulk to Thin Films and Interfaces, Tokyo, Japan (Jan. 2016). |

## Ⅱ. Physical Science Laboratory

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|---|---|
| (1) | A. Fujiwara, "Silicon Single-Electron Devices for Ultimate Electronics", DC & Quantum Metrology Meeting, Bern, Switzerland (May 2015). |
| (2) | I. Mahboob and H. Yamaguchi, "An Electromechanical Van der Pol Resonator", 3rd International Conference on Phononic Crystals/Metamaterials, Phonon Transport and Phonon Coupling (Phononics 2015), Paris, France (May 2015). |
| (3) | K. Muraki, "Probing and Controlling Disorder Effects for the Studies of Fractional Quantum Hall effects", Quantum transport on 2D systems Session Workshop II (W2), Luchon, France (May 2015). |
| (4) | K. Nishiguchi, "What happens in a Small Transistor with Single-Electron Resolution?", The 5th International Symposium on Organic and Inorganic Electronic Materials and Related Nanotechnologies (EM-NANO 2015), Niigata, Japan (June 2015). |
| (5) | J. Noborisaka, K. Nishiguchi, and A. Fujiwara, "Gate Tuning of Direct Optical Transitions in Silicon", 2015 Asia-Pacific Workshop on Fundamentals and Applications of Advanced Semiconductor Devices, Jeju, Korea (June 2015). |
| (6) | N. Clement, G. Larrieu, K. Nishiguchi, and A. Fujiwara, "Ultra-Low Noise Nanoscale Transistors for Metrology of Noise, Energy Harvesting and Biosensing Applications", International Conference on Noise and Fluctuation (ICNF), Xi'an, China (June 2015). |

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|---|---|
| (7) | D. Hatanaka, I. Mahboob, K. Onomitsu, and H. Yamaguchi, "Phononic Crystal Waveguides with Dynamic Control",19th International Conference on Electron Dynamics in Semiconductors, Optoelectronics and Nanostructures (EDISON-19), Salamanca, Spain (June 2015). |
| (8) | A. Fujiwara, G. Yamahata, J. Noborisaka, and K. Nishiguchi, "Nanoscale Silicon MOSFET for Metrology and Valleytronics Applications", 2015 UK-Japan Si Nano2 Symposium, Southampton, U.K. (July 2015). |
| (9) | I. Mahboob, H. Okamoto, and H. Yamaguchi, "Correlated Phonon Pair Generation in an Electromechanical Resonator",17th International Conference on Modulated Semiconductor Structures (MSS-17), Sendai, Japan (July 2015). |
| (10) | S. Foelsch, J. Martinez-Blanco, J. Yang, K. Kanisawa, and S. C. Erwin, "Quantum Dots with Single-Atom Precision", 17th International Conference on Modulated Semiconductor Structures (MSS-17), Sendai, Japan (July 2015). |
| (11) | Y. Matsuzaki, "Quantum Sensing Basics", Diamond Quantum Sensing Workshop 2015, Takamatsu, Japan (Aug. 2015). |
| (12) | H. Yamaguchi, D. Hatanaka, I. Mahboob, and H. Okamoto, "III-V Semiconductor Micro/Nanomechanical Resonators", 5th International Workshop on Epitaxial Growth and Fundamental Properties of Semiconductor Nanostructures (SemiconNano 2015), Hsinchu, Taiwan (Sep. 2015). |
| (13) | A. Fujiwara, G. Yamahata, and K. Nishiguchi, "Gigahertz Single-Electron Pump Towards a Representation of the New Ampere", 2015 International Conference on Solid State Devices and Materials, Sapporo, Japan (Sep. 2015). |
| (14) | I. Mahboob and H. Yamaguchi, "Phonon Dynamics in Electromechanical Resonators", 2015 IEEE International Ultrasonics Symposium (2015 IUS), Taipei, Taiwan (Oct. 2015). |
| (15) | H. Yamaguchi, D. Hatanaka, I. Mahboob, and H. Okamoto, "Phonon Confinement, Transport, and Piezoelectric Manipulation in Semiconductor Micromechanical Structures", Material Research Society (MRS) 2015 Fall meeting, Boston, U.S.A. (Nov. 2015). |
| (16) | K. Muraki, T. D. Rhone, K. Yonaga, and N. Shibata, "NMR Probing of Charge-Density-Wave States in the Third Landau Level", International Workshop on Emergent Phenomena in Quantum Hall Systems, Mumbai, India (Jan. 2016). |
| (17) | H. Yamaguchi, "Mechanical Systems Hybridized with Semiconductor Quantum Structures", Gordon Research Conference (GRC) - Mechanical Systems in the Quantum Regime -, Ventura, U.S.A. (Mar. 2016). |

## Ⅲ. Optical Science Laboratory

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|---|---|
| (1) | W. J. Munro and K. Nemoto, "Quantum Repeaters: Form the First Generation to the Third?", 1st Workshop on Quantum Repeaters and Quantum Networks, Pacific Grove, U.S.A. (May 2015). |
| (2) | K. Oguri, H. Mashiko, T. Yamaguchi, K. Kato, A. Suda, and H. Gotoh "Dynamical Core-Level Spectroscopy Based on Attosecond High-Order Harmonic Pulse Sources", The 6th Shanghai-Tokyo Advanced Research Symposium on Ultrafast Intense Laser Science(STAR6), Hangzhou, China (May 2015). |
| (3) | H. Takesue, T. Inagaki, K. Inoue, and Y. Yamamoto, "Time-Division-Multiplexed Degenerate Optical Parametric Oscillator for Coherent Ising machine", IEEE Photonics Society Summer Topical Meeting on Nonlinear-Optical Signal Processing (NOSP), Nassau, Bahamas (July 2015). |

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| (4) | K. Oguri, T. Tsunoi, K. Kato, H. Nakano, T. Nishikawa, K. Tateno, T. Sogawa, and H. Gotoh, "High-Order Harmonic Source Based Femtosecond Core-Levelphotoelectron Spectroscopy for Carrier Transport Dynamics on Semiconductor Surface", The International Conference on Advanced Laser Technologies (ALT 15), Faro, Portugal (Sep. 2015). |
| (5) | H. Sanada, Y. Kunihashi, H. Gotoh, K. Onomitsu, M. Kohda, J. Nitta, and T. Sogawa, "Transport of Electron Spin Coherence in Persistent Spin Helix Condition", 12th Sweden-Japan QNANO Workshop, Hindas, Sweden (Sep. 2015). |
| (6) | K. Azuma, "All-Photonic Quantum Internet", Physical Science Symposium-2015-Boston, Boston, U.S.A. (Sep. 2015). |
| (7) | K. Tamaki, "Security of Quantum Key Distribution with Imperfect Light Sources", Physical Science Symposium-2015-Boston, Boston, U.S.A. (Sep. 2015). |
| (8) | K. Tamaki, "Security of Quantum Key Distribution with Imperfect Light Sources", 3rd the European Telecommunications Standards Institute/Institute for Quantum Computing Workshop on Quantum-Safe Cryptography (ETSI/IQC), Seoul, Korea (Oct. 2015). |
| (9) | Y. Kunihashi, H. Sanada, H. Gotoh, K. Onomitsu, and T. Sogawa, "Electrical Control of Drifting Spin Coherence", International Workshop : Quantum Nanostructures and Electron-Nuclear Spin Interactions, Sendai, Japan (Oct. 2015). |
| (10) | H. Mashiko, K. Oguri, T. Yamaguchi, A. Suda, and H. Gotoh, "Characterizing Ultrafast Dipole Dynamics with Isolated Attosecond Pulse", Sino-German Symposium on Attosecond Photonics 2015 (SGSAP-2015), Shanghai, China (Nov. 2015). |
| (11) | H. Takesue, "Towards Large Scale Coherent Ising Machine", US-Japan Workshop; New-Generation Computers: Quantum Annealing and Coherent Computing, Stanford, U.S.A. (Dec. 2015). |
| (12) | W. J. Munro, Y. Matsuzaki, K. Kakuyanagi, K. Nemoto, and S. Saito, "Hybridization, a Nice Tool for Quantum Engineering", ARC Centre of Excellence for Engineered Quantum Systems Annual Workshop 2015 (EQuS), Benowa QLD, Australia (Dec. 2015). |
| (13) | W. J. Munro, Y. Matsuzaki, S. Dooley, E. Yukawa, K. Kakuyanagi, H. Toida, K. Semba, H. Yamaguchi, K. Nemoto, and S. Saito, "Quantum Engineering Using Hybridization: When 1+1 > 2", RIKEN Center for Emergent Matter Science International Symposium on Dynamics in Artificial Quantum Systems (DAQS 2016), Tokyo, Japan (Jan. 2016). |
| (14) | W. J. Munro, K. Azuma and K. Nemoto, "Towards Quantum Networking for QKD", UK-Japan Quantum Technology Workshop, Tokyo, Japan (Mar. 2016). |
| (15) | N. Matsuda, "Spectral Engineering of Single Photon Wave Packets Using Cross Phase Modulation", Spectral and Spatial Engineering of Quantum Light (SSEQL), Warsaw, Poland (Mar. 2016). |

## Ⅳ. Nanophotonics Center

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|---|---|
| (1) | E. Kuramochi and M. Notomi, "All-Optical Memories on a Photonic Crystal Chip", SPIE Optics + Optoelectronics 2015, Praha, Chech (Apr. 2015). |
| (2) | M. Notomi, A. Yokoo, M. D. Birowosuto, M. Takiguchi, K. Tateno, G. Zhang, and E. Kuramochi, "Hybrid Nanohpotonics Systems Combined with Functional Nanomaterials", The 20th Opto Electronics and Communications Conference (OECC), Shanghai, China (June 2015). |

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|---|---|
| (3) | S. Matsuo, K. Takeda, T. Fujii, and T. Satou," Photonic Crystal Lasers on Si ", The European Conference on Lasers and Electro-Optics (CLEO 2015), Munchen, Germany (June 2015). |
| (4) | S. Matsuo, T. Fujii, and K. Takeda, "Low-Operating-Energy Membrane-Buried Heterostructure Lasers on $SiO_2$/Si Substrate", The 20th Opto Electronics and Communications Conference (OECC), Shanghai, China (June 2015). |
| (5) | A. Shinya and M. Notomi, "Nanophotonics Technology Toward Optical Logic Circuits", 15th International Forum on MPSoC for Software-defined Hardware, Ventura, U.S.A. (July 2015). |
| (6) | M. Notomi, A. Yokoo, M. D. Birowosuto, M. Takiguchi, K. Tateno, G. Zhang, and E. Kuramochi, "III-V Nanowire-Induced Nanocavity in Si Photonic Crystals", 17th International Conference on Modulated Semiconductor Structures (MSS-17), Sendai, Japan (July 2015). |
| (7) | S. Matsuo, T. Fujii, K. Takeda, H. Nishi, K. Hasebe, and T. Kakitsuka, "On-Silicon Integration of Compact and Energy-Efficient DFB Laser with 40-Gbit/s Direct Modulation", 2015 IEEE International Conference on Group IV Photonics (IEEE), Vancouver, Canada (Aug. 2015). |
| (8) | M. Notomi, "Ultralow-Power Integrated Photonic Crystal Devices", European Conference on Optical Communication (ECOC), Valencia, Spain (Sep. 2015). |
| (9) | S. Matsuo, T. Fujii, and K. Takeda, "Directly Modulated Membrane Lasers on Si ", The 76th JSAP Autumn Meeting, 2015, Nagoya, Japan (Sep. 2015). |
| (10) | A. Yokoo, "Nano-Fabrication for Photonic Crystal Functional Device - a Route for Functional Photonic Integration -", International Symposium on Frontier Applied Physics 2015, Bandung, Indonesia (Oct. 2015). |
| (11) | K. Nozaki, S. Matsuo, T. Fujii, K. Takeda, E. Kuramochi, and M. Notomi, "Photonic Crystal Photodetector-Modulator Integration for Ultra-Compact Wavelength Converter", 2015 IEEE Photonics Conference (IPC), Reston, U.S.A. (Oct. 2015). |
| (12) | M. Notomi, A. Yokoo, M. D. Birowosuto, M. Takiguchi, M. Ono, K. Tateno, G. Zhang, and E. Kuramochi, "Hybrid Nanophotonics Systems Based on Sub-Wavelength Nanowires", NANOWIRES 2015, Barcelona, Spain (Oct. 2015). |
| (13) | K. Takeda, T. Fujii, A. Shinya, E. Kuramochi, M. Notomi, K. Hasebe, T. Kakitsuka, and S. Matsuo, "Photonic-Crystal Lasers on Silicon for Chip-Scale Optical Interconnects", SPIE Photonics West 2015, San Francisco, U.S.A. (Feb. 2016). |
| (14) | A. Shinya, K. Nozaki, E. Kuramochi, K. Takeda, T. Kakitsuka, H. Taniyama, T. Fujii, K. Hasebe, S. Mastuo, and M. Notomi, "Integrated Nanophotonics for fJ/Bit on-Chip Optical Communications", Design, Automation and Test in Europe (DATE), Dresden, Germany (Mar. 2016). |
| (15) | M. Notomi, "Enhanced Light-Matter Coupling in Nanoemitters and Nanolasers in Nanophotonic Systems", Physics of Light-Matter Coupling in Nanostructures (PLMCN 17), Nara, Japan (Mar. 2016). |
| (16) | S. Matsuo, "Ultra-Low Threshold Semiconductor Lasers", Optical Fiber Communication Conference and Exhibition 2015 (OFC), Anaheim, U.S.A. (Mar. 2016). |

**Research Activities in NTT-BRL**
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