Research Activities in NTT Basic Research Laboratories

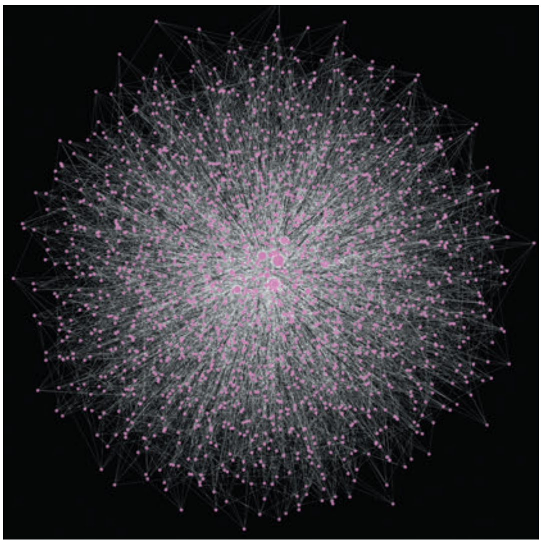
Fiscal 2016

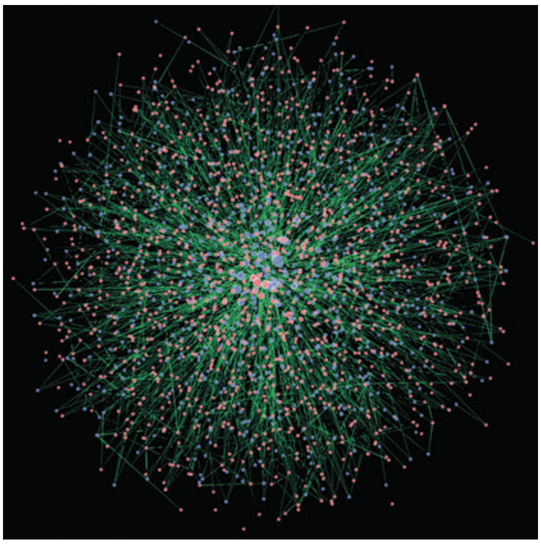
VOL. 27

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

Cover : Coherent Ising Machine for Combinatorial Optimization Problems

Combinatorial optimization problems can be mapped onto ground-state-search problems of the Ising model, which can be solved efficiently with the artificial spin system. We realized a coherent Ising machine based on networked 2048 degenerate optical parametric oscillators to solve the Ising problem. The coherent Ising machine could obtain good approximate solutions for MAX-CUT problems on 2000 node graphs. (see page 40)





(left) Figure shows the structure of a G39 graph, which is a scale-free graph with 2000 nodes and 11778 edges.
(right) A solution to the MAX-CUT problem on the G39 graph obtained with the coherent Ising machine in 5 ms. The red and blue nodes correspond to up and down spin states of the Ising model, respectively. The green lines show the edges between the divided subsets.

Message from the Director

We at NTT Basic Research Laboratories (BRL) are extremely grateful for your interest and support of research activities. BRL’s mission is to promote progress in science and innovations in leading-edge technology to advance NTT's business. To achieve this mission, researchers in fields including physics, chemistry, biology, mathematics, electronics, informatics, and medicine, conduct basic research in the fields of 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, the 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 encourage 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.

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, 2017

Tetsuomi Sogawa
Director
NTT Basic Research Laboratories

Table of Contents

- Cover : Coherent Ising Machine for Combinatorial Optimization Problems
- Message from the Director
- Organogram 1
- Member List 2

I Research Topics

- Overview of Research in Laboratories 20

Materials Science Laboratory

- Surface Morphology Control of Nonpolar *m*-plane AlN Homoepitaxial Layers by Flow-rate Modulation Epitaxy 22
- Enhancement of Heat Dissipation in AlGaN/GaN High-electron-mobility Transistors Using Substrate-transfer Technique 23
- Atmospheric Pressure Chemical Vapor Deposition Growth of Millimeter-scale Single-crystalline Graphene on the Copper Surface with a Native Oxide Layer 24
- Theory of a Carbon-nanotube Polarization Switch 25
- Shubnikov-de Haas Quantum Oscillations Reveal a Reconstructed Fermi Surface Near Optimal Doping in a Thin Film of the Cuprate Superconductor $Pr_{1.86}Ce_{0.14}CuO_{4\pm\delta}$ 26
- Conductive Silk Film Electrode for Manipulation and Electrical Stimulation of Adherent Cells 27
- Fabrication of a Hydrogel Array for Facilitating Lipid Membrane Formation 28
- Bio-interface on Graphene for Protein Detection 29

Physical Science Laboratory

- World-record Accuracy of Gigahertz High-speed Single-electron Transfer 30
- A Planar Cold Cathode Based on Multilayer-graphene/SiO_2/Si Heterostructure 31
- Experimental Test of Macroscopic Realism Using a Superconducting Flux Qubit 32
- Coherent Coupling Between 4300 Superconducting Qubits and a Superconducting Resonator 33
- Simulating the Spin Ising Model with Phonons 34
- A Strongly Coupled Λ-type Micromechanical System 35
- Engineering Quantum Spin Hall Insulators by Strained-layer Heterostructures 36
- Andreev Reflection and Bound State Formation in a Ballistic Two-dimensional Electron Gas Probed by a Quantum Point Contact 37
- Evaluation of Disorder Introduced by Electrolyte Gating through Transport Measurements in Graphene 38

Optical Science Laboratory

- Spectroscopic Analysis for Measuring Quantum Phase Transitions of Bosonic Atoms in an Optical Lattice 39
- Coherent Ising Machine for Combinatorial Optimization Problems 40
- Quantum State Tomography for High-dimensional Time-bin States 41
- Fundamental Rate-loss Trade-off for the Quantum Internet 42
- Hybrid Quantum Engineering Using Spectral Hole Burning in Microwave Photonics 43
- Generation of Low-noise Millimeter-wave by Using an Electro-optics-modulator-based Optical Frequency Comb 44
- Light-Field Driven Petahertz Electronic Oscillation with Attosecond Periodicity in GaN Semiconductor 45
- Bridging the Gap Between the Nanometer-scale Bottom-up and Micrometer-scale Top-down Approaches for Site-defined InP/InAs Nanowires 46

Nanophotonics Center

- Demonstration of Efficient Mode Conversion for Deep-subwavelength Plasmonic Waveguides 47
- Subwavelength Nanowire-induced Silicon Photonic Crystal Lasers 48
- Efficient Light-to-voltage Conversion by Ultralow-capacitance Nano-photodetector 49
- Superconducting Nanowire Single Photon Detector on Si Platform 50
- LEAP Lasers Integrated on Si Waveguides 51

Ⅱ Data

- The 9th Advisory Board 54
- Science Plaza 2016 55
- List of Visitors' Talks 56
- List of Award Winners 58
- List of In-house Award Winners 59
- Number of Papers 60
- Number of Presentations 61
- Number of Patents 61
- Publication List 62
- List of Invited Talks 69

Organogram

As of March 31, 2017

Director
Tetsuomi Sogawa

- **Quantum and Nano Device Research**
  Senior Distinguished Researcher
  Hiroshi Yamaguchi
- **Biomedical･Exercise Physiology Research**
  Senior Distinguished Researcher
  Shingo Tsukada
- **Research Planning Section**
  Executive Manager
  Hideki Gotoh
- **Nanophotonics Center**
  Project Manager
  Masaya Notomi
- **Materials Science Laboratory**
  Executive Manager
  Hideki Yamamoto
- **Physical Science Laboratory**
  Executive Manager
  Akira Fujiwara
- **Optical Science Laboratory**
  Executive Manager
  Hideki Gotoh

Member List

As of March 31, 2017
(*/ 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

Executive Research Scientist	**Dr. Hideki Gotoh**
Senior Research Scientist, Supervisor	Dr. Yoshitaka Taniyasu
Senior Research Scientist, Supervisor	Dr. Katsuhiko Nishiguchi
Senior Research Scientist, Supervisor	Dr. Shiro Saito*
Senior Research Scientist	Dr. Norio Kumada

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. Hisashi Sato

Thin-Film Materials Research Group

Dr. Kazuhide Kumakura (Group Leader)

Dr. Tetsuya Akasaka

Dr. Masanobu Hiroki

Dr. Kazuyuki Hirama

Dr. Kouta Tateno

Dr. Kazuaki Ebata

Dr. Junichi Nishinaka

Low-Dimensional Nanomaterials Research Group

Dr. Kazuhide Kumakura (Group Leader)

Dr. Satoru Suzuki

Dr. Ken-ichi Sasaki

Dr. Yoshiharu Krockenberger

Dr. Yoshiaki Sekine

Dr. Shengnan Wang

Dr. Ai Ikeda

Dr. Hiroo Omi

Dr. Koji Onomitsu

Dr. Shin-ichi Karimoto

Dr. Makoto Takamura

Dr. Yui Ogawa

Molecular and Bio Science Research Group

Dr. Hiroshi Nakashima (Group Leader)

Dr. Shingo Tsukada

Dr. Nahoko Kasai

Dr. Aya Tanaka

Dr. Tetsuhiko Teshima

Dr. Yuko Ueno

Dr. Yoshiaki Kashimura

Dr. Azusa Oshima

Physical Science Laboratory

Executive Manager **Dr. Akira Fujiwara**

Dr. Takeshi Ota

Takeshi Karasawa

Nanodevices Research Group

Dr. Akira Fujiwara (Group Leader)

Dr. Toru Yamaguchi

Hirotaka Tanaka

Dr. Gento Yamahata

Dr. Rento Osugi

Dr. Toshiaki Hayashi

Dr. Jinichiro Noborisaka

Dr. Kensaku Chida

Dr. Nicolas Clement

Hybrid Nanostructure Physics Research Group

Dr. Hiroshi Yamaguchi (Group Leader)

Dr. Shiro Saito

Dr. Hajime Okamoto

Dr. Yuichiro Matsuzaki

Dr. Hiraku Toida

Dr. Rangga Budoyo

Dr. Imran Mahboob

Dr. Kosuke Kakuyanagi

Dr. Daiki Hatanaka

Dr. Ryuichi Ohta

Quantum Solid State Physics Research Group

Dr. Koji Muraki (Group Leader)

Dr. Kiyoshi Kanisawa

Dr. Kyoichi Suzuki

Dr. Keiko Takase

Dr. Takafumi Akiho

Dr. Ngoc Han Tu

Dr. Satoshi Sasaki

Dr. Takeshi Ota

Dr. Hiroshi Irie

Dr. Francois Couedo*

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. Toshimori Honjo
Dr. Fumiaki Morikoshi
Dr. Takahiro Inagaki
Dr. Hsin-Pin Lo
Dr. Makoto Yamashita
Dr. Hiroyuki Tamura
Dr. Kensuke Inaba
Dr. Nobuyuki Matsuda
Takuya Ikuta

Theoretical Quantum Physics Research Group

Dr. William John Munro (Group Leader)

Dr. Kiyoshi Tamaki
Dr. Fabian Furrer*
Dr. Yanbao Zhang
Dr. Koji Azuma
Dr. Stefan Bäuml

Quantum Optical Physics Research Group

Dr. Hideki Gotoh (Group Leader)

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

Photonic Nano-Structure Research Group

Dr. Masaya Notomi (Group Leader)

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

Nanostructured Device Research Group

Dr. Shinji Matsuo
Dr. Hiroshi Fukuda
Dr. Tai Tsuchizawa
Dr. Takaaki Kakitsuka
Dr. Koichi Hasebe*
Dr. Koji Takeda
Hidetaka Nishi
Dr. Kota Okazaki*
Tatsurou Hiraki
Ryo Nakao
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.S., 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.E., M.E., 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.E., M.E., 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.

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 -), the University of Leeds in the UK (2009 -) and the University of Queensland in Australia (2012 -). He was appointed as Distinguished Scientist of NTT in 2015 and Senior Distinguished Scientist of NTT in 2016. He 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).

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 two-dimensional systems. 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 and the IEEE.

Shiro SAITO received his B.E., M.E., and Ph.D. 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. During this period he studied nonlinear dynamics in electromechanical resonators with notable achievements including mechanical memory and logic processors, parametric frequency conversion, parametric mode coupling, all-mechanical phonon-lasing, two-mode squeezed states all using phonons for the first time. Since 2017 he has been engaged in the development of microwave quantum optics for quantum technology applications. 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, the RIEC Award from Tohoku University in 2014, and the Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology of Japan (the Young Scientists' Prize) in 2016. 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 Ph.D. 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 highly efficient energy conversion devices using nitride semiconductors and two-dimensional layered materials. 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 and Low-Dimensional Nanomaterials 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.

Kengo NOZAKI received his B.E., M.E., and Ph.D. degrees in electrical engineering from Yokohama National University, Japan, in 2003, 2005, and 2007 respectively. He joined NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corporation in 2008. His current interests are ultralow-power nanophotonic semiconductor devices based on photonic crystal. He was appointed as Distinguished Scientist of NTT in 2016. He is currently a member of Photonic Nanostructure Research Group.

He received the Best Paper Award at Photonics in Switching 2012, and the Young Researchers Award from IEICE Lasers and Quantum Electronics in 2014, and the Best Paper Award from OECC/PS in 2016. He is a member of the Japan Society of Applied Physics.

Advisory Board Members

Name	Affiliation
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
Andrew Browning	The University of British Columbia, Canada	May 2015 - Apr. 2016
Jun Ki Kim	Georgia Institute of Technology, U.S.A.	Sep. 2015 - Apr. 2016
Isabel Gonzalvez	University of Edinburgh, U.K.	Sep. 2015 - Aug. 2016
Monika Schied	Ulm University, Germany	Jan. 2016 - Aug. 2016
Veronika Zagar	University of Ljubljana, Slovenia	Jan. 2016 - Aug. 2016
Carla Garcia	Carlos III University of Madrid, Spain	Jan. 2016 - Aug. 2016
Giacomo Mariani	Politecnico di Milano, Italy	Jan. 2016 - Aug. 2016
Dominika Gnatek	Jagiellonian University, Poland	Jan. 2016 - Aug. 2016
Javier Cambiasso	Imperial College London, U.K.	Jan. 2016 - Apr. 2016
Paul Brasseur	Ecole Centrale de Paris, France	May 2016 - Nov. 2016
Caleb John	University of Calgary, Canada	May 2016 -
Alice Dearle	University of Edinburgh, U.K.	July 2016 -
Calum Henderson	University of Edinburgh, U.K.	July 2016 -
Harry Parke	University of Bath, U.K.	July 2016 - Dec. 2016
Romain Monsarrat	ESPCI Paris Tech (École supérieure de physique et de chimie industrielles de la ville de Paris), France	July 2016 - Dec. 2016
Ruben Ohana	ESPCI Paris Tech (École supérieure de physique et de chimie industrielles de la ville de Paris), France	July 2016 - Dec. 2016
Vincent Vinel	ESPCI Paris Tech (École supérieure de physique et de chimie industrielles de la ville de Paris), France	July 2016 - Dec. 2016
Alexandre Gourmelon	ESPCI Paris Tech (École supérieure de physique et de chimie industrielles de la ville de Paris), France	July 2016 - Dec. 2016

Paul Renault	ESPCI Paris Tech (École supérieure de physique et de chimie industrielles de la ville de Paris), France	July 2016 - Dec. 2016
Elizabeth Brockman	University of Victoria, Canada	Sep. 2016 -
Luca Rigovacca	Imperial College London, U.K.	Sep. 2016 - Nov. 2016
David Wood	Imperial College London, U.K.	Sep. 2016 - Nov. 2016
Dino Ibrahimagic	Lund University, Sweden	Jan. 2017 -
Fabian Böhm	Technische Universität Berlin, Germany	Jan. 2017 -
Mark IJspeert	Delft University of Technology, The Netherlands	Jan. 2017 -
Tiffany Tsu	University of British Columbia, Canada	Jan. 2017 -
Thuong Phan	Georgia Institute of Technology, U.S.A.	Jan. 2017 -
Tommy Boykin II	University of Central Florida, U.S.A.	Jan. 2017 -
Anthony Hayes	University of Leeds, U.K.	Feb. 2017 -

Domestic Trainees

Name	Affiliation	Period
Masafumi Horio	The University of Tokyo	Apr. 2016 - Mar. 2017
Takuya Ohrai	Tokyo University of Science	Apr. 2016 - Mar. 2017
Megumi Kurosu	Tohoku University	Apr. 2016 - Mar. 2017
Gento Nakamura	The University of Electro-Communications	Apr. 2016 - Mar. 2017
Kzutaka Hara	Tokyo Denki University	Apr. 2016 - Mar. 2017
Go Taniguchi	Tokyo Denki University	Apr. 2016 - Mar. 2017
Yuya Hasegawa	Tokyo Denki University	Apr. 2016 - Mar. 2017
Hisashi Chiba	Tokyo Institute of Technology	Apr. 2016 - Mar. 2017
Masanori Hata	Tokyo Institute of Technology	Apr. 2016 - Mar. 2017
Suguru Endo	Keio University	Apr. 2016 - Dec. 2016
Hiroyuki Masuda	Yokohama National University	Apr. 2016 - Mar. 2017
Yuta Chisuga	Yokohama National University	Apr. 2016 - Mar. 2017
Takuya Ikemachi	The University of Tokyo	June 2016 - Mar. 2017
Keita Nakagawara	Tohoku University	July 2016 - Sep. 2016
Kan Hayashi	Kyoto University	Aug. 2016
Wataru Tomita	Tohoku University	Aug. 2016 - Mar. 2017
Rina Asai	Kyushu University	Aug. 2016 - Sep. 2016
Yoshiaki Taniguchi	Tokushima University	Aug. 2016 - Sep. 2016
Yuki Itoh	Tohoku University	Aug. 2016 - Sep. 2016
Tatsuya Ogawa	Hirosaki University	Sep. 2016 - Jan. 2017
Takahito Saito	Tohoku University	Sep. 2016 - Nov. 2016
Yoshifumi Suzuki	Tokyo Institute of Technology	Oct. 2016 - Mar. 2017
Yoshiko Nanao	Tokyo University of Agriculture and Technology	Nov. 2016 - Mar. 2017
Kenta Imai	Toyohashi University of Technology	Jan. 2017 - Feb. 2017
Kento Toume	Tokyo University of Science	Feb. 2017 - Mar. 2017
Riku Takahashi	Hokkaido University	Feb. 2017
Taiki Yoda	Tokyo Institute of Technology	Feb. 2017 - Mar. 2017

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 including typical compound semiconductors such as 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 and high-precision and high-resolution measurements of structures and properties along with theoretical studies.

This year, we succeeded in controlling the surface morphologies of non-polar AlN heteroepitaxial layers, which points toward the realization of high-performance light emitting devices operating in the deep ultraviolet spectral region. We also prepared millimeter-scale single-crystalline graphene. Our high-quality samples allowed us to observe quantum oscillations for the first time using high-temperature superconductor thin films. Furthermore, we fabricated conductive and highly biocompatible silk gel films with which we have developed a new method for cell manipulation and the electrical stimulation of specific cells. Last but certainly not least, electrodes and electrical leads made of a functional sensing fabric “hitoe”, which we developed in collaboration with Toray Industries Inc., have been officially registered as general medical devices and offer a broad scope for medical use.

Physical Science Laboratory

Akira Fujiwara

The aim of the Physical Science Laboratory is to develop semiconductor- and superconductor-based devices and 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 could lead to nanodevices for ultimate electronics and sensors 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 achieved the world’s most accurate gigahertz single-electron transfer using a silicon nanotransistor, and we performed an experimental test on the macroscopic realism problem using a superconducting flux qubit. We also studied the quasi-Ising coupling of electromechanical resonators and coherent coupling between thousands of superconducting qubits and a superconducting resonator to explore functional physical coupled systems. Moreover, we developed novel material and device technology including band-engineered two-dimensional topological insulators in $InAs/In_xGa_{1-x}Sb$ heterostructures and graphene-based electron emitters and liquid-gated transistors.

Optical Science Laboratory

Hideki Gotoh

The aims of the Optical Science Laboratory is 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 as regards quantum computers has been the demonstration of a new computing scheme with a laser cavity composed of an optical fiber and a phase sensitive amplifier. This scheme, known as a “quantum neural network”, has been employed to solve a max-cut problem, which is a combinatorial optimization problem, and has realized a 50 times faster computation time than conventional computers. Moreover, we have achieved the electronic oscillation of the 1 PHz regime with attosecond optical technologies and suppressed the noises of microwave sources by employing optical-comb technologies.

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 Technology Laboratories. Our aim is to develop a full-fledged large-scale photonic integration technology that will allow the dense integration of 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 achieved super-efficient optical-to-electrical energy conversion by using ultrasmall-capacitance nano-photodetectors integrated with resistors. We have also demonstrated the high-speed modulation of sub-wavelength nanowire photonic-crystal lasers. Furthermore, we have achieved various nanophotonic devices (deep sub-wavelength plasmonic waveguides, superconducting single-photon detectors, and photonic-crystal lasers) efficiently coupled to Si waveguides.

Surface Morphology Control of Nonpolar *m*-plane AlN Homoepitaxial Layers by Flow-rate Modulation Epitaxy

Junichi Nishinaka, Yoshitaka Taniyasu, Tetsuya Akasaka, and Kazuhide Kumakura
Materials Science Laboratory

AlGaN is an attractive material for light-emitting devices in the deep ultraviolet spectral region. Particularly, nonpolar AlGaN-based heterostructures can improve internal quantum efficiency and light extraction efficiency compared to the conventional *c*-plane devices [1]. However, it is difficult to obtain *m*-plane AlN and AlGaN with a flat surface, although high-quality *m*-plane AlN bulk substrates have become available. It has been reported that a high growth temperature is required for promoting adatom migration to achieve smooth a surface of the *m*-plane AlN homoepitaxial layers [2]. On the other hand, flow-rate modulation epitaxy (FME) can also promote adatom migration by modulating the amount of source gas [3]. In this study, we investigated the surface morphologies of nonpolar *m*-plane AlN homoepitaxial layers grown by the FME technique.

The samples were grown by metalorganic chemical vapor deposition with trimethylaluminum (TMA) and ammonia (NH_3). We employed four types of source supply sequences: continuous supply, group-III-source FME (III-FME), group-V-source FME (V-FME), and FME with groups III and V alternated (A-FME).

Figure 1 shows the source supply sequences and corresponding atomic force microscopy (AFM) images of the *m*-plane AlN homoepitaxial layers grown by (a) continuous supply, (b) V-FME, and (c) A-FME. The flow rates of TMA and NH_3 were unchanged, but the average V/III ratios differed depending on the source supply sequences. We found that *a*-steps tend to appear when the average V/III ratio is large [Fig. 1(a)], whereas +*c*-steps tend to appear when it is small [Fig. 1(c)]. This is probably because the *a*- and +*c*-steps have different dangling bonds and because the average V/III ratio affects the anisotropic step-flow velocity in *a*- and +*c*-directions, which determines step direction. Atomically flat surfaces can be obtained by choosing appropriate growth conditions [Fig. 1(b)]. In addition, +*c*-steps tend to bunch under the V-FME or A-FME with N-poor conditions. This is probably due to enhanced adatom migration in the absence of the NH_3 flow. Thus, we can control the surface morphologies of *m*-plane AlN homoepitaxial layers by using the FME technique.

This work was supported by JSPS KAKENHI JP25246022.

[1] R. Banal et al., Appl. Phys. Lett. **105**, 053104 (2014).
[2] I. Bryan et al., J. Appl. Phys. **116**, 133517 (2014).
[3] T. Akasaka et al., Appl. Phys. Lett. **90**, 121919 (2007).

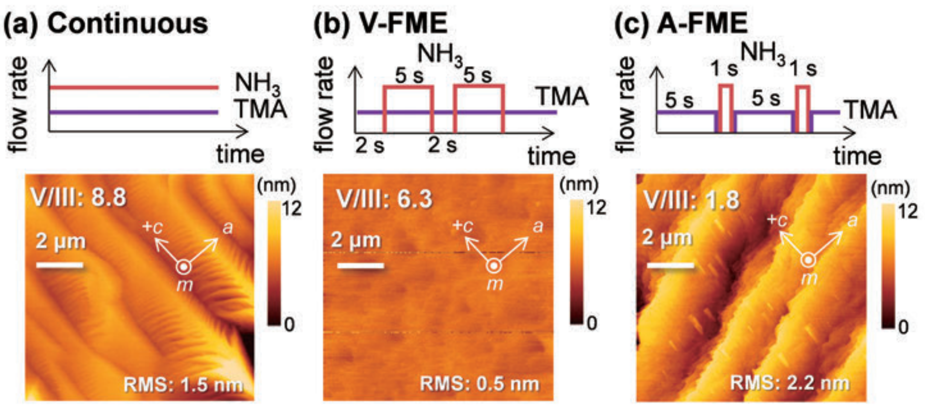


Fig. 1. Source supply sequences and 10×10 μm^2 AFM images of *m*-plane AlN homoepitaxial layers. (a) Continuous (average V/III: 8.8). (b) V-FME (average V/III: 6.3). (c) A-FME (average V/III: 1.8).

Enhancement of Heat Dissipation in AlGaN/GaN High-electron-mobility Transistors Using Substrate-transfer Technique

Masanobu Hiroki, Kazuhide Kumakura, and Hideki Yamamoto
Materials Science Laboratory

III-nitride semiconductor materials can be applied for high-power devices by exploiting their high critical electric field. Under high current operation, however, power performance is limited due to the generation of Joule heat. We transferred AlGaN/GaN high electron mobility transistors (HEMTs) from a sapphire substrate to a copper plate using the hexagonal boron nitride epitaxial lift-off technique [1,2]. In this study, we transferred the HEMTs to a copper plate using Au-Au thermocompression bonding and found an increase in drain current (I_d) and significant improvement of the heat dissipation [3].

Figure 1 shows an *I-V* characteristics of an AlGaN/GaN HEMT before release and after transfer. Before release, a large reduction in drain current I_d vs drain bias (V_{ds}) was observed in the saturation region. In contrast, for the HEMT after transfer, the negative slope of I_d vs V_{ds} decreased. In addition, we found a significant increase in maximum I_d from 0.72 to 0.91 A/mm after transfer. The maximum transconductance also increased from 110 to 140 mS/mm. These indicate an increase in two-dimensional electron gas (2DEG) density. The increase in 2DEG density is likely caused by the reduction in compressive stress in the GaN layer, which is revealed from the E_2 peak shift of –1.3 cm^{-1} in Raman spectroscopy measurement.

Figure 2 shows temperature maps of a HEMT transferred to a copper plate and another HEMT on a sapphire substrate. For the transferred HEMT, the temperature increased from 50 to 150°C with increasing power dissipation (P) from 0.3 to 1.5 W. For the HEMT on sapphire (before release), the temperature reached 240°C at P of 0.7 W. Our results indicate that the transfer technique using the h-BN release layer can enhance the heat dissipation and boost the power performance of GaN-based devises.

[1] Y. Kobayashi et al., Nature **483**, 223 (2012).
[2] M. Hiroki et al., Appl. Phys. Lett. **105**, 193509 (2014).
[3] M. Hiroki et al., Jpn. J. Appl. Phys. **55**, 05FH07 (2016).

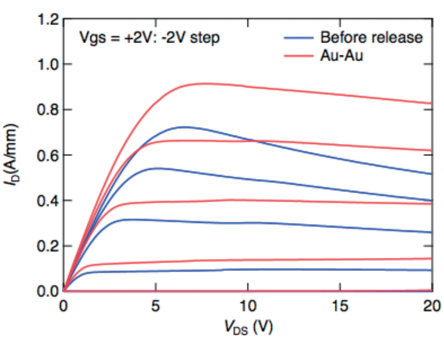


Fig. 1. *I-V* characteristics of AlGaN/GaN HEMT before release and after transfer.

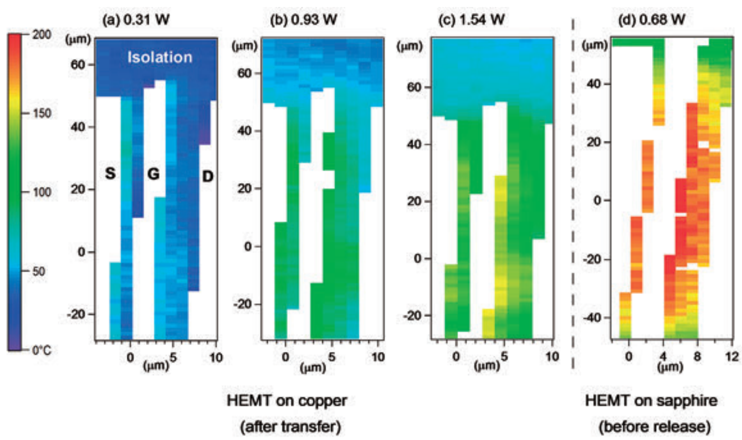


Fig. 2. Temperature maps of a HEMT transferred to copper and another HEMT on sapphire.

Atmospheric Pressure Chemical Vapor Deposition Growth of Millimeter-scale Single-crystalline Graphene on the Copper Surface with a Native Oxide Layer

Shengnan Wang, Hiroki Hibino, Satoru Suzuki, and Hideki Yamamoto
Materials Science Laboratory

Graphene fabricated by "bottom-up" methods always contains various kinds of structural defects, which are introduced during the fabrication process. For example, 1 mm^2 chemical vapor deposition (CVD) grown graphene can be composed of over ten thousand single crystalline domains and centimeter-long domain boundaries [1]. These domain boundaries, as well as lattice defects, have been identified as main disorders to affect the electrical and mechanical performance of graphene. Thus, fabrication of large scale single crystalline graphene is important for its potential technological applications in nanoelectronics and related fields.

Here, we present an atmospheric pressure CVD approach to synthesize millimeter-scale graphene single crystals on commercial Cu foils [2]. A hydrogen-excluded annealing step is used to flatten the Cu surface and maintain the native oxide layer, which is catalytic inactive and is used to restrict the nucleation of graphene on Cu surface in the following growth process. A resulted density of ~12 nuclei cm^{-2} is obtained with an optimized annealing period. Combined with the annealing step, the growth of graphene is further modified by placing the catalyst foils on roughness-defined solid supports (quartz or sapphire), which generate two different types of reaction space: open and confined space on the double sides of the foils. Due to the variation in the kinetics role of oxide layer, reproducible results are observed that the domain size of as-grown graphene is larger on the confined surface, as shown in Fig. 1. With a polished quartz support, ~3 mm isolated graphene islands with an average growth rate of ~25 μm/min are achieved. The as-grown hexagonal domains are confirmed to be single-crystalline monolayer graphene with a field-effect mobility of ~4900 cm^2/Vs at room temperature.

[1] S. Wang et al., Nanoscale **6**, 13838 (2014)
[2] S. Wang et al., Chem. Mater. **28**, 4893 (2016).

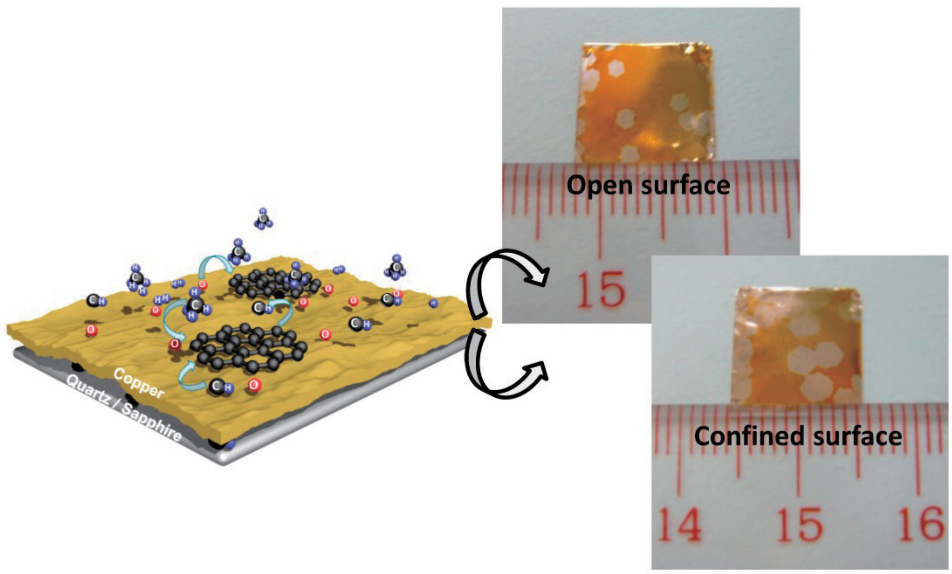


Fig. 1. Schematic and optical images of single crystalline graphene domain grown on the Cu surface w/ and w/o support under same CVD procedure.

Theory of a Carbon-nanotube Polarization Switch

Ken-ichi Sasaki
Materials Science Laboratory

Polarized light is one of the most-familiar natural phenomena as the origin of variety seen in reflection and transmission of light at the surface of a physical object. On the other hand, as the profound spin degree of freedom (helicity) possessed by a massless gauge boson (photon), two components of polarized light have been used to acquire a new knowledge on so many natural laws [1]. Therefore, it would be beneficial if there is a device by which the polarization direction is switched by an electrical means.

We predicted a novel phenomenon that the polarization direction of light transmission of carbon nanotube (CNT) changes by charge doping [2]. A CNT absorbs light whose linear polarization is parallel to the tube's axis, but not when the polarization is perpendicular to it [Fig. 1(left)]. This is a well-known property of an undoped CNT, which enables aligned CNTs to function as an optical polarizer [3]. Charge doping of a CNT inverts the polarization dependence. That is, a doped CNT transmits parallel polarized light and absorbs perpendicular polarized light [Fig. 1(right)].

To change the polarization direction of light transmitted through a typical Polaroid lens, it is necessary to rotate the lens itself. However, according to the theory of doping dependence, a CNT polarizer can invert the polarization of the transmitted light by 90 degrees without having to spatially rotate the polarizer; in other words, it is expected to function as an electrnoic polarization switch. In regard to cutting-edge optical transmission technology, the two degrees of freedom of polarized light are utilized to double the amount of information being transmitted. Different information like images and sound is transcribed to orthogonal polarization and transmitted. A polarization switch based on CNTs can be used to manipulate information within highly miniaturized structure for optical transmission.

[1] B. H. Billings, Ed., Selected Papers on Applications of Polarized Light (2012); W. K. Wootters and W. H. Zurek, Nature **299**, 802 (1982).
[2] K. Sasaki, S. Murakami, and H. Yamamoto, Appl. Phys. Lett. **93**, 125402 (2016).
[3] S. Shoji et al., Phys. Rev. B **77**, 153407 (2008); B. G. Kang et al., Nanotechnology **21**, 405202 (2010).

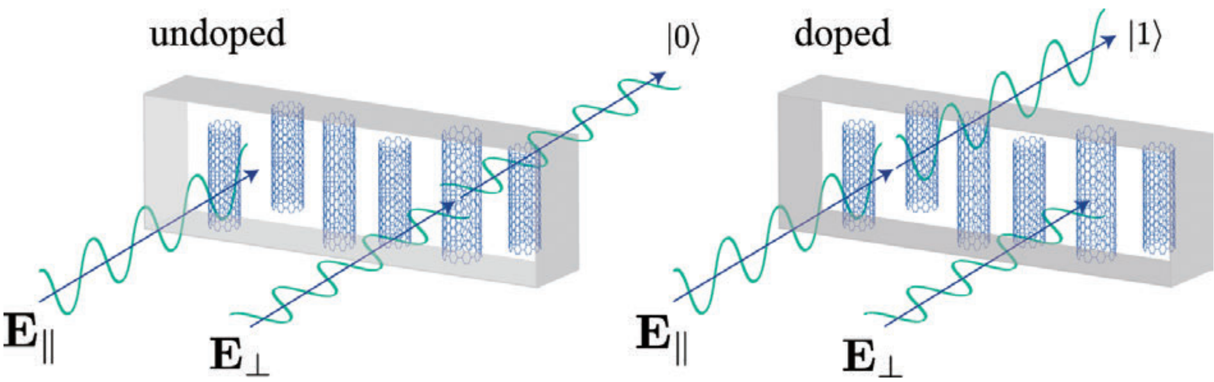


Fig. 1. (left) Undoped CNTs transmit only perpendicular polarized light. (right) Doped CNTs transmit only parallel polarization. Since the polarization of the transmiited light rotates 90 degrees by doping, the aligned CNTs function as a polarization switch.

Materials Science Laboratory

Shubnikov-de Haas Quantum Oscillations Reveal a Reconstructed Fermi Surface Near Optimal Doping in a Thin Film of the Cuprate Superconductor $Pr_{1.86}Ce_{0.14}CuO_{4\pm\delta}$

Yoshiharu Krockenberger[1], Ai Ikeda[1], Hiroshi Irie[2], Hideki Yamamoto[1], Nicholas P. Breznay[3], Ian M. Hayes[3], Ross McDonald[4], and James G. Analytis[3]
[1]Materials Science Laboratory, [2]Physical Science Laboratory,
[3]University of California, Berkeley, [4]NHMFL, Los Alamos National Laboratory

Understanding the ordering phenomena that compete or coexist with superconductivity in the cuprate superconductors remains an outstanding challenge. Central to this effort is the identification of Fermi surface topology and evolution with doping via studies of magnetic quantum oscillations (QO), led by initial observations of QO in hole-doped $YBa_2Cu_3O_{6.5}$ [1]. We reported [2] on the Fermi surface topology and effective mass in the electron-doped cuprate superconductor $Pr_{2-x}Ce_xCuO_4$ (PCCO) with $x = 0.14$. PCCO thin films have been grown by molecular beam epitaxy onto (001) $SrTiO_3$ substrates and annealed in order to maximize the mean-free path length [3]. We observe Shubnikov-de Haas QO in a PCCO thin film measured under extreme magnetic fields up to 92 T, where magneto-transport data [Fig. 1(A)] show evidence for a small Fermi surface pocket (255 T), a light quasi-particle with effective mass of $m^* = 0.43\ m_e$, allowing direct determination of the orbitally averaged Fermi velocity of $v_F = 2.4\times10^5$ m/s. For comparison, the Hall conductivity at 2 K is 0.9×10^{-9} Ωm/T, resulting in a charge carrier density per CuO_2 plane of 0.66 by assuming a single parabolic band [Fig. 1(B)]. The small Fermi surface pocket indicates a reconstruction [Fig. 1(C)], coupled with a similar observation of Ce-free Pr_2CuO_4 films [4], suggests that small Fermi surface pockets are a universal feature of cuprate superconductors with square-planar coordinated copper.

[1] D. LeBoeuf et al., Nature **450**, 533 (2007).
[2] N. P. Breznay, I. M. Hayes, B. J. Ramshaw, R. D. McDonald, Y. Krockenberger, A. Ikeda, H. Irie, H. Yamamoto, and J. G. Analytis, Phys. Rev. B **94**, 104514 (2016).
[3] A. Ikeda, H. Irie, H. Yamamoto, and Y. Krockenberger, J. Mater. Res. **31**, 3522 (2016).
[4] N. P. Breznay, R. McDonald, Y. Krockenberger, K. A. Modic, Z. Zhu, I. M. Hayes, N. L. Nair, T. Helm, H. Irie, H. Yamamoto, and J. G. Analytis, arXiv:1510.04268 (2015).

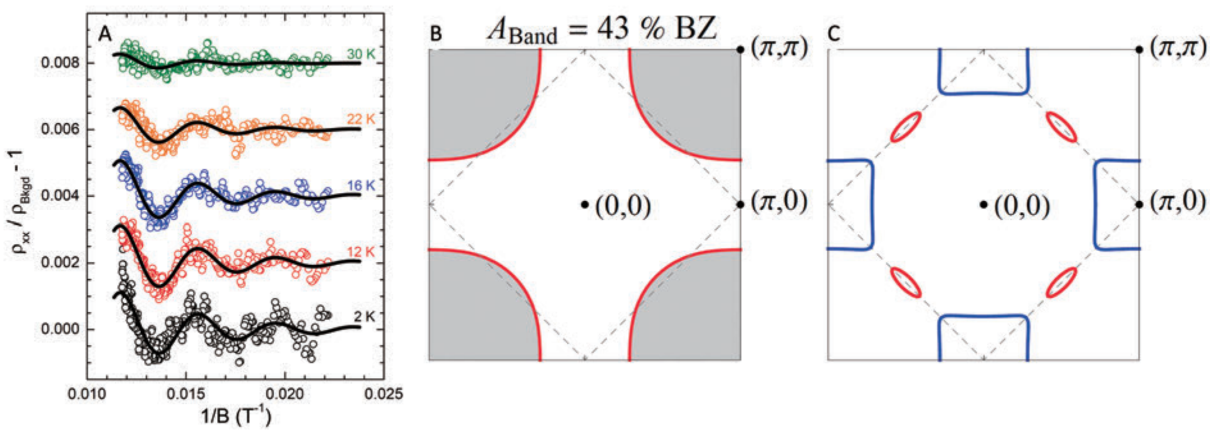


Fig. 1. (A) Low-temperature magneto-resistance of a superconducting $Pr_{2-x}Ce_xCuO_4$ thin film measured up to 92 T at temperatures between 2 and 30 K. (B) 2D Fermi surface area [A_{Band} = 43% of Brillouin zone (BZ)] estimated using Hall effect measurements as discussed in the text. (C) 2D Fermi surface area (red pockets) estimated from magnetic quantum oscillations [A_{QO} = 0.97% of Brillouin zone (BZ)].

Conductive Silk Film Electrode for Manipulation and Electrical Stimulation of Adherent Cells

Tetsuhiko Teshima, Hiroshi Nakashima, and Shingo Tsukada
Materials Science Laboratory

Action potentials generated by ion channels are involved in a wide range of cellular processes. Microelectrode arrays (MEAs) or transistor biosensors have been developed to stimulate cells or measure electrical signals. However, there is a technical issue as regards controlling the location of cells on the electrodes. This is because the cells adhere randomly to the surface, which hampers experimental reproducibility and accuracy. We thus approach this issue by developing a mobile, conductive film-based interface (nano-pallet) that enables us to manipulate and electrically activate specific cells. We fabricated the nano-pallet by using a combination of silk fibroin hydrogel and PEDOT:PSS [1] to improve transparency, biocompatibility, mechanical stiffness, and electrical conductivity.

The micropatterned nano-films were formed with a controllable size and shape by using a photolithographic technique [Fig. 1(a)] [2]. The silk fibroin matrix with embedded PEDOT:PSS is optically transparent in both the visible and ultraviolet regions, enabling the observation with various types of microscopes. The FTIR spectra had peaks at 1535 and 1630 cm^{-1} assigned to the amino-1 band, which indicated that the film contained β-sheet crystalline fractions. The gelled silk fibroin proteins improved the mechanical properties of the film (elastic coefficient = 100 MPa). Interestingly, the fabricated nano-film realized 500 times higher conductivity (at a maximum of 1 mS) than pristine PEDOT:PSS film, implying that the silk fibroin molecules help the rearrangement of the PEDOT:PSS chains and enhance charge transfer in inter-chains or inter-particles.

Since silk fibroin and PEDOT:PSS are highly biocompatible, the cells tend to migrate and proliferate at the nano-pallet surface [Fig. 1(b)]. We micropatterned the film to modulate the behavior of specific cells and activate them while retaining their adhesive property. We further utilized these films to individually measure and apply cellular action potentials to a target cell by incorporating them in capillary electrodes. By applying a voltage to cell-laden nano-films, cells expressing P/Q-type calcium channels (Ca*v*2.1) were selectively activated under a homogeneous condition [Fig. 1(c)]. These properties along with non-cytotoxicity and long-term implantation capability could provide a prototype biocompatible electrode for cells and tissues. We believe that the nano-films can be used for both *in vitro* electrophysiological analysis and various biomedical applications.

[1] S. Tsukada et al., PLoS One **7**, e33689 (2012).
[2] T. Teshima et al., Adv. Funct. Mater. **26**, 8185 (2016).

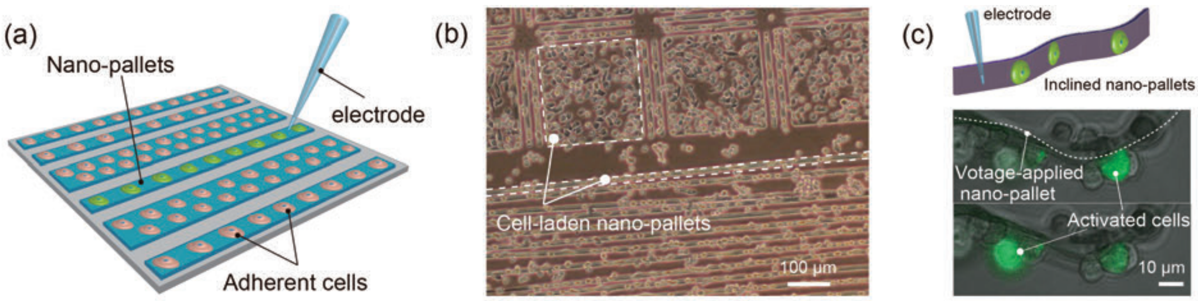


Fig. 1. (a) Schematic illustration of cell-laden nano-pallet electrodes. (b) Micrograph of cell-laden nano-pallets. (c) Merged micrographs of phase-contrast and confocal images of voltage-applied nano-pallets.

Fabrication of a Hydrogel Array for Facilitating Lipid Membrane Formation

Aya Tanaka, Yoshiaki Kashimura, and Hiroshi Nakashima
Materials Science Laboratory

The integration of biological substances in electronic devices has great potential for various applications such as biosensing and drug discovery. Of the many kinds of biological molecules, membrane proteins have received a lot of attention due to their importance in relation to cellular survival and communication. We have already developed nano-bio devices for the optical and electrophysiological analysis of membrane proteins by using microwells on a silicon substrate covered with lipid bilayers [1]. In addition, we have improved the fragility of a suspended lipid membrane by using hydrogel as a water permeable and mechanical support [2]. Here, we describe the fabrication of a cationic hydrogel array that can electrostatically facilitate the formation of a planar lipid membrane over microwells by the fusion of negatively charged small unilamellar vesicles (SUVs) with a diameter smaller than the microwell aperture (Fig. 1) [3].

The hydrogel array was produced as follows: microwells 1, 2, 4, and 8 μm in diameter and 1 μm deep were fabricated on a silicon substrate using a conventional lithographic and etching technique. The hydrogel was prepared by photo-initiating free radical polymerization from a cationic gel-precursor aqueous solution including a green fluorescent dye, calcein. The hydrogel precursor solution was dropped onto the substrate and polymerized by UV light irradiation through a photomask covering half the area of the substrate. After removing excess hydrogel from the substrate, a lipid membrane was prepared on the hydrogel-confined microwell by rupturing negatively charged SUVs with a diameter smaller than the microwell aperture. The lipid membrane formation on the hydrogel-confined microwell array was observed with fluorescence microscopy (Fig. 2).

The positively charged hydrogels were only confined in the microwells on the substrate where light was irradiated [Fig. 2(a)]. Planar lipid membranes were formed on the microwells confining the positively charged hydrogels [Fig. 2(b)]. By comparison, lipid membranes were not formed in microwells with no positively charged hydrogels [Fig. 2(c)]. These results indicate that the function of the hydrogels confined in the microwells is to both stabilize the lipid membranes mechanically and facilitate the formation of a lipid membrane via an attractive electrostatic interaction between SUVs and hydrogels. We expect these hydrogel supports to allow us to prepare a lipid membrane from a proteoliposome. Since the chemical composition of a hydrogel is easily modified, we can obtain a hydrogel array with desirable properties such as high mechanical strength, electric charge, and responsiveness to a stimulus.

[1] K. Sumitomo et al., Biosens. Bioelectron. **31**, 445 (2012).
[2] A. Tanaka et al., Appl. Phys. Express **7**, 017001 (2014).
[3] A. Tanaka et al., Colloids Surf. A **477**, 63 (2015).

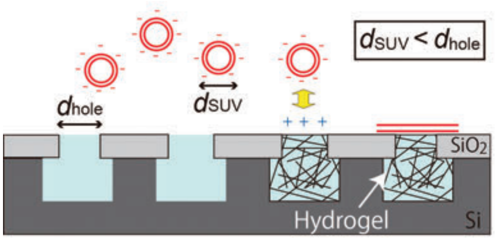


Fig. 1. Schematic illustration of lipid membrane formation by fusing SUVs on a hydrogel array.

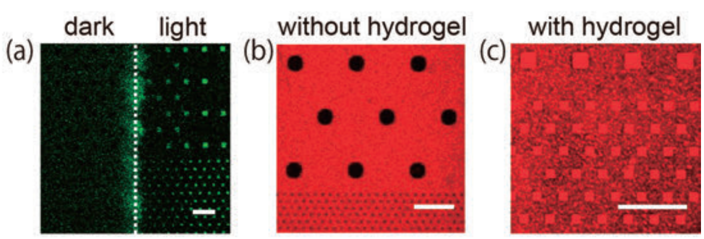


Fig. 2. (a) Fluorescence image of a substrate after light irradiation over half the substrate area. (b, c) Lipid membrane formation on the substrate (b) without and (c) with light exposure. Scale bar: 20 μm

Bio-interface on Graphene for Protein Detection

Yuko Ueno[1] and Kazuaki Furukawa[2]
[1]Materials Science Laboratory, [2]Meisei University

We have developed a two-dimensional graphene biomolecular interface to detect biologically important proteins such as cancer markers. Until this work, water-dispersive graphene oxide (GO) in aqueous media has been preferred as a biosensor platform. By contrast, we have designed and demonstrated a protein detection system on a solid surface where we can use either water-dispersive GO or hydrophobic graphene as the sensor platform [Fig. 1(left)]. This allows us to combine the protein detection system with microfluidic techniques to realize an on-chip type sensor. We have successfully demonstrated the quantitative detection of multiple targets by using a sensor array built in a multichannel configuration [1].

We compared the protein detection performance quantitatively by using graphene and GO biosensors prepared on the same chip. We fixed graphene and GO on the SiO_2 surface of a solid substrate and modified both surfaces with a dye-labeled aptamer (single-stranded DNA that recognizes and forms a complex with a specific target molecule such as a protein) under the same conditions. Here we used prostate specific antigen (PSA, a cancer marker) as the target molecule. We observed increases in the fluorescence intensity on both the graphene and GO surfaces when we added PSA (33 μg/mL @ t = 100 s) [Fig. 1(right)]. After performing several observations under constant PSA concentration conditions, we added deionized water to dilute the PSA solution. The fluorescence intensities became weaker as the concentration of the PSA solution decreased (20, 14, 11, 9 μg/mL @ t = 300 s, 400 s, 500 s, and 600 s). We thus demonstrated the successful operation of the sensor on both graphene and GO surfaces. We compared the performance of the graphene sensor with that of the GO sensor by subtracting the average fluorescence intensities before PSA addition from the maximum fluorescence intensities after PSA detection. The graphene sensor yielded a larger intensity than GO, and the ratio exceeded 3 [2]. We conclude that the graphene is superior to GO in terms of building a biomolecular interface for fluorescence-based sensors.

This work was supported by JSPS KAKENHI JP26286018.

[1] Y. Ueno, K. Furukawa et al., Anal. Chim. Acta **866**, 1 (2015): Featured on Cover
[2] K. Furukawa, Y. Ueno et al., ACS Sens. **1**, 710 (2016).

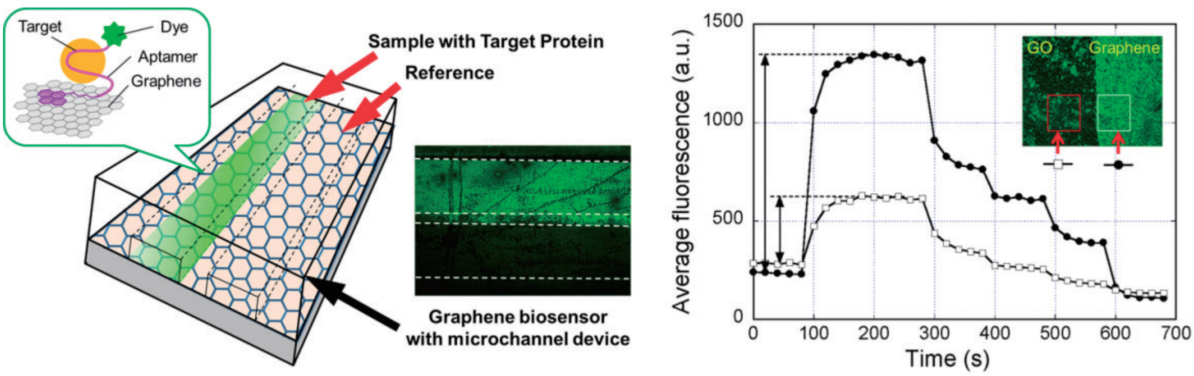


Fig. 1. (Left) Schematic of graphene biosensor.
(Right) Quantitative comparison of PSA detection performance of graphene and GO sensors.

World-record Accuracy of Gigahertz High-speed Single-electron Transfer

Gento Yamahata[1], Stephen P. Giblin[2], Masaya Kataoka[2],
Takeshi Karasawa[1], and Akira Fujiwara[1]
[1]Physical Science Laboratory, [2]National Physical Laboratory

A single-electron (SE) pump can transfer electrons one by one with clock control. When the clock frequency is f, the pump generates accurate electric current ef, where e is the elementary charge. The accurate current can be used for the current standard, which corresponds to a ruler with which to measure electric current. Although there are many reports on SE transfer, it has been difficult to achieve high-accuracy operation at more than 1 GHz. Here, using a high-accuracy measurement system, we precisely measure a current generated by a Si SE pump [1] and demonstrate an ultralow transfer error rate of less than 9.2×10^{-7} at 1 GHz [2].

Figure 1(a) shows a schematic of the device, which has double-layer gate electrodes on a Si wire with a diameter on the order of 10 nm. By applying a DC voltage to the upper gate, we induce electrons in the Si wire. In addition, by applying a high-frequency clock signal and DC voltage (V_{G2}) to lower gates G1 and G2, respectively, an electron from the source is captured by the island between G1 and G2, followed by its ejection to the drain. We measure the transfer current using a high-accuracy current measurement system [Fig. 1(b)], which has an ultralow measurement uncertainty of 8.8×10^{-7} achieved by the calibration using the Josephson voltage standard and quantum Hall resistance standard.

Figure 1(c) shows the ratio of the difference from ef at 1 GHz as a function of V_{G2}. While the standard uncertainty of the measurements is 9.2×10^{-7}, the mean of the measured values (normalized by ef) in the current plateau deviates only -6.4×10^{-7}. This means that the measured current matches ef in the range of the standard uncertainty. In addition, the current plateau is flat with the level of 9.2×10^{-7}. These results indicate that the transfer error rate is less than 9.2×10^{-7}, which is a world-record accuracy in the gigahertz regime. Furthermore, we observe a transfer error rate of about 3×10^{-6} at 2 GHz. This indicates that our device breaks the 1-GHz barrier and is suitable for high-speed operation. In future work, we will optimize the measurement system and device structure to further improve accuracy, with the aim of realizing a high-accuracy current standard.

[1] A. Fujiwara, K. Nishiguchi, and Y. Ono, Appl. Phys. Lett. **92**, 042102 (2008).
[2] G. Yamahata et al., Appl. Phys. Lett. **109**, 013101 (2016).

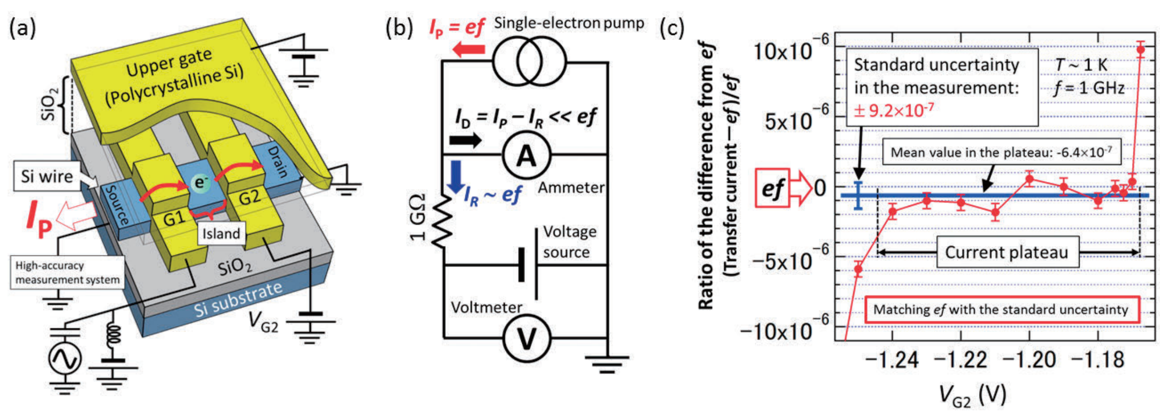


Fig. 1. (a) Schematic of the SE pump. (b) High-accuracy current measurement system, which has a 1-GΩ standard resistor and voltmeter calibrated by the primary standards. When $I_R \sim ef$ by setting the value of the voltage source, $I_D << ef$. In this case, we can neglect the measurement uncertainty of I_D.
(c) High-accuracy measurement results at 1 GHz.

A Planar Cold Cathode Based on Multilayer-graphene/SiO_2/Si Heterostructure

Katsuhiko Nishiguchi[1], Daisuke Yoshizumi[2], Yoshiaki Sekine[3], Kazuaki Furukawa[3], Akira Fujiwara[1], and Masao Nagase[2]
[1]Physical Science Laboratory, [2]Tokushima University, [3]Materials Science Laboratory

Cathodes that emit electrons are used for various applications such as electron microscopy, electron beam lithography, material reformation, and vacuum gauges. The most commonly used cathode is a hot cathode that uses a filament heated up by current, and a Spindt-type cathode composed of a sharp cone [1] has been studied as a cold cathode with high functionality. While each cathode type has some advantages, there are also some problems: cathodes operate by using a high voltage supply in a high vacuum and electrons emitted spread widely; both of which lead to complicated systems. In this work, we demonstrated a planar cold cathode based on a multilayer-graphene/SiO_2/Si heterostructure [2] to solve these problems.

Figure 1 shows the schematic and cross-sectional views of the cold cathode based on a multilayer-graphene (~10 nm)/SiO_2 (6 nm)/Si heterostructure. Figure 2 shows the mechanism of electron emission from the cathode. When voltage $V_{graphene}$ is applied to the multilayer graphene, electrons in the Si layer tunnel to the multilayer graphene through the SiO_2. Electrons with energy larger than the work function (~5 eV) of the multilayer graphene are emitted from it to a vacuumed space and reach the anode, which leads to current I_{anode}. However, when the energy of electrons in the multilayer grapheme is smaller than its work function, the electrons (current $I_{graphene}$) flow into the multilayer graphene without electron emission. Figure 3 shows the electron-emission characteristics. The increase in $V_{graphene}$ increases the tunneling current $I_{graphene}$. At $V_{graphene}$ larger than the work function of the multilayer-graphene, I_{anode} flows because the electrons are emitted from the cathode and reach the anode. The electron-emission efficiency is defined as 0.3%, which is four orders of magnitudes larger than in our previous results using polycrystalline Si instead of multilayer graphene [3]. This improvement originates from a small scattering of electrons in the multilayer graphene due to its thinness, which means that single-layer graphene is promising for further improvement of the efficiency. On the other hand, since multilayer-graphene's conductivity is not sensitive to electron-emission characteristics, wide graphene grown by chemical vapor deposition can be used to make a wide-area cathode. Additionally, since electrons are emitted perpendicular to the multilayer graphene with a small voltage in low vacuum, a simple system for electron emission targeting various applications can be achieved.

[1] C. A. Spindt, J. Appl. Phys. **39**, 3504 (1968).
[2] K. Nishiguchi et al., Appl. Phys. Express **9**, 105101 (2016).
[3] K. Nishiguchi et al., Jpn. J. Appl. Phys. **47**, 5106 (2008).

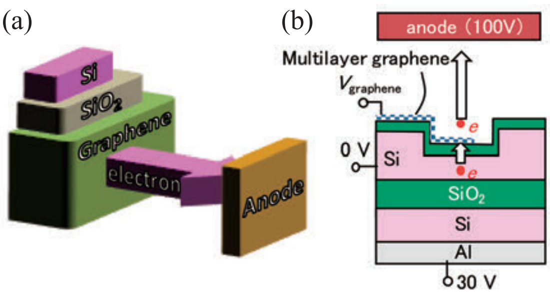


Fig. 1. (a) Schematic and (b) cross-sectional view of the cathode.

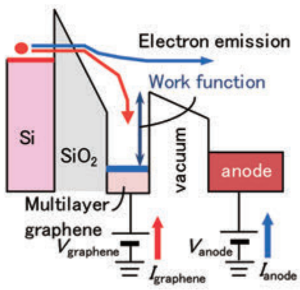


Fig. 2. A mechanism of electron emission.

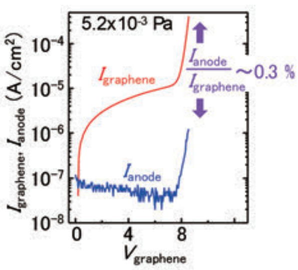


Fig. 3. Electron-emission characteristics.

Experimental Test of Macroscopic Realism Using a Superconducting Flux Qubit

Kosuke Kakuyanagi[1], George C. Knee[2], Mao-Chuang Yeh[3],
Yuichiro Matsuzaki[1], Hiraku Toida[1], Hiroshi Yamaguchi[1], Shiro Saito[1],
Anthony J. Leggett[3], and William J. Munro[2]
[1]Physical Science Laboratory, [2]Optical Science Laboratory, [3]University of Illinois

Realism is an idea that a state of the object is determined before its observation. Although this idea is widely believed to hold in our lives, it has been shown that "realism" is broken in a microscopic world. The microscopic world is governed by the principles of quantum mechanics that allows a state to have a superposition. For a superposed state, the measurable values are not determined until they are observed. Since the macroscopic world is composed of microscopic objects, quantum mechanics could be valid even in this macroscopic world. Or there could be so limitation to the application of the quantum mechanics to the macroscopic world. Currently, there is still no consensus about which is likely to be true.

Here we aim to address this. A superconducting flux qubit is a circuit composed of several Josephson junctions and a superconducting loop. Due to the non-linearity of the Josephson junctions, this device provides a two-level system with clockwise and anti-clockwise current states. These two states contain 10^{12} electrons flowing around the circuit per a second. We test whether realism is broken with this macroscopic device or not.

In our normal world, it is accepted that we can measure macroscopic objects without disturbing them (non-invasiveness). If realism is true, any non-invasively measured results on this device should satisfy the Leggett-Garg inequality. However, if quantum mechanics is true, we could observe a violation of the inequality using non-invasive measurements.

We show that the Leggett-Garg inequality is mathematically equivalent to an experimental test to check if the non-invasive measurements affect the state of the device. Interestingly, even if the measurement is designed to be non-invasive, observation by the measurement induces a projection according to quantum mechanics. This can change the state of the device.

In our test, we perform two experiments. First we check the non-invasiveness of the measurements by evaluating the classical disturbance that our measurement device on the flux qubit has. Second, we compare the measured state of the flux qubit with a not measured state of the flux qubit. From these experiments, we have shown that there is a large difference in these measured results, which cannot be explained by the classical disturbance [Fig.1(a)]. This is a manifestation of quantum superposition. Our results conclusively demonstrate that "realism" is broken even for a macroscopic device such as a superconducting qubit [Fig. 1(b)] [1].

This work was partly supported by JSPS KAKENHI JP15H05870 and JP15H05867.

[1] G. C. Knee, K. Kakuyanagi, M-C. Yeh, Y. Matsuzaki, H. Toida, H. Yamaguchi, S. Saito, A. J. Leggett, and W. J. Munro, Nature Commun. **7**, 13253 (2016).

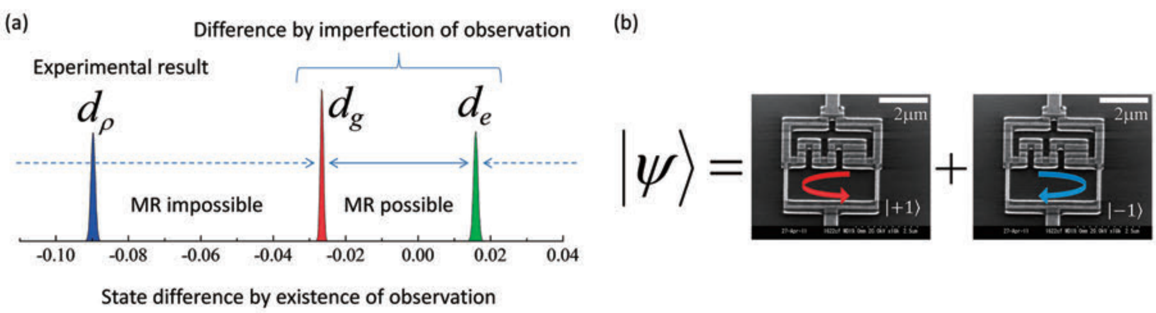


Fig. 1. (a) Differences by observation. (b) Quantum superposition of current state.

Coherent Coupling Between 4300 Superconducting Qubits and a Superconducting Resonator

Kosuke Kakuyanagi[1], Yuichiro Matsuzaki[1], Corentin Déprez[1], Hiraku Toida[1], Kouichi Semba[2], Hiroshi Yamaguchi[1], William J. Munro[3], and Shiro Saito[1]
[1]Physical Science Laboratory, [2]NICT, [3]Optical Science Laboratory

Hybridization between a superconducting resonator and ensembles of two level systems has been considered as a promising way to realize quantum technologies. The conventional approaches have used natural systems such as atoms & molecules to realize the ensemble where the properties of such "atoms" are difficult to tailor to the properties of the device [1]. Our approach is to create the ensemble from artificial atoms such as superconducting qubits. The properties such superconducting qubits are not intrinsic but can be largely changed even after the fabrication. Moreover, due to their large size, we can in principle achieve individual controllability. In this direction, only a small number of superconducting qubits (8 in total and not an ensemble) has shown collective coupling to a resonator [2]. Here, we fabricate a hybrid device composed of 4300 superconducting flux qubits embedded in a superconducting resonator [3]. We observe a large dispersive frequency shift in the spectrum of 250 MHz as shown in Fig. 1. From our theoretical analysis, we show that this frequency shift is evidence of a coherent coupling between the resonator and thousands of flux qubits. Although the coupling strength of a single flux qubit with the resonator is much smaller than the inhomogeneous width of the ensemble, the coupling can be enhanced by collective effects. This provides us with a measurable signal for the experiments. Our results represent the largest number of coupled superconducting qubits realized so far.

This work was supported by JSPS KAKENHI JP15K17732 and JP25220601. This work was also partly supported by MEXT KAKENHI JP15H05869 and JP15H05870.

[1] Z-L. Xiang et al., Rev. Mod. Phys. **85.2** 623 (2013).
[2] P. Macha et al., Nature Commun. **5**, 5146 (2014).
[3] K. Kakuyanagi et al., Phys. Rev. Lett. **117**, 210503 (2015).

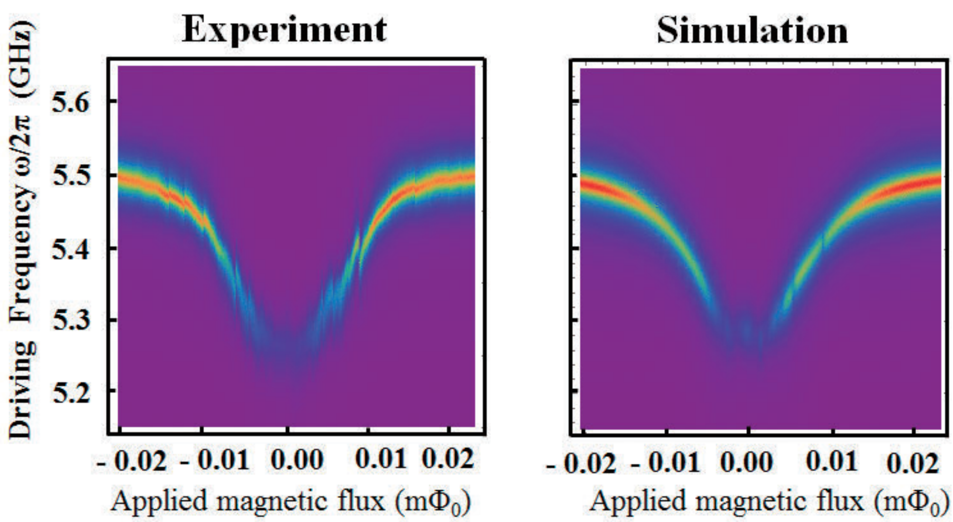


Fig. 1. Energy spectrum of a superconducting microwave resonator coupled to an ensemble of flux qubits. (Left) Experimental results. (Right) Theoretical analysis.

Physical Science Laboratory

Simulating the Spin Ising Model with Phonons

Imran Mahboob and Hiroshi Yamaguchi
Physical Science Laboratory

Physical simulators, composed of atoms, ions, photons or electrons, have emerged as a novel means for solving intractable mathematical problems [1]. Here this concept is extended to phonons that are localised in spectrally pure resonances in an electromechanical system [Fig. 1(a)] which enables their interactions to be exquisitely fashioned via piezoelectricity [2]. Specifically the electromechanical system is developed to mimic the spin Ising Hamiltonian where its spin 1/2 particles are replicated by the phase bi-stable vibration from a mechanical parametric resonance where multiple resonances play the role of a spin bath [Figs. 1(c),(d)]. The coupling between the mechanical spins is created via non-degenerate parametric down-conversion which entwines the resonances resulting in correlated vibrations [Fig. 1(b)]. The combination of parametric resonance and parametric down-conversion can then be harnessed to imitate a ferromagnetic, random or an anti-ferromagnetic state on-demand, whose statistical dynamics are consistent with the idealized spin Ising interaction. These results suggest that the electromechanical system could be further developed to imitate the spin Ising model in a non-trivial configuration, namely with a large number of spins with multiple degrees of coupling, a task that would overwhelm a conventional computer [3].

This work was supported by MEXT KAKENHI JP15H05869.

[1] I. Buluta and F. Nori, Science **326**, 108 (2009).
[2] I. Mahboob et al., New J. Phys. **18**, 083009 (2016).
[3] I. Mahboob et al., Sci. Adv. **2**, e1600236 (2016).

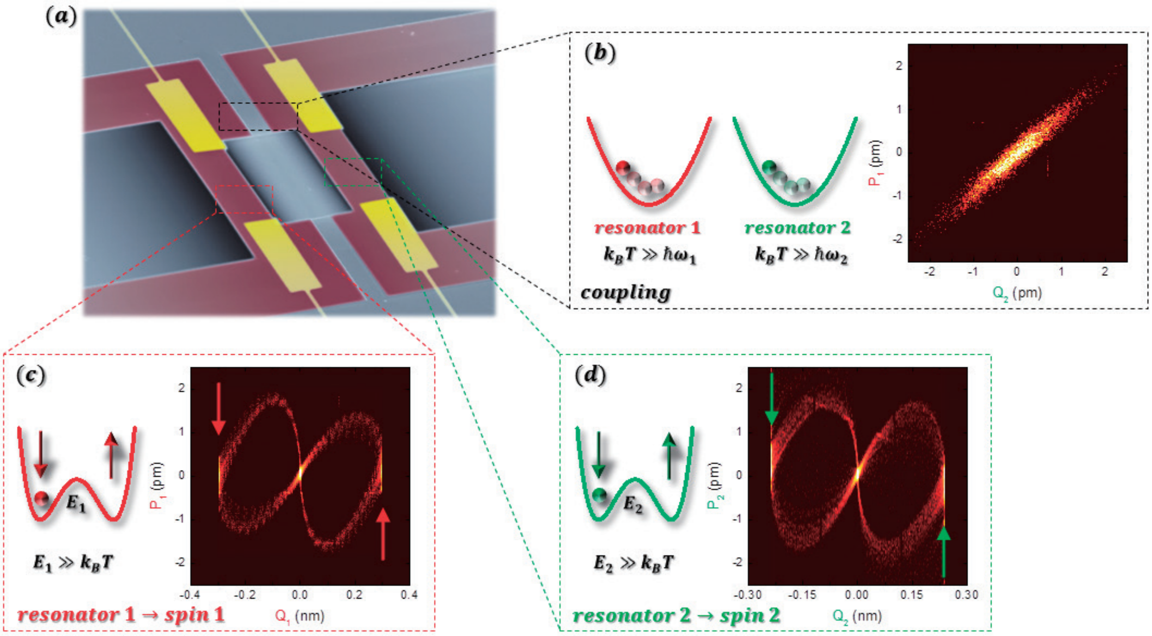


Fig. 1. (a) A false colour scanning electron micrograph of the electromechanical system. Each mechanical resonator (1 and 2) has a vibration in its position which can be decomposed into in-phase (Q) and quadrature (P) components. (b) The vibration of the resonators, with frequency ω, can be visualised as balls rolling in harmonic potentials driven by thermal energy k_BT. The parametric down-conversion correlates the vibration of the two resonators, effectively coupling them, which is confirmed via a linear inter-dependence of the in-phase and quadrature components of the two resonator's motion. (c) and (d) Parametric resonance is manifested as either resonator having two large amplitude vibrations, with opposite phases, in phase-space and an *off* thermal state at the origin. This behaviour corresponds to the underlying harmonic potential of the resonators evolving into a double well potential, with barrier energy E being greater than k_BT thus enabling spin information to be encoded.

A Strongly Coupled Λ-type Micromechanical System

Hajime Okamoto and Hiroshi Yamaguchi
Physical Science Laboratory

The ability to control phonon transport in semiconductor micromechanical systems has important consequences for applications, such as ultralow-power-consumption mechanical memories and logic gates [1,2]. Such phonon manipulation requires strong coupling of adjacent mechanical resonators, that is, energy exchange between the resonators at a rate larger than the energy dissipation. Parametrically coupling mechanical resonators via the periodic modulation of stress is an effective way to realize strong coupling. This has been recently demonstrated in GaAs mechanical systems using the piezoelectric or photothermal effect [1,3], where the modulation with the frequency difference between the mechanical resonators (modes) allows strong on-chip coupling as well as its on-off switching. However, such a demonstration has been limited to two-resonator systems and not yet expanded to multiple-resonator (array) ones. Here, we demonstrate strong coupling among three SiN mechanical resonators via dielectric stress modulation with an electric field [4].

The sample consists of three SiN doubly clamped beams, where the middle beam (beam M) is sandwiched by two metalized beams (beams L and R) [Fig. 1(a)]. Because the mode frequency of beam M (f_M) is higher than that of beams L (f_L) and R (f_R), it forms a Λ-type three-level system as shown in Fig. 1(b). All the levels are frequency-shifted in an electric field applied between beams L and R, that is, the three resonators are coupled via the dielectrically induced attractive force. However, strong coupling is not achieved only with this DC field because of the frequency mismatch between beam M and beam L (R). To compensate for this frequency mismatch, the electric field is AC-modulated with the frequency difference between the two modes ($\Delta_{L(R)} = f_M - f_{L(R)}$). Then, beam M and beam L (R) are parametrically coupled, leading to the splitting of each level. When the two modulation tones (Δ_L, Δ_R) are simultaneously applied, each of the three levels splits into three. Here, one state of beam M is "dark", where the vibration amplitude is canceled out [Fig. 1(b)]. This is due to the destructive interference of the three beams and is evidence of the formation of a strongly coupled Λ-type mechanical system.

This work was supported by MEXT KAKENHI JP15H05869, JP15K21727 and collaborated with Swiss Federal Institute of Technology in Lausanne (EPFL).

[1] H. Okamoto et al., Nature Phys. **9**, 480 (2013).
[2] T. Faust et al., Nature Phys. **9**, 485 (2013).
[3] R. Ohta et al., Appl. Phys. Lett. **107**, 091906 (2015).
[4] H. Okamoto et al., Appl. Phys. Lett. **108**, 153105 (2016).

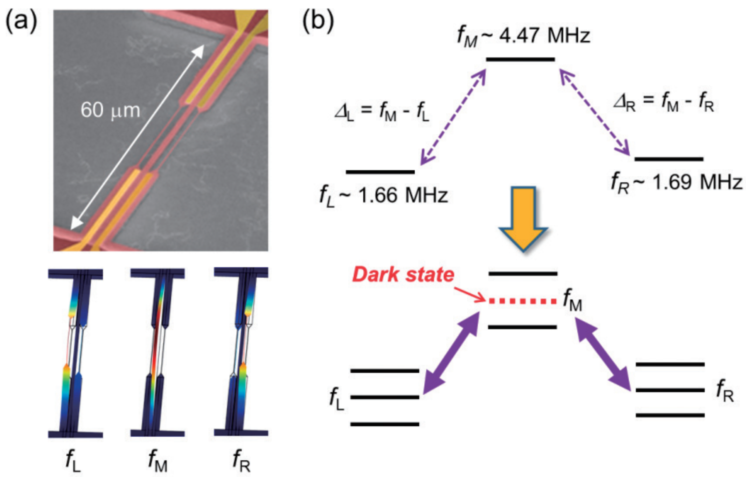


Fig. 1. (a) Scanning electron micrograph of the device: red, SiN (100 nm thickness); yellow, Au (45 nm thickness); grey, Si substrate. Simulated mode shape of the three mechanical resonators is also shown. (b) Energy level diagram of the Λ-type micromechanical system. Each of the three levels splits into three when the two frequency modulation tones (Δ_L, Δ_R) are simultaneously applied. Notably, one state of beam M is "dark" in the sense that it involves no motion of the middle beam.

Engineering Quantum Spin Hall Insulators by Strained-layer Heterostructures

Takafumi Akiho[1], François Couëdo[1], Hirhoshi Irie[1], Kyoichi Suzuki[1], Koji Onomitsu[2], and Koji Muraki[1]
[1]Physical Science Laboratory, [2] Materials Science Laboratory

Quantum spin Hall insulators (QSHIs) have insulating bulk and conductive edges originating from nontrivial inverted band structures. Owing to these unique properties of the spin-helical edge modes, QSHIs have been proposed as a platform for exploring spintronics applications and exotic quasiparticles useful for topological quantum computation. InAs/GaSb quantum wells (QWs) have been predicted to offer a QSHI and have a key advantage of being *in situ* tunable between trivial and topological insulating phases. However, the residual bulk conductivity associated with the small energy gap in the QSHI phase has been an obstacle to the unambiguous identification of edge properties. In this study, we propose a strained InAs/InGaSb heterostructure as a QSHI candidate and demonstrate that the strain enhances the energy gap and leads to superior bulk insulation properties [1].

The QWs were grown by MBE and comprise InAs with the thickness of t (8.5~10.9 nm) and 5.9-nm-thick $In_{0.25}Ga_{0.75}Sb$ layers, sandwiched between AlSb barrier layers. Compressive strain induced in the InGaSb layer enhances heavy-hole light-hole splitting and impacts the energy dispersion in the QSHI phase.

We determined the density of electrons (n_e) and holes (n_h) separately through the fast Fourier transform (FFT) analysis of the longitudinal resistance (R_{xx}) vs. magnetic field (B) trace [Fig. 1(a)]. We confimed the coexsitence of electrons and holes at high densities, which indicates that the QW is deep in the band-invered regime. From the linear fit of gate voltage (V_{FG}) dependence of n_e and n_h (inset), we obtained the density n_{cross} at the charge neutrality point (where $n_e = n_h$) to be 3.6×10^{15} m^{-2}, which gives a quantitative measure of the band overlap. We emphasize that the linear fit in the two-carrier regime gives an accurate evaluation of the band overlap.

The R_{xx} peak height at the the charge neutrality point, which mainly reflects in-gap states in the bulk, increased with decreasing InAs thickness and reached 889 kΩ (corresponding resistivity of ~$10h/e^2$) [Fig. 1(b)]. All samples have bulk resistivity two orders of magnitude higher than those of the InAs/GaSb system. These results demonstrate that InAs/InGaSb strained QWs are promising for investigating edge transport properties.

This work was supported by JSPS KAKENHI JP15H05854 and JP26287068.

[1] T. Akiho et al., Appl. Phys. Lett. **109**, 192105 (2016).

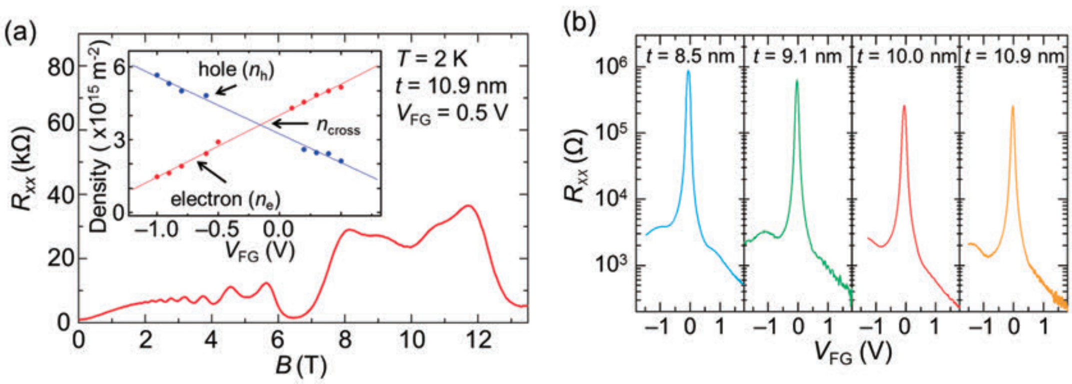


Fig. 1. (a) R_{xx} vs. B trace. (Inset) V_{FG} dependence of n_e and n_h. (b) R_{xx} peaks with different InAs thickness.

Andreev Reflection and Bound State Formation in a Ballistic Two-dimensional Electron Gas Probed by a Quantum Point Contact

Hiroshi Irie[1], Clemens Todt[1], Norio Kumada[1], Yuichi Harada[1], Hiroki Sugiyama[2], Tatsushi Akazaki[1], and Koji Muraki[1]
[1]Physical Science Laboratory, [2]NTT Device Technology Laboratories

The superconducting proximity effect in superconductor-semiconductor hybrid structures has gained increased interest for studying exotic quantum phases [1] and developing novel electronic devices [2]. In such hybrid structures, charge transport near the interface is governed by Bogoliubov quasiparticles generated by Andreev reflections. Better control and sensitive detection of electronic properties of the quasiparticle are among the major challenges in the studies of the proximity effect.

We study transport properties of Bogoliubov quasiparticles in a high-mobility $In_{0.75}Ga_{0.25}As$ two-dimensional electron gas (2DEG) coupled to a superconducting Nb electrode [3]. By using a quantum point contact (QPC) formed in the vicinity of the InGaAs/Nb interface as a single-mode probe with a tunable transmission [Fig. 1 (a)], we can study the effects of the boundary condition on the quasiparticle transport in the ballistic regime. Figure 1 (b) shows a differential conductance spectrum of a fully open QPC. The QPC shows a single-channel conductance greater than the conductance quantum $2e^2/h$ at zero bias, which indicates the presence of Andreev-reflected quasiparticles returning back through the QPC. When the QPC transmission T_{QPC} is reduced to the tunneling regime, the differential conductance spectrum probes the single-particle density of states in the proximity area. Measured conductance spectra exhibit a double peak within the superconducting gap of Nb [Fig. 1 (c)], demonstrating the formation of Andreev bound states in the 2DEG. Both of these results, obtained in the open and closed geometries, underpin the coherent nature of quasiparticles, i.e., phase-coherent Andreev reflection at the InGaAs/Nb interface and coherent propagation in the ballistic 2DEG.

[1] V. Mourik et al., Science **336**, 1003 (2012).
[2] T. W. Larsen et al., Phys. Rev. Lett. **115**, 127001 (2015).
[3] H. Irie et al., Phys. Rev. B **94**, 155305 (2016).

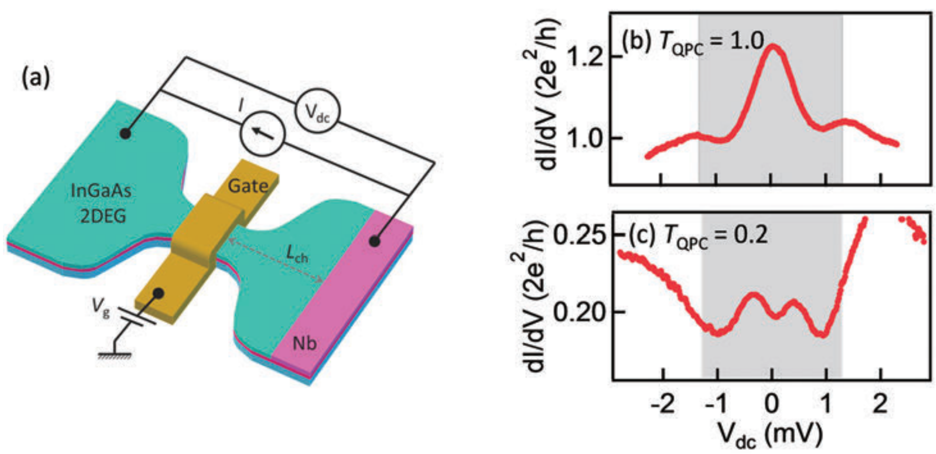


Fig. 1. (a) Superconductor/semiconductor hybrid device studied. The distance between QPC and Nb contact L_{ch} is 220 nm. (b,c) Differential conductance spectra measured in (b) the open-channel regime and (c) the tunneling regime. The grey areas represent the superconducting gap energy of Nb (1.3 meV).

Evaluation of Disorder Introduced by Electrolyte Gating through Transport Measurements in Graphene

Norio Kumada[1], Andrew Browning[1], Yoshiaki Sekine[2], Hiroshi Irie[1], Koji Muraki[1], and Hideki Yamamoto[2]
[1]Physical Science Laboratory, [2]Materials Science Laboratory

Owing to the large capacitance as well as the flexibility, transparency, and facile processing of ionic liquids, electrolyte gating has been used for widespread applications. However its drawback, namely contamination of the surface of the base material, has been overlooked. In this work, we evaluate the degree of disorder introduced by the electrolyte gating structure using graphene, in which the carrier transport is sensitive to disorder scattering [1].

We used graphene grown by thermal decomposition of a 6H-SiC(0001) substrate. Two different types of samples were fabricated; one using an ionic liquid gate and the other having a metal gate for reference. For the ion-gated samples, the graphene Hall bar and coplanar Cr/Au gate electrode were coated by EMIM-TFSI [Fig. 1(a)]. To quantitatively investigate the disorder effects from the ionic liquid, we compare the transport properties for the ion- and metal-gated samples through a wide range of the carrier densities. From the slope of the conductivity as a function of the carrier density, we found that the deposition of the ionic liquid introduces charged impurities with a density of approximately 6×10^{12} cm^{-2} [Fig. 1(b)]. This limits the low-temperature mobility of graphene to 3×10^{3} cm^{2}/Vs [Fig. 1(c)]. We also found that at higher temperature (> 50 K), phonons in the ionic liquid further reduce the mobility; restricting the upper limit at room temperature to approximately 2×10^{3} cm^{2}/Vs at room temperature. Since the degree of disorder does not depend on the base material, our results provide useful information on estimating the disorder effects in any type of electrolyte gating experiments.

[1] A. Browning et al., Appl. Phys. Express **9**, 065102 (2016).

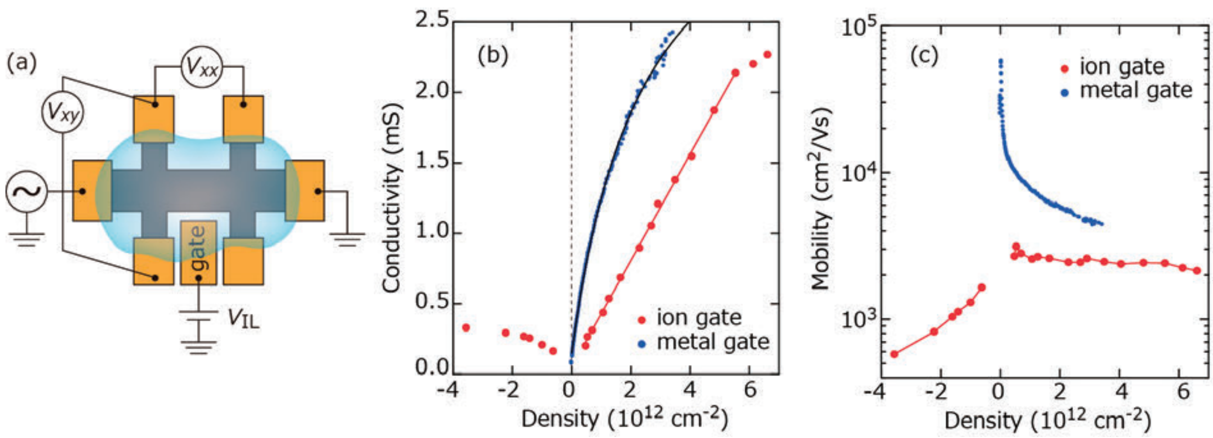


Fig. 1. (a) Schematic top view of the ion-gated sample. (b) and (c) Conductivity and mobility, respectively, as a function of the carrier density at 4 K for the ion-gated sample (red dots) and metal-gated sample (blue dots). The solid lines in (b) represent results of the fitting.

Spectroscopic Analysis for Measuring Quantum Phase Transitions of Bosonic Atoms in an Optical Lattice

Kensuke Inaba and Makoto Yamashita
Optical Science Laboratory

Ultra-cold atoms in an optical lattice, which are highly controllable and quite clean quantum systems, allow us to simulate quantum many-body phenomena found in condensed matters and related fields. As a typical example, a quantum phase transition from superfluid (SF) to Mott insulator (MI) of bosons has been experimentally demonstrated by tuning lattice depths [1]. However, systematic and comprehensive measurements across the two phases, SF and MI, are still lacking. This is because measurement methods used in the previous works are basically standing on the strategy to detect a certain characteristic signal for one of the two phases and then to determine the critical point where such a signal disappears: For example, the time-of-flight imaging has been used to identify SF-MI transitions by detecting the disappearance of the coherent peak that characterizes the existence of SF states [1].

Kyoto Univ. and NTT collaboratively developed high-resolution spectroscopy [2] and a numerical scheme for calculating observed spectra [3], respectively. The developed spectroscopy has been used to comprehensively measure spectra of bosons in a three-dimensional optical lattice across the SF and MI phases [2]. Our numerical scheme takes into account the physical sum rule [3], which allows us to systematically analyze the spectra without any fitting parameters. As shown in Fig. 1, experiments and calculations show good agreements with each other, and the obtained spectra clearly capture the signatures of the existence of both SF and MI states in shallow and deep lattices, respectively [2]. Furthermore, we found that SF and MI states coexist in a middle lattice [2]. A combination of the high-resolution spectroscopy and the numerical scheme can determine quantum phase transitions of bosons in detail, and in addition, it will be applicable to the future quantum simulation on the various systems, e.g., fermions or boson-fermion mixtures confined in optical lattices.

This work was partly supported by CREST (JPMJCR08F5), JST and JSPS KAKENHI JP25287104.

[1] I. Bloch, J. Dalibard, and W. Zwerger, Rev. Mod. Phys. **80**, 885 (2008), and references therein.
[2] S. Kato, K. Inaba et al., Nature Commun. **7**, 11341 (2016).
[3] K. Inaba and M. Yamashita, Phys. Rev. A **93**, 043608 (2016).

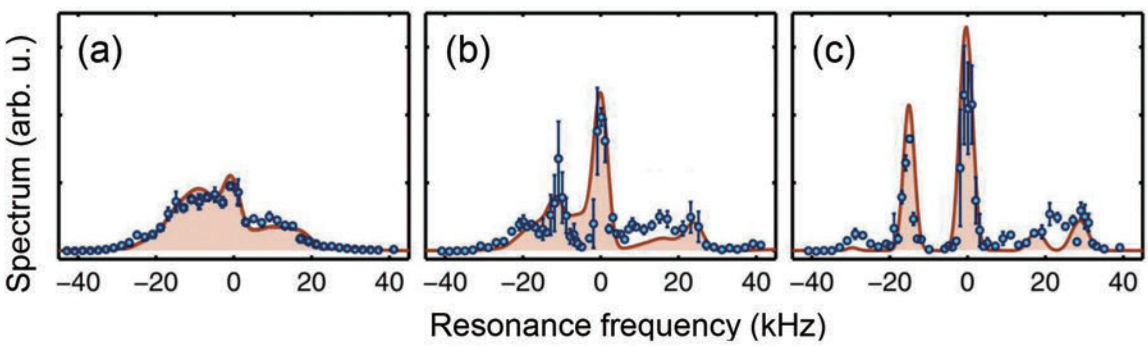


Fig. 1. Spectrum of bosons obtained experimentally (blue circles) and those calculated numerically (orange solid lines) in (a) shallow, (b) middle, and (c) deep optical lattices. The broadened spectra originate from the superfluid states, and the discrete narrow spectra result from the Mott insulators. The both characteristics can be seen in the middle region. The data is extracted from Ref. [2].

Coherent Ising Machine for Combinatorial Optimization Problems

Takahiro Inagaki, Kensuke Inaba, Toshimori Honjo, and Hiroki Takesue
Optical Science Laboratory

It is known that combinatorial optimization problems can be mapped onto ground-state-search problems of the Ising model. Recently, several approaches have been demonstrated to solve the Ising problems using artificial spin systems. A coherent Ising machine (CIM) can simulate the Ising model with networked degenerate optical parametric oscillators (DOPOs). A DOPO takes only a 0 or π phase relative to the pump pulse, so this binary phase mode can represent the binary spin state of the Ising model. To solve complex problems with the CIM, we need to prepare a large number of DOPOs and connect them with each other through mutual optical couplings. We generated over 10,000 DOPOs via time-domain multiplexing in a 1-km fiber ring cavity [1,2]. Using those DOPOs, a one-dimensional Ising model was simulated by introducing nearest-neighbor optical coupling with a 1-bit delay interferometer. We observed the ferromagnetic and anti-ferromagnetic behavior of low-temperature Ising spins with the networked DOPOs.

To implement all-to-all optical couplings among DOPOs, we employed a measurement and feedback (MFB) scheme [Fig. 1 (left)]. A portion of the DOPOs are measured using a balanced homodyne detector. The measured signals are then input into a field-programmable gate array (FPGA) module, where a feedback signal for each DOPO is calculated according to the network structure. The calculated feedback signals are converted into optical pulses, and launched into the cavity to achieve the virtual optical couplings between DOPOs. With the MFB scheme, we developed a CIM that could find solutions to optimization problems on arbitrary graph structures with up to 2,048 nodes [3]. We performed a benchmark study to investigate the performance of our CIM to solve an optimization problem and compared it with a simulated annealing (SA) algorithm. We used the CIM and SA to solve the maximum-cut (MAX-CUT) problem for a 2,000-node complete graph with 1,999,000 undirected edges. The times needed to reach the target Ising energy were about 70 μs for the CIM and 3.2 ms for SA [Fig. 1, (right)]. The CIM obtained the benchmark Ising energy nearly 50 times faster than SA. These results suggest that a CIM can outperform SA on a CPU when solving dense graph problems.

This work was supported by the ImPACT Program.

[1] T. Inagaki et al., Nature Photon. **10**, 415 (2016).
[2] H. Takesue et al., Opt. Lett. **41**, 4273 (2016).
[3] T. Inagaki et al., Science **354**, 603 (2016).

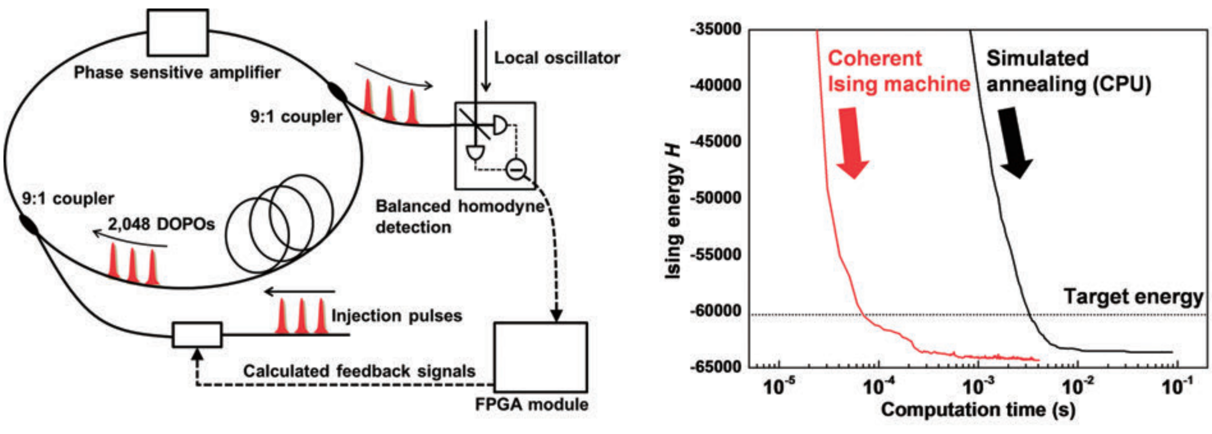


Fig. 1. (Left) Experimental setup of CIM with measurement and feedback scheme.
(Right) Time evolutions of Ising energy when solving the MAX-CUT problem for a 2000-node complete graph.

Quantum State Tomography for High-dimensional Time-bin States

Takuya Ikuta and Hiroki Takesue
Optical Science Laboratory

High-dimensional quantum states are being investigated as resources of advanced quantum information processing. Because a high-dimensional state has multiple orthogonal states, for example, we can increase the information that a particle can carry (multiple bits per particle). A time-bin state is often used in photonic quantum communication systems because a time bin state is robust against disturbances caused by optical fiber transmission. Furthermore, we can easily enlarge the number of dimensions of the state simply by increasing the number of time slots that form it. To evaluate the quality of the state, it is important to fully characterize the quantum state via quantum state tomography [1,2]. However, a method of quantum state tomography for high-dimensional time-bin states was not known prior to our research. Here, we demonstrated a quantum state tomography scheme for high-dimensional time-bin states using cascaded Mach-Zehnder interferometers [3]. With this scheme, the number of the measurement settings scales linearly with the dimension of the state [3].

Figure 1 shows the concept of quantum state tomography using cascaded Mach-Zehnder interferometers. The information of a high-dimensional time-bin state is encoded at multiple temporal positions and in the relative phases between the positions. After a photon passes through the cascaded Mach-Zehnder interferometers, it makes an interference pattern of single photon counts depending on its state and the settings of the interferometers. By observing the interference pattern while changing the settings of the interferometers, we can obtain information on the temporal positions and relative phases encoded in the photon and reconstruct the state with that information.

We performed quantum state tomography on four-dimensional time-bin entangled states generated via spontaneous parametric down-conversion in a periodically poled lithium niobate waveguide. We obtained a reconstructed state that was close to the four-dimensional maximally entangled time-bin state (Fig. 2). The number of measurement settings was 16, which was equal to the dimension of the Hilbert space for the two entangled photons. Thus, we successfully demonstrated an efficient quantum state tomography for high-dimensional time-bin states.

[1] D. F. V. James et al., Phys. Rev. A **64**, 052312 (2001).
[2] R. T. Thew et al., Phys. Rev. A **66**, 012303 (2002).
[3] T. Ikuta and H. Takesue, New J. Phys. **19**, 013039 (2017).

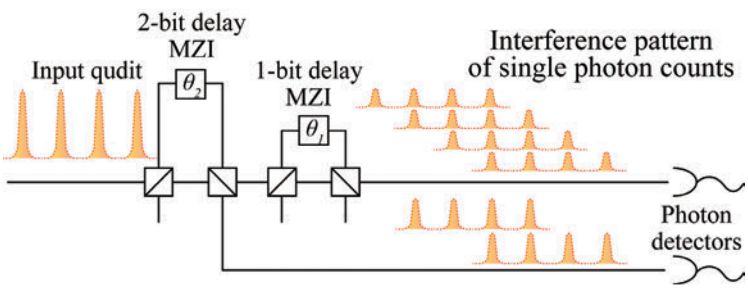


Fig. 1. Concept of the quantum state tomography using cascaded Mach-Zehnder interferometers.

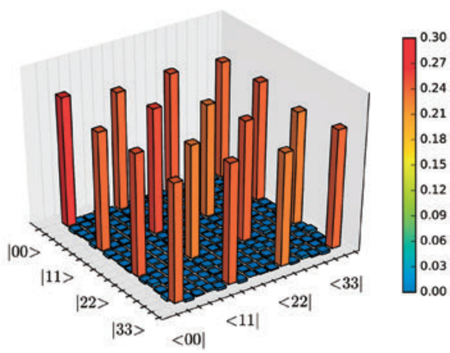


Fig. 2. Real parts of the reconstructed four-dimensional maximally entangled state.

Fundamental Rate-loss Trade-off for the Quantum Internet

Koji Azuma[1], Akihiro Mizutani[2], and Hoi-Kwong Lo[3]
[1]Optical Science Laboratory, [2]Osaka University, [3]University of Toronto

The quantum internet holds promise for accomplishing many quantum communication tasks —such as quantum teleportation and quantum key distribution (QKD)—freely between any clients all over the globe, as well as the simulation of the evolution of quantum many-body systems. The most primitive function of the quantum internet is to provide quantum entanglement or a secret key (for secure communication) to two points in the network [such as A and B in Fig. 1(a)] efficiently.

In our work, we present a general theoretical limit on the performance of such quantum internet protocols [Fig. 1(b)], determined only by the properties of communication channels in the network [1]. This theoretical limit is obtained by generalizing the Takeoka-Guha-Wilde (TGW) bound [2] which upper bounds the private/quantum capacities of single communication channels. Therefore, our theoretical limit inherits a feature of the TGW bound that it can be estimated for any communication channel, and our limit can thus be estimated irrespectively of what kind of communication channel constructs the quantum network. In fact, for any quantum communication protocol working over linear networks composed of optical fibres, this feature enables us to derive a trade-off relation between the communication rate and the loss in the network. This trade-off has essentially no scaling gap with the quantum communication efficiencies of known protocols such as intercity QKD protocols and quantum repeater protocols. In other words, this implies that there remains not much room to improve known intercity QKD protocols and quantum repeater protocols with respect to the efficiency. As another example of applications of our theoretical limit, we apply the limit to one of most famous quantum repeater schemes, called Duan-Lukin-Cirac-Zoller-type (DLCZ-type) schemes [3]. As a result, we conclude that the matter quantum memories in the DLCZ-type schemes should have coherence time (T_2) larger than 0.1 ms at least, in order to enjoy the blessing of the DLCZ-type schemes. Our result—reveraling a practical but general limitation on the quantum internet—enables us to grasp the potential of the future quantum internet.

[1] K. Azuma, A. Mizutani, and H.-K. Lo, Nature Commun. **7**, 13523 (2016).
[2] M. Takeoka, M. Guha, and M. M. Wilde, Nature Commun. **5**, 5245 (2014).
[3] N. Sangouard et al., Rev. Mod. Phys. **83**, 33 (2011).

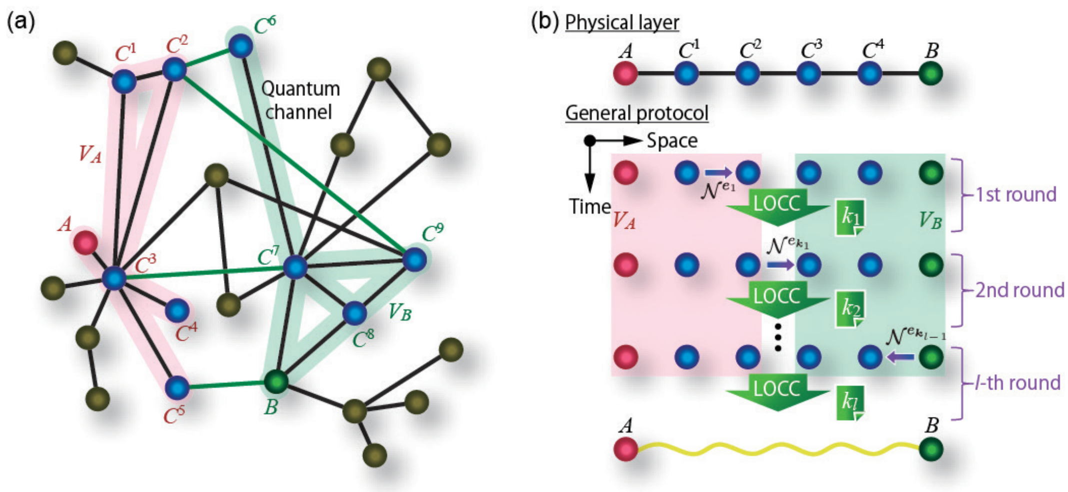


Fig. 1. (a) Quantum network. (b) General quantum internet protocol. In the protocol, quantum channels, local operations and classical communication (LOCC) are freely combined.

Hybrid Quantum Engineering Using Spectral Hole Burning in Microwave Photonics

Stefan Putz[1], Andreas Angerer[1], Dmitry O. Krimer[1], Ralph Glattauer[1], William J. Munro[2], Stefan Rotter[1], Jorg Schmiedmayer[1], and Johannes Majer[1]
[1]TU Wien, [2]Optical Science Laboratory

Spectral hole burning of inhomogeneously broadened ensembles using optical fields is now a well-established technique [1] that allows one to selectively bleach the absorption spectrum of materials. These spectral holes have been used in a variety of applications ranging from spectroscopy in photochemistry to slow light in photonics, and the storage of quantum information by the creation of optical solid-state frequency combs. Similarly, in microwave photonics hybrid solid-state devices with ensembles of electron spins are considered as a versatile component for future quantum memories with high storage capacities [2], but their operational capability lag behind those of full optical systems. To demonstrate the potential of electron spin ensembles in circuit-QED (Quantum Electrodynamics) systems, we implement spectral hole burning using a cavity in the microwave domain. This enables us to selectively bleach the ensembles microwave absorption spectrum and thus engineer long-lived collective dark states in a hybrid system, composed of an ensemble of electron spins hosted by nitrogen-vacancy centers in diamond strongly coupled to a superconducting microwave cavity.

We show how to eliminate the ensembles inhomogeneous broadening, which is a severe issue that limits the memory's storage time. The coherence rates are significantly better than either those given by the ensembles free induction decay or the bare cavity dissipation rate. Our hybrid quantum system truly lives up to the promise of this technology to perform better than its individual subcomponents as is shown in Fig. 1. To further demonstrate the potential of our approach for the selective preparation of "decoherence-free" states, we engineer multiple long-lived dark states [3], a key step towards a solid-state microwave frequency comb. Our technique allows the advantages given by spectral hole burning using optical fields to come to the solid-state microwave world opening up the way for long-lived quantum memories, spin squeezed states, optical-to-microwave quantum transducers and novel metamaterials. Furthermore, our approach also paves the way for a new class of cavity QED experiments with dense spin ensembles, where dipole spin-spin interactions become important and many-body phenomena are directly accessible on a chip.

[1] W. E. Moerner, Persistent Spectral Hole-Burning: Science and Applications (Springer Science & Business Media, 2012).
[2] J. Nunn et al., Phys. Rev. Lett. **101**, 40 260502 (2008).
[3] S. Putz et al., Nature Photon. **11**, 3639 (2016).

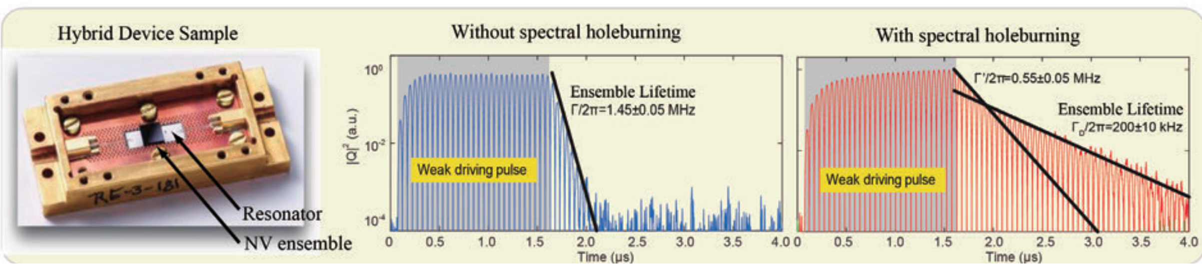


Fig. 1. (Left) Image of the hybrid system composed of a superconducting resonator and NV- electron spin ensemble. (Middle) Cavity response to a weak driving pulse without spectral hole burning (Right) Cavity response to a weak driving pulse after spectral holes are burnt.

Generation of Low-noise Millimeter-wave by Using an Electro-optics-modulator-based Optical Frequency Comb

Atsushi Ishizawa[1], Kenichi Hitachi[1], Tadashi Nishikawa[2],
Takahiro Goto[2], Tetsuomi Sogawa[1], and Hideki Gotoh[1]
[1]Optical Science Laboratory, [2]Tokyo Denki University

We are trying to generate ultralow-noise microwave and millimeter-waves using an optical frequency standard toward high-accuracy time and frequency synchronization. We have focused on an electro-optics-modulator-based optical frequency comb (EOM comb), which acts as an optical ruler and developed one with 25-GHz mode spacing. The EOM comb is a useful light source for large capacity optical transmission systems and astronomy. On the other hand, the noise increases and the spectral linewidth widens with distance from the frequency comb's center wavelength.

We exploited this "disadvantage" to demonstrate that an EOM comb can work as a noise booster and a high-sensitivity detector for detecting the magnified noise from microwave and millimeter-wave signal generators [1]. Our method can generate low-noise and continuously frequency-variable microwave and millimeter-wave signals. In addition, we can overcome the disadvantage of the EOM comb. The interference signal between an optical frequency comb and reference laser with narrow linewidth (i.e. low noise) includes information about the noise from microwave and millimeter-wave signal generators. The noise information is converted into an electrical signal and detected with high sensitivity. Finally, by using the electrical signal, the noise from microwave and millimeter-wave signal generators is reduced with a feedback circuit [Fig. 1(a)]. The further the wavelength is away from the center wavelength of the semiconductor laser, the wider the spectral linewidth becomes. The noise in 25-GHz millimeter-wave signals can be reduced to –110 dBc/Hz at a 1-kHz offset frequency from the center frequency [Fig. 1(b)]. The noise with our method is one-hundred times lower than the lowest noise reported for commercially available signal generators. Even lower noise will be achieved if we use a reference laser that is further away from the center wavelength of the semiconductor laser. In addition, the output frequency of microwave and millimeter-wave signal generators can be expanded for their universal use. We succeeded in generating low-noise signals at continuously variable frequencies over the range from 6 to 72 GHz.

[1] A. Ishizawa et al., Sci. Rep. **6**, 24621 (2016).

(a) (b)

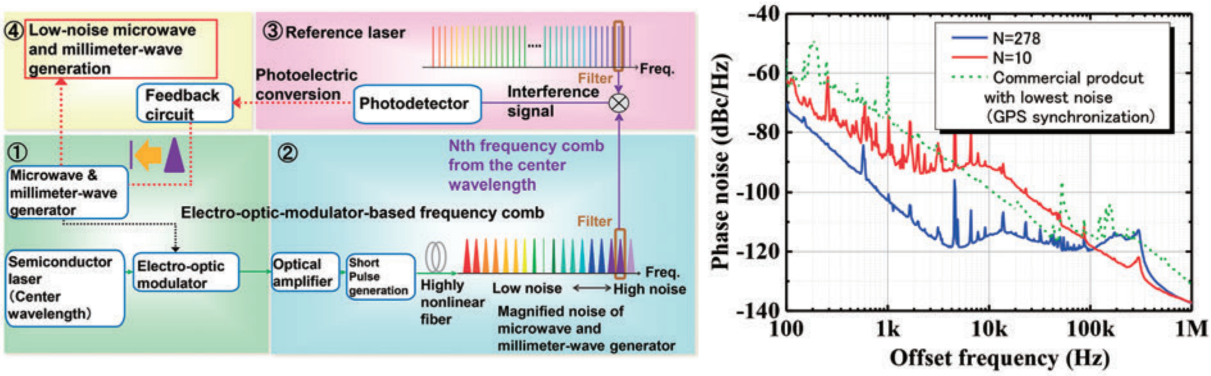


Fig. 1. (a) Diagram showing how the noise of microwave and millimeter-wave signal generators is reduced.
(b) Experimental noise reduction results for 25-GHz signal.

Light-Field Driven Petahertz Electronic Oscillation with Attosecond Periodicity in GaN Semiconductor

Hiroki Mashiko, Katsuya Oguri, and Hideki Gotoh
Optical Science Laboratory

High-speed photonic and electronic devices at present rely on radio-frequency (RF) electric fields to control the physical properties of a semiconductor, which limits their operating speed to terahertz (10^{12} Hz) frequencies. Using the electric field from light pulses, however, could extend the operating frequency into the petahertz (10^{15} Hz: PHz) regime. Here we demonstrate optical drive at 1.16-PHz frequency in the gallium nitride (GaN) semiconductor characterized by an isolated attosecond (10^{-18} Hz: as) pulse (IAP) [1].

Figure 1(a) shows a schematic view of the transient absorption spectroscopy. The collinearly propagated IAP (660-as duration, 20.5-eV center photon energy [2]) and near-infrared (NIR) pulse (7-fs duration, 1.6-eV center photon energy, 1×10^{10} W/cm^2) are focused onto stand-alone 102-nm thick GaN[0001] (bandgap energy: 3.4 eV). The NIR pulse induces ultrafast electronic interband polarization with the three photon process. Figure 1(b) displays the measured transient absorption trace. The trace shows the deviation of optical density (*ΔOD*) with and without the NIR pulse as a function of time delay. The coherent broadband IAP excites the superposition state of electrons in the valence band (VB) and conduction band (CB). Figure 1(c) shows the electric oscillation with 860-as periodicity. The resultant frequency reaches 1.16 PHz, making this the first time the ultrafast electric dipole oscillation with PHz frequency is observed in Solid-state materials [1]. This study shows the potential of future PHz signal processing technology based on the semiconductor devices.

This work was supported by JSPS KAKENHI JP16H05987 and JP16H02120.

[1] H. Mashiko et al., Nature Phys. **12**, 741 (2016) : Featured on cover.
[2] H. Mashiko et al., Nature Commun. **5**, 5599 (2014) .

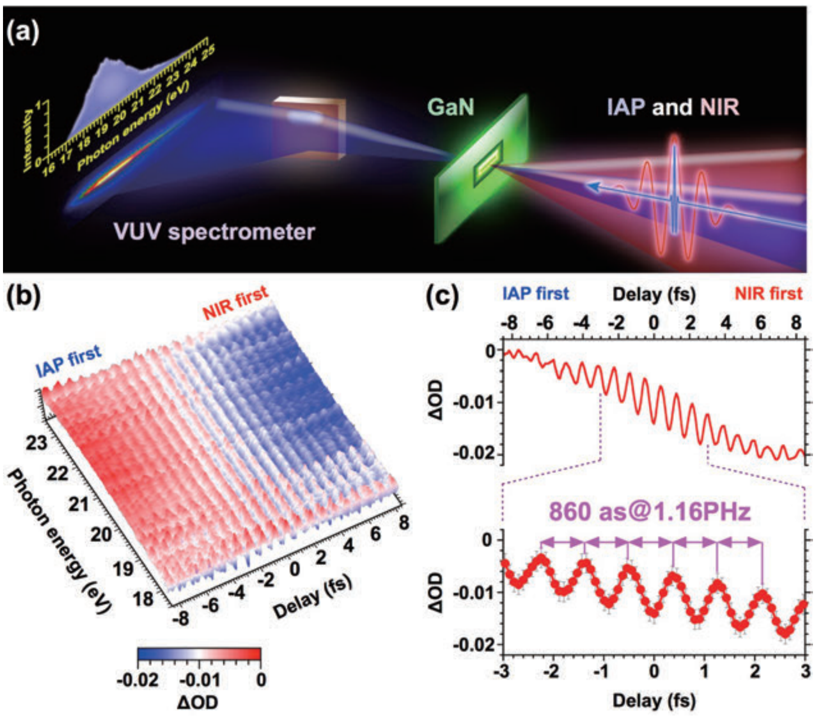


Fig. 1. Experimental setup and as transient absorption trace. (a) Schematic view of experimental setup. (b) Measured transient absorption trace of GaN. (c) The upper graph shows the integrated line profile structure for the photon energy region in Fig. 1(b). The bottom graph shows the profile in the shorter delay region.

Bridging the Gap Between the Nanometer-scale Bottom-up and Micrometer-scale Top-down Approaches for Site-defined InP/InAs Nanowires

Guoqiang Zhang[1,2] and Hideki Gotoh[1]
[1]Optical Science Laboratory, [2]NTT Nanophotonics Center

The field of microelectronics has been attempting to come to grips with the issue of miniaturization for decades as the demand for ever-smaller products puts pressure on manufacturers to make smaller components [1]. Despite the state-of-the-art Extreme Ultraviolet (EUV) photolithography technique, the low cost feature of the conventional UV photolithography is greatly advantageous over the high-cost EUV photolithography. This issue has opened the door to the development of other device fabrication methods [2]. Another competing method, self-assembly, relies on a bottom-up process that is driven energetically as the system reaches a lower energy state.

III-V compound semiconductor nanowires (NWs) are successful example of the bottom-up approach. For site-defined growth of III-V NWs with nanoscale diameter, top-down techniques like conventional photolithography are not feasible. This work presents a method that bridges the gap between the nanometer-scale bottom-up and micrometer-scale top-down approaches for site-defined NWs, which has long been a significant challenge for applications that require low-cost and high-throughput manufacturing processes [3]. We realized the bridging by controlling the seed indium nanoparticle position inside the open window through the optimization of the temperature and the pitch size. Site-defined InP NWs were then grown from the indium-nanoparticle array [Fig. 1(left)]. We demonstrated that the developed method can be used to grow a uniform InP/InAs axial-heterostructure NW array. The ability to form a heterostructure NW array makes it possible to tune the emission wavelength over a wide range through quantum confinement [Fig. 1(right)]. Successful pairing of a controllable bottom-up growth technique with a top-down substrate preparation technique greatly improves the potential for the mass-production and widespread adoption of this technology.

This work was supported by JSPS KAKENHI JP15H05735 and JP16H03821.

[1] G. A. Brown et al., Mater. Today **7**, 20 (2004).
[2] B. D. Gates et al., Annu. Rev. Mater. Res. **34**, 339 (2004).
[3] G. Zhang et al., ACS Nano **9**, 10580 (2015).

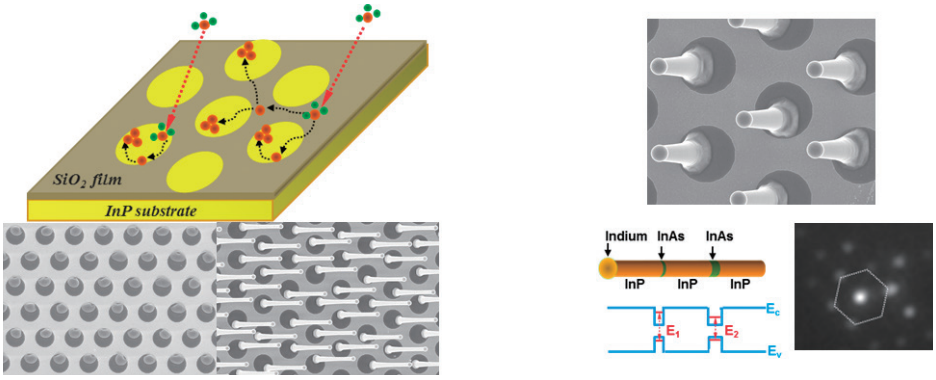


Fig. 1. (Left) Schematic diagram of absorption, decomposition, surface diffusion, and accumulation of materials on the surface of SiO_2 film and circular InP open windows. SEM images of indium seed particle array by self-assembly of indium adatoms and InP NWs grown from the particle array. (Right) SEM image of InP/InAs NWs with two InAs segments. Schematic structure and band diagram of the NW and spatial PL image with luminescence spots from InAs quantum disks.

Demonstration of Efficient Mode Conversion for Deep-subwavelength Plasmonic Waveguides

Masaaki Ono[1,2], Hideaki Taniyama[1,2], Hao Xu[1,2], Masato Tsunekawa[2,3], Eiichi Kuramochi[1,2]
Kengo Nozaki[1,2], and Masaya Notomi[1,2,3]
[1]NTT Nanophotonics Center, [2]Optical Science Laboratory, [3]Tokyo Institute of Technology

Plasmonic waveguides enable us to utilize light-propagating modes much smaller than a wavelength dimension in photonic integrated circuits. In particular, nanomaterials such as nanowires and two-dimensional (2D) materials interact efficiently with light in deep-subwavelength plasmonic waveguides, and their combination may lead to ultracompact, ultrahigh-speed photonic devices. On the other hand, plasmonic waveguides have a large propagation loss, and thus conventional low-loss dielectric waveguides are needed for long distance propagation. However, it is difficult to efficiently connect two waveguide modes that have fundamentally different sizes and characteristics. Thus, the waveguide thickness was almost unchanged in previously reported mode converters. In this study, we demonstrate highly efficient (–1.7 dB) mode conversion between a Si-wire waveguide (400 × 200 nm^2 core size) and a plasmonic waveguide with a metal-insulator-metal (MIM) structure (50 × 20 nm^2 core size) [1]. The waveguide thickness was reduced from 200 nm to 20 nm, resulting in a large reduction in core size. In addition, the core size of the connected MIM waveguide decreased to $(\lambda/n)^2/2000$ (λ = wavelength, n = reflective index).

Our converter consists of a 2D laterally tapered structure, and there is a small gap between the Si and the metal [Fig. 1(a)]. Figures 1(b) and (c) show the calculated field profile at a wavelength of 1.55 μm. The eigenmode of the Si-wire waveguide has side lobes, which are attracted to the air gap and are adiabatically connected to the MIM mode. Investigating the structural parameter dependence of the coupling efficiency, we found that the coupling efficiency is greatly increased both by optimizing the taper length and by introducing the small air gap. This enables highly efficient, full three-dimensional (3D) mode conversion, where the mode size is squeezed laterally and vertically, without the need to introduce a 3D tapered structure accompanied by a complicated fabrication process. We measured the fabricated samples and estimated the coupling efficiency. The experimentally obtained coupling efficiency was very high and –1.7 dB for an air gap width of 40 nm and a taper length of 600 nm. This efficiency value was consistent with the calculated result (–1.4 dB). We believe that our mode converter will provide a new deep-subwavelength photonic platform.

This work was supported by JSPS KAKENHI JP15H05735.

[1] M. Ono et al., Optica **3**, 999 (2016).

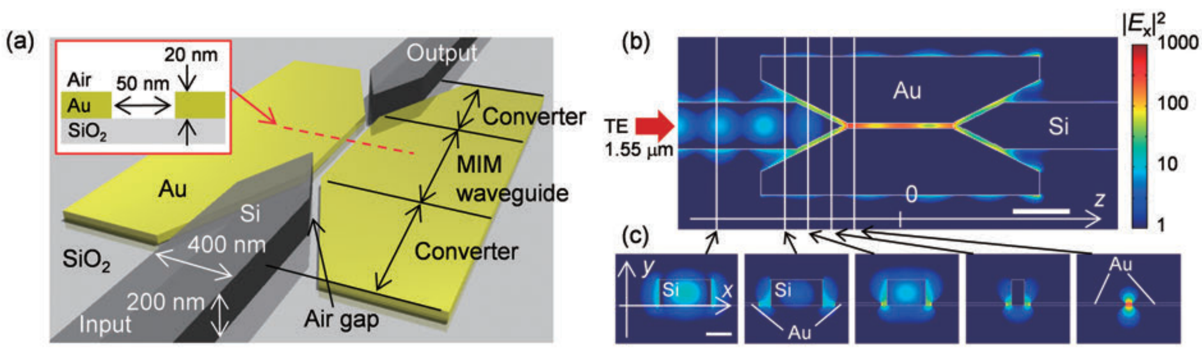


Fig. 1. (a) Schematic structure of the mode converter. (b) Cross-sectional top view of the calculated field profile for an air gap width of 40 nm and a taper length of 400 nm at y = 10 nm. Scale bar, 500 nm. (b) Cross-sectional side views of the calculated field profile. Scale bar, 200 nm.

Subwavelength Nanowire-induced Silicon Photonic Crystal Lasers

Masato Takiguchi[1,2], Atsushi Yokoo[1,2], Kengo Nozaki[1,2],
Muhammad Danang Birowosuto[1,2], Kouta Tateno[1,3], Guoqiang Zhang[1,2],
Eiichi Kuramochi[1,2], Akihiko Shinya[1,2], and Masaya Notomi[1,2]
[1]NTT Nanophotonics Center, [2]Optical Science Laboratory, [3]Materials Science Laboratory

While many nanowire (NW) lasers have been demonstrated at visible and near-visible wavelengths, it is difficult to make nanowire lasers that operate in telecom-bands because the gain is too small. In this study, we devised an NW induced photonic crystal cavity by using atomic force microscopy [Fig. 1(a)] [1] and demonstrated telecom-band nanowire lasers on Si. This is a new technique to build nano-lasers in Si photonic circuits [2,3].

In the experiment, the number of quantum wells in each NW was increased to 100 to increase the gain volume. In addition, the quality of the NW's crystal was improved so that the polarization of the intrinsic emission of the nanowire could be optimized to the cavity polarization therefore increasing the extraction efficiency. The NW was 2.5 μm long and about 111 nm in diameter. The emission was at about 1330 nm. Figure 1(b) shows the spectrum of a NW laser under 0.25 and 2.5 mW continuous wave (CW) pumping conditions at 4K. Figure 1(c) shows the light-in vs light-out (L-L) property and full width at half maximum. It shows a kink structure in the L-L plot and that indicates lasing. We also measured photon statistics [Fig. 1(d)] and confirmed that the sample truly achieves CW lasing [3]. The lasing wavelength can be tuned by moving the NW [Fig. 1(e)] [1,2]. Next we estimated the dynamic property of the laser. The single NW laser was pumped by a modulated laser (pseudo-random bit sequence), and the signal from the NW laser was measured with a superconducting single photon detector. It is generally difficult to measure a modulation signal in micro-photoluminescence because the coupling efficiency to the vertical direction is very low. However our measurement system is very sensitive and makes it possible to obtain the signal. We also obtained 10 Gbps opened eye-pattern from the measured modulated signal [Fig. 1(f)] [3]. This is the first demonstration of directly modulated nanowire lasers.

[1] M. D. Birowosuto et al., Nature Mater. **13**, 279 (2014).
[2] A. Yokoo, M. Takiguchi et al., ACS Photonics **4**, 355 (2017).
[3] M. Takiguchi et al., APL Photonics **2**, 046106 (2017).

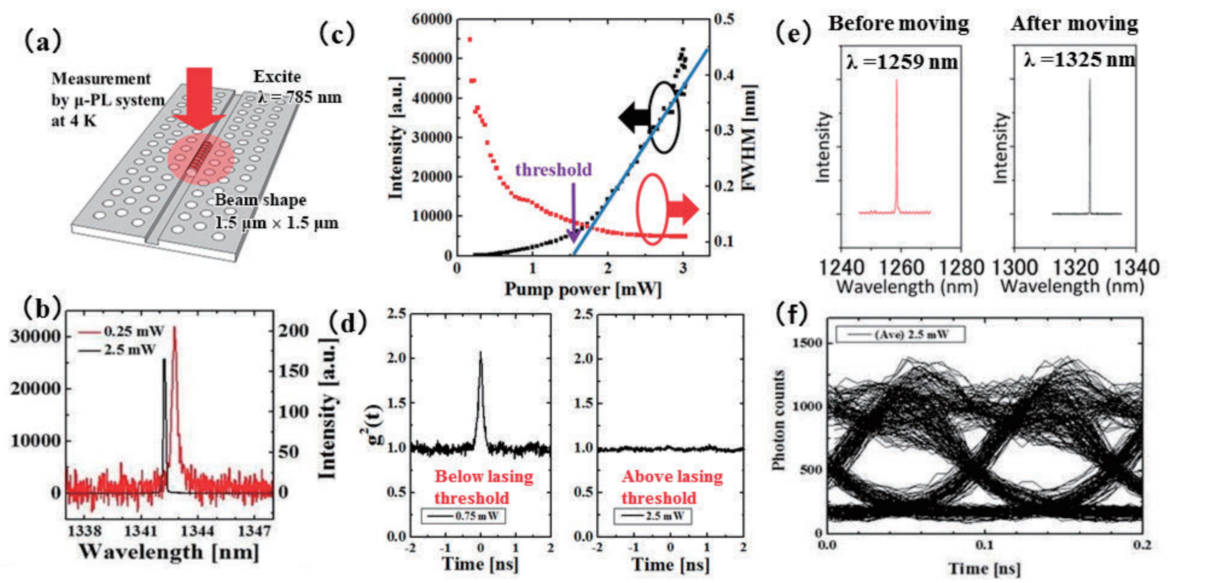


Fig. 1. (a) Schematic image. (b) PL spectrum. (c) L-L. (d) Photon correlation. (e) Tuned spectrum. (f) Eye diagram.

Efficient Light-to-voltage Conversion by Ultralow-capacitance Nano-photodetector

Kengo Nozaki[1,2], Shinji Matsuo[1,3], Takuro Fujii[1,3], Koji Takeda[1,3], Masaaki Ono[1,2], Eiichi Kuramochi[1,2], and Masaya Notomi[1,2]
[1]NTT Nanophotonics Center, [2]Optical Science Laboratory,
[3]NTT Device Technology Laboratories

Photodetectors (PDs) to use as a receiver in a dense on-chip photonic processor requires low-energy consumption and small size. However, the energy consumption of a conventional photoreceiver is dominated by the electric amplifiers connected to the PD. An ultralow-capacitance PD can overcome this limitation, because it can generate large voltage without an amplifier when connected with a high-impedance load. By our fabrication technique of the buried heterostructure to embed the compact InGaAs absorber in the photonic crystal (PhC) waveguide [Fig. 1(a)] [1], we demonstrated the ultrasmall PD with a length of 1.7 μm and a theoretical capacitance of only 0.6 fF. Such a short PD still showed the optical responsivity as high as 1 A/W and the fast response with a bit rate of 40 Gbit/s. A resistor-loaded PD was also fabricated to evaluate the light-to-voltage conversion [Fig. 1(b)]. We utilized an electro-optic probing method to measure the voltage across the strip lines, which is generated from the photocurrent and the load resistor. As a result, we obtained a light-to-voltage conversion efficiency of 4 kV/W [Fig. 1(c)], which is actually as large as conventional receivers integrated with amplifiers. Although the operation bandwidth was limited by the parasitic capacitance of the strip lines that were required in the EO probe measurement, a 40 Gbit/s operation will be expected if we only take the ultrasmall PD capacitance into account. These results offer the realization of an ultralow-energy amplifier-less receiver by using an ultrasmall-capacitance PD, and therefore are step toward a densely-integrated photonic network/processor on a chip.

This work was partly supported by CREST (JPMJCR15N4), JST.

[1] K. Nozaki et al., Optica **3**, 483 (2016).

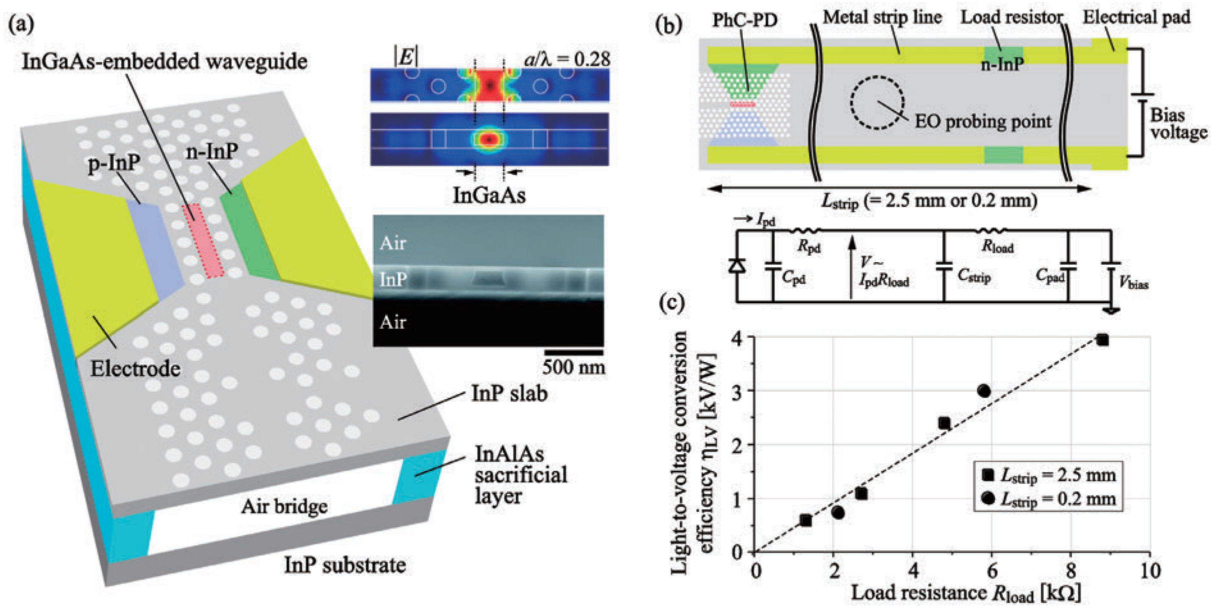


Fig. 1. (a) Photonic crystal PD. Insets show the optical field distribution (upper) and the cross-sectional photograph (lower). (b) Resistor-loaded PD and its equivalent circuit. (c) Light-to-voltage conversion efficiency vs load resistance characteristic.

Superconducting Nanowire Single Photon Detector on Si Platform

Tatsurou Hiraki[1,2], Tai Tsuchizawa[1,2], Hiroyuki Shibata[3], and Shinji Matsuo[1,2]
[1]NTT Nanophotonics Center, [2]NTT Device Technology Laboratories,
[3]Kitami Institute of Technology.

Quantum photonics technology has attracted attentions for quantum computing and quantum-code communications. In particular, a silicon (Si) photonics technology is widely studied for the scalable quantum photonics system. One of key challenges for the Si photonics is to integrate a single-photon detector, because traditional Si avalanche photodiodes cannot detect infrared photons. The promising solution is a waveguide-integrated superconducting nanowire single-photon detector (SNSPD) [1] on Si platform, because it can detect infrared photons with low noise and small jitter. However, the system detection efficiency of the SNSPD is still limited by a large fiber coupling loss [2]. In this work, we demonstrated a high-system-detection SNSPD integrated with Si nanowire waveguide and spot-size converter (SSC), which efficiently couples to the fiber.

Figure 1(a) shows a schematic of waveguide-integrated SNSPD with SSC. The superconducting nanowire was comprised of niobium nitride (NbN) whose thickness and width were 7 nm and 60 nm, respectively. The NbN nanowire was evanescently coupled to the Si nanowire waveguide. The Si waveguide has inverse taper structure, which is covered with a 3-μm-square SiO_x waveguide to construct SSC [3]. The mode-field diameter of the SiO_x core nearly matched that of the high-numerical aperture fiber. The key fabrication process is the low-temperature formation of the SiO_x waveguide (< 200°C), which prevents thermal damage to the NbN film.

We measured the system detection efficiency of the fabricated SNSPD in a cryostat. In the experiment, input continuous-wave light power was attenuated to have 10^6 photons per second outside the cryostat. The cryostat state was at 0.3 K. Figure 1(b) shows measured relationship between system detection efficiency and bias current. The system detection efficiency was around 32%, which is over ten times larger than that of the previous devices. The fiber-chip coupling loss was remarkably small (1.9 dB/facet). It is notable that the on-chip detection efficiency of the SNSPD was over 90%. It means the low-temperature integration process successfully prevent thermal damages to NbN nanowires. These results indicated the Si-NbN-SiO_x integration technology is a promising solution for constructing future quantum photonics systems.

[1] J. P. Sprengers et al., Appl. Phys. Lett. **99**, 181110 (2011).
[2] O. Kahl et al., Sci. Rep. **5**, 10941 (2015).
[3] T. Hiraki et. al., Proc. in Frontiers in Optics, FW5F.3 (2016).

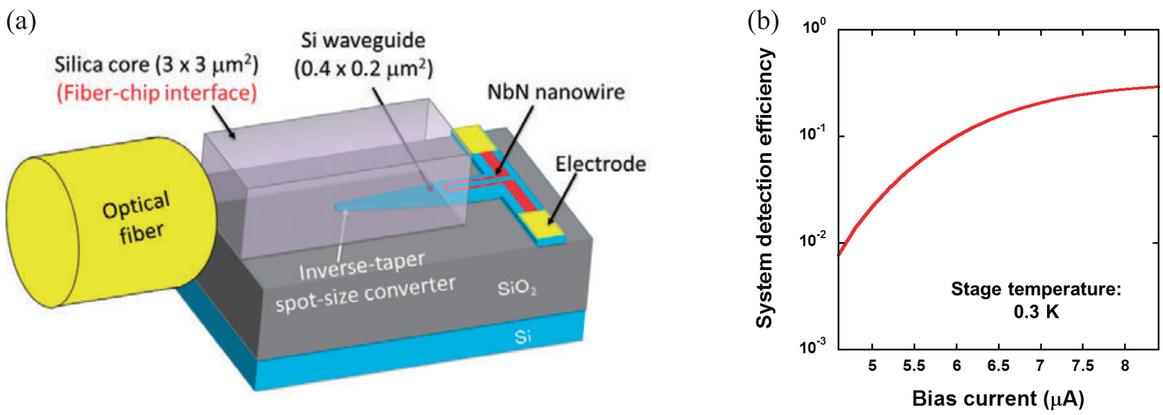


Fig. 1. (a) Schematic of SNSPD with SSC. (b) measured system detection efficiency.

LEAP Lasers Integrated on Si Waveguides

Koji Takeda[1,2], Takuro Fujii[1,2], Akihiko Shinya[1,3], Tai Tsuchizawa[1,2], Hidetaka Nishi[1,2], Eiichi Kuramochi[1,3], Masaya Notomi[1,3], Takaaki Kakitsuka[1,2], and Shinji Matsuo[1,2]
[1]NTT Nanophotonics Center, [2]NTT Device Technology Laboratories,
[3]Optical Science Laboratory

Data transfer is becoming a performance bottleneck in datacenters and high-performance computing. For further improvement, short-distance optical interconnects with large capacity and low energy cost are desired [1]. Since the required bandwidth is large in such interconnects, many photonic devices, which can operate with very small energy, need to be integrated with large bandwidth density [2]. In this context, we are studying photonic crystal (PhC) lasers integrated on Si waveguides, which enables large density owing to the large refractive index contrast. Here, we report the first continuous-wave (CW) operation of our PhC lasers on Si waveguides.

The device fabrication procedure was as follows. First, InGaAsP 6-quantum wells and InGaAs etch stop layers were grown on InP substrates and Si waveguides were formed by using silicon-on-insulator (SOI) substrates. SiO_2 layers were deposited on InP substrates, and InP and Si substrates were bonded by oxygen-plasma-assisted bonding. After removing the InP substrate and InGaAs layer, we defined buried heterostructure patterns, followed by etching and regrowth to bury the active regions with InP. After fabricating the buried active region, a lateral *p*-*i*-*n* junction was formed by implantation and diffusion. Then we formed PhC air holes by electron-beam lithography and dry etching. Finally, electrodes were formed on top of the III-V slab. A schematic of a fabricated laser is shown in Fig. 1(a). From their structural feature, we call our lasers lambda-scale embedded active region PhC (LEAP) lasers.

We measured output light power and applied voltage as a function of injected current at 25°C, and the results are shown in Fig. 1(b). CW operation was successfully achieved with a threshold current of 42 µA. Maximum output power from the device was 0.72 µW at the lensed fiber at an injected current of 0.5 mA. The inset in Fig. 1(b) shows an infrared image of the device taken during measurements. From this image, we confirmed that the lasing light was successfully guided through the Si waveguides. We believe this achievement is an important step towards realizing short-distance, large-bandwidth-density optical interconnects.

[1] A. Benner, Proc. OFC Tutorial (2012).
[2] Y. Arakawa et al., Com. Mag. IEEE, **51**, 72 (2013).

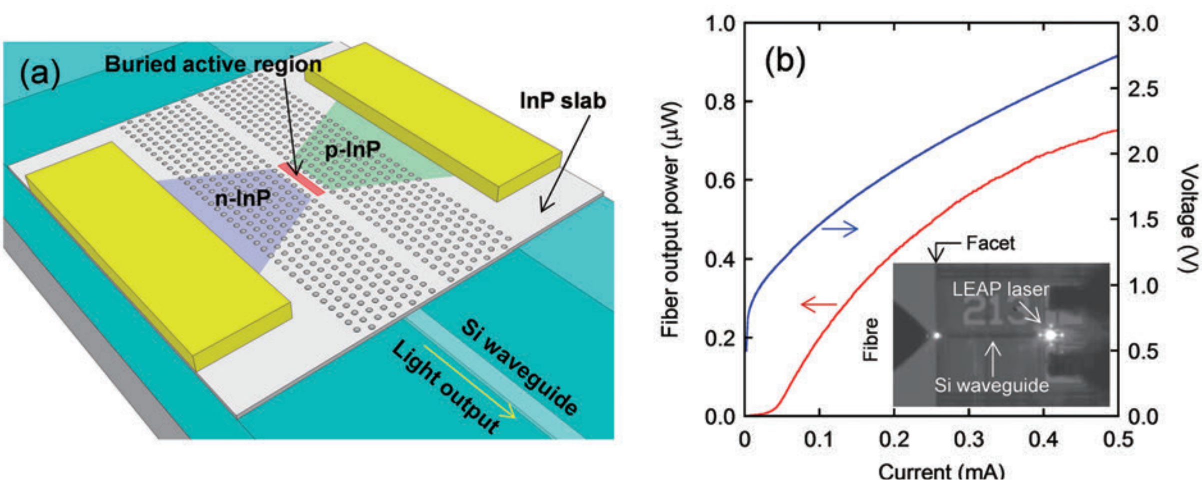


Fig. 1. (a) Schematic of LEAP lasers fabricated on Si waveguides. (b) *L*-*I*-*V* characteristic and infrared image of the device.

Ⅱ. Data

The 9th Advisory Board

The NTT BRL Advisory Board, which was first convened in 2001, held its 9th meeting on January 30 - 31, 2017. The aim of the Advisory Board is to provide an objective evaluation of our research plans and activities to enable us to employ strategic management in a timely manner. On this occasion, we had the meeting with five board members.

Over the course of the two days, the board made valuable suggestions and comments in relation to our research and management activities. They commented that the research level was generally high on a worldwide point of view, and that it was important for us to maintain this top-level research and transmit information on our research achievements to the world. They also raised several issues related to human resources, the research budget and internal and external collaboration. We will improve research issues and managements based on these valuable suggestions.

At this meeting, the BRL researchers had a lunch with the board members and a poster session, where they had chances to present their researches to the board members. The poster session was performed with the dinner party where the board members and the BRL researchers were able to interact in a casual atmosphere. For the BRL and NTT executives, we organized a Japanese style dinner, which provided a good chance to discuss the future management strategy of NTT BRL from an international perspective. The next board meeting will be held in two years.

Board members	Affiliation	Research field
Prof. John Clarke	Univ. California, Berkeley	Superconductor physics
Prof. Evelyn Hu	Harvard Univ.	Nanodevice
Prof. Mats Jonson	Univ. Gothenburg	Condensed matter
Prof. Sir Peter Knight	Imperial College London	Quantum optics
Prof. Anthony J. Leggett	Univ. Illinois	Quantum physics
Prof. Allan H. MacDonald	Univ. Texas	Condensed matter
Prof. Andreas Offenhäusser	Forschungszentrum Jülich	Nano-bio electronics
Prof. Halina Rubinsztein-Dunlop	Univ. Queensland	Quantum electronics
Prof. Klaus von Klitzing	Max-Planck-Inst.	Semiconductor physics

Science Plaza 2016

"Science Plaza 2016", an NTT Basic Research Laboratories (BRL) open-house event, was held at NTT Atsugi R&D Center on 23rd November, 2016. Under the banner "Frontier Science: Open Door to the Future", Science Plaza aimed at disseminating our latest research accomplishments to various groups of people inside and outside NTT and to gather diverse opinions. This event was held jointly with NTT Device Innovation Center, NTT Device Technology Laboratories, and NTT Communication Science Laboratories.

Following an opening address by Dr. Tetsuomi Sogawa (director of BRL) and an introduction to NTT Laboratories by the Executive Managers, Dr. Akira Fujiwara (Senior Distinguished Researcher) presented a symposium lecture entitled "Ultimate Electronics Using Nano-devices". In the afternoon session, Prof. Hiroshi Amano (Nagoya University) gave a special lecture entitled "Illuminating the World by LEDs". Each lecture was well attended and followed by lively question and answer sessions.

In the poster session, 52 posters were presented, including 13 from joint research institutes. These posters described the originality and impact of various areas of research as well as outlining future prospects. They provoked intense discussions, and many meaningful opinions were heard. This year's "Lab Tour"—a guided tour of the research facilities that has been receiving high praise from visitors over the years—took place at ten different labs. After all the lectures, presentations, and exhibitions had finished, a banquet was held in the Center's dining room, and friendships were established and deepened by the lively conversations engaged in by the participants.

198 people from research institutes, universities, and industries as well as from NTT Group companies attended Science Plaza 2016. Thanks to the efforts of all the participants, the conference ended on a high note. We would therefore like to express our sincere gratitude to all who took part.

List of Visitors' Talks

Date	Speaker (Affiliation)	Title
Apr. 26	Prof. Peter Smith (University of Southampton, U.K.)	Integrated photonic circuits for quantum information processing
June 22	Prof. Jacob. M. Taylor (National Institute of Standards and Technology, U.S.A.)	Solving quantum information challenges with light
June 22	Mr. Riku Takahashi (Hokkaido University, Japan)	Hydrogen - For developing functional biocompatible materials -
June 24	Dr. Zhechao Wang (Ghent University-IMEC, Belgium)	Monolithic integration of III-V semiconductor lasers on Si
July 4	Dr. Rakchanok Rungsawang (Imagine Optic, France)	Wavefront sensing, adaptive optics for microscopy and optical metrology
July 4	Prof. Henning Riechert (Paul Drude Institut for Solid State Electronics, Germany)	III-nitride nanowires — understanding MBE growth and pathways towards true nanostructures
July 19	Dr. David Elkouss (Delft University of Technology, The Netherlands)	Benchmarking quantum channels for private communications
Aug. 9	Dr. Erika Kawakami (Delft University of Technology, The Netherlands)	Allelectrical universal control of electron spin qubits in Si/SiGe quantum dots
Aug. 9	Dr. Fabien Lafont (Weizmann Institute, Israel)	New paradigm for edge reconstruction of hole-conjugate fractional states
Sep. 9	Prof. Hideki Kawakatsu (The University of Tokyo, Japan) Dr. Eric Leclerc (The University of Tokyo, Japan)	Introduction of the international Lab LIMMS at Tokyo University and Development of microfluidic devices for hepatic induced pluripotent stem cell differentiation
Sep. 26	Prof. Christian A. Nijhuis (National University of Singapore, Singapore)	Mechanisms of charge transport and light-matter interactions across (bio) molecular tunnel junctions
Oct. 3	Dr. Takeshi Ohtsuka (Gunma University, Japan) Dr. Vladimír Chalupecký (Fujitsu Limited, Japan) Dr. Norbert Požá (Kanazawa University, Japan)	Mathematical aspects of crystal growth : recent topics on growth dynamics

Oct. 11	Prof. Shinobu Ohya (The University of Tokyo, Japan) Mr. Kento Takeshima (The University of Tokyo, Japan)	Spintronics with ferromagnetic epitaxial single-crystalline heterostructures
Oct. 18	Dr. Yuxi Fu (RIKEN Center for Advanced Photonics, Japan)	Recent progress on high-energy ultrafast laser systems in RIKEN
Oct. 27	Prof. Toshiharu Saiki (Keio University, Japan)	Nanoscale light-matter and nanofluidics interactions in biomaterials
Nov. 1	Prof. Ryota Negishi (Osaka University, Japan)	High-quality graphene films obtained from graphene oxides — Syntheses and bio-sensing applications
Nov. 15	Dr. Stefan Fölsch (Paul Drude Institut for Solid State Electronics, Germany)	Artificial lattices created by electrostatic gating of surface state electrons
Dec. 15	Dr. Takuya Higuchi (Friedrich-Alexander University of Erlangen-Nürnberg, Germany)	Light-field controlled currents in graphene
Dec. 16	Prof. Hidetoshi Nishimori (Tokyo Institute of Technology, Japan)	Progress of quantum annealing
Dec. 26	Mr. Cheng Wang (Harvard University, U.S.A.)	Lithium niobate nonlinear nanophotonics
Jan. 25	Dr. Pooya Ronagh (1Qbit, Canada)	Global optimization of quadratic functions
Mar. 2	Dr. Frank Deppe (Walther-Meißner-Institut, Germany)	Continuous-variable propagating quantum microwaves
Mar. 9	Dr. Sébastien Gleyzes (Laboratoire Kastler Brossel, France)	A sensitive electrometer based on a Rydberg atom in a Schrödinger-cat state

List of Award Winners

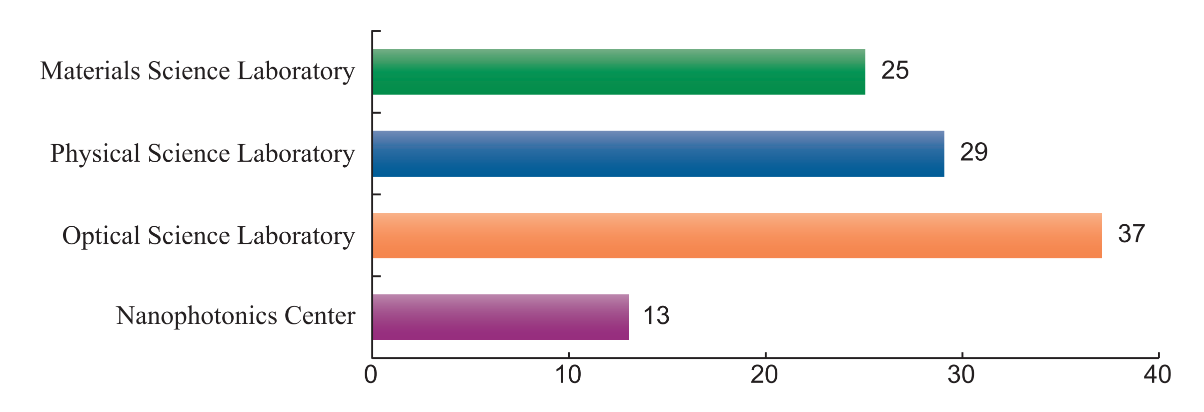
Award	Award Winners	Title	Date
JSAP Spring Meeting, 2016, Poster Award	M. Ono H. Taniyama M. Tsunekawa E. Kuramochi K. Nozaki M. Notomi	Demonstration of Efficient Mode Conversion to Slot Waveguides with λ^2/2000 Cross-Sectional Area	Apr. 1, 2016
The Young Scientists' Prize of the Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology	H. Sanada	Electron spin manipulation in semiconductor quantum structures	Apr. 20, 2016
OECC/PS 2016 Best Paper Award	K. Nozaki S. Matsuo T. Fujii K. Takeda M. Ono A. Shakoor E. Kuramochi M. Notomi	Sub-fF-capacitance photonic-crystal photodetector towards fJ/bit on-chip receiver	July 6, 2016
The Japan Society of Applied Physics (JSAP) Fellow	T. Sogawa	Control of Photonic and Spin-Related Properties in Semiconductor Quantum Structures by Surface Acoustic Waves	Sep. 13, 2016
The Japan Society of Applied Physics (JSAP) Young Scientist Award	P. A. Carles	Deviation from the law of energy equipartition in a small dynamic-random-access memory	Sep. 13, 2016
The Chemical Society of Japan, Division of Colloid and Surface Chemistry Early Career Award	T. Teshima H. Nakahsima Y. Ueno S. Sasaki S. Tsukada	Self-folded Thin Polymer Film for Encapsulation and Manipulation of Cells	Nov. 10, 2016
IOP Publishing Outstanding Reviewer Award 2016	W. J. Munro	Outstanding Reviewer for New Journal of Physics in 2016	Feb. 3, 2017
The Japan Society of Applied Physics (JSAP) Young Scientist Presentation Award	M. Kurosu	Dispersion effects on phonon temporal waveforms in a phononic crystal waveguide	Mar. 14, 2017
The Japan Society of Applied Physics (JSAP) Young Scientist Presentation Award	T. Ikuta	Implementation of quantum state tomography for high-dimensional time-bin entanglements	Mar. 14, 2017

List of In-house Award Winners

Award	Award Winners	Title	Date
NTT Corporation President Award	H. Takesue T. Inagaki K. Inaba T. Honjyo T. Umeki	Coherent Ising Machine for Combinatorial Optimization Problems	Oct. 24, 2016
NTT Science and Core Technology Laboratory Group Director’s Award	I. Mahboob D. Hatanaka H. Okamoto H. Yamaguchi	Proposal and demonstration of nonlinear phononics devices	Dec. 12, 2016
BRL Director’s Award Award for Achievements	S. Tsukada T. Ogasawara H. Kurasawa M. Yamaguchi N. Kasai H. Nakashima	Creation, demonstration and practical realization of "hitoe" wear and system for precise vital signal measurement	Mar. 27, 2017
BRL Director’s Award Award for Achievements	K. Kakuyanagi G. Knee Y. Matsuzaki H. Toida W. J. Munro S. Saito	Development of proof-of-principle experiments for testing quantumness in superconducting circuits	Mar. 27, 2017
BRL Director’s Award Award for Achievements	H. Mashiko K. Kato K. Oguri	Pioneering ultrafast dynamics based on attosecond pulse generation technology	Mar. 27, 2017
BRL Director’s Award Award for Excellent Papers	S. Wang H. Hibino S. Suzuki H. Yamamoto	"Atmospheric Pressure Chemical Vapor Deposition Growth of Millimeter-Scale Single-Crystalline Graphene on the Copper Surface with a Native Oxide Layer" Chemistry of Materials **28**, 4893 (2016).	Mar. 27, 2017
BRL Director’s Award Award for Excellent Papers	T. Inagaki T. Honjo T. Umeki K. Enbutsu O. Tadanaga H. Takenouchi H. Takesue	"A coherent Ising machine for 2000-node optimization problems" Science **354**, 603 (2016).	Mar. 27, 2017
BRL Director’s Award Award for Best Paper for Environmental Contribution	K. Nishiguchi A. Fujiwara	"Single-electron counting statistics of shot noise in nanowire Si metal-oxide-semiconductor field-effect transistors" Applied Physics Letters **98**, 193502 (2011).	Mar. 27, 2017
BRL Director’s Award Award for Encouragement	Y. Kunihashi	Control of electron spin dynamics using spin-orbit interaction in semiconductors	Mar. 27, 2017

Number of Papers

The number of papers published in international journals in fiscal 2016 is 104. The number of papers published in major journals are listed below.



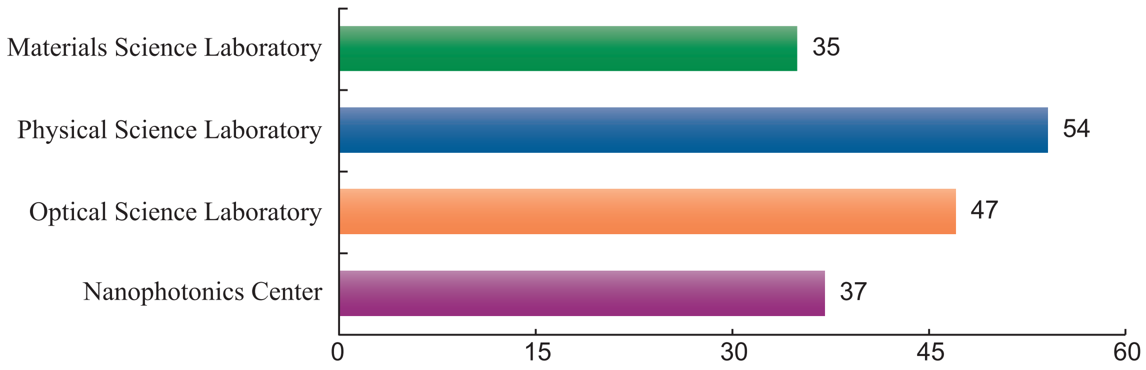
Journals	IF2015	Numbers
Physical Review A	2.765	10
Physical Review B	3.718	8
Applied Physics Express	2.265	8
Applied Physics Letters	3.142	7
Nature Communications	11.329	6
Scientific Reports	5.228	5
New Journal of Physics	3.570	5
Japanese Journal of Applied Physics	1.122	5
Optics Express	3.148	4
Science	34.661	3
Optica	5.205	3
Nature Photonics	31.167	2
Nature Physics	18.791	2
Chemistry of Materials	9.407	2
Physical Review Letters	7.645	2
Optics Letters	3.040	2
Journal of the Physical Society of Japan	1.559	2
APL Photonics	—	2
Advanced Functional Materials	11.382	1
Nanoscale	7.760	1
ACS Photonics	5.404	1
Journal of Materials Chemistry C	5.066	1
Nanophotonics	4.333	1
Science Advances	—	1

***IF2015 Impact Factor 2015**

The average IF2015 for all research papers from NTT Basic Research laboratories is 5.568

Number of Presentations

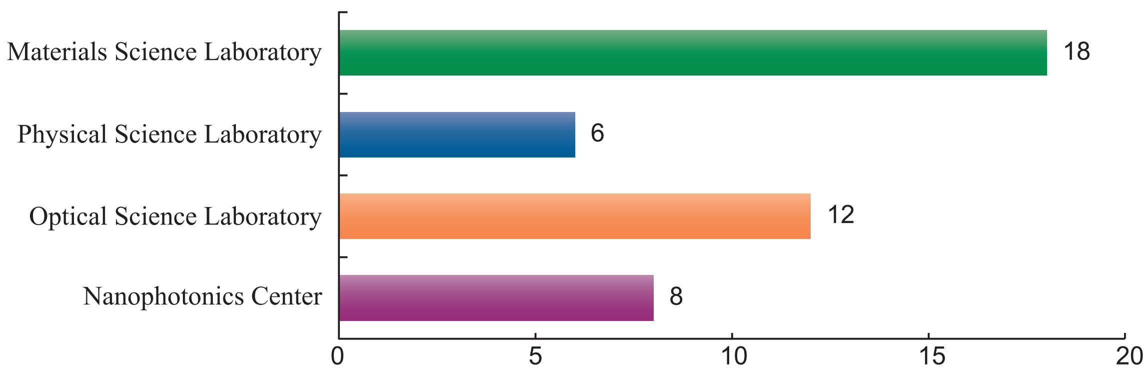
The number of presentations at international conferences in fiscal 2016 is 173. The number of presentations in major conferences are listed below.



Conferences	Numbers
The 2016 Compound Semiconductor Week (CSW2016) : The 43rd International Symposium on Compound Semiconductors / The 28th International Conference on Indium Phosphide and Related Materials	10
The 22nd International Conference on High Magnetic Fields in Semiconductor Physics (HMF-22)	9
Conference on Lasers and Electro-Optics (CLEO2016)	9
33rd International Conference on the Physics of Semiconductors (ICPS2016)	7
International Conference on Quantum Communication, Measurement and Computing (QCMC2016)	6
Joint Center for Quantum Information and Computer Science (QuICS2016)	6
2016 International Conferences on Solid State Devices and Materials (SSDM2016)	5
The 11th SPSJ International Polymer Conference (IPC2016)	5

Number of Patents

The number of applied patents in fiscal 2016 is 44.



Data

Publication List

(1) T. Akasaka, C. H. Lin, H. Yamamoto, and K. Kumakura, "Surface Supersaturation in Flow-rate Modulation Epitaxy of GaN", J. Cryst. Growth. **468**, 821 (2017).

(2) T. Akiho, F. Couedo, H. Irie, K. Suzuki, K. Onomitsu, and K. Muraki, "Engineering Quantum Spin Hall Insulators by Strained-layer Heterostructures", Appl. Phys. Lett. **109**, 192105 (2016).

(3) K. Azuma, A. Mizutani, and H. K. Lo, "Fundamental Rate-loss Trade-off for the Quantum Internet", Nature Commun. **7**, 13523 (2016).

(4) S. Bevilacqua, E. Novoselov, S. Cherednichenko, H. Shibata, and Y. Tokura, "Wideband MgB_2 Hot-electron Bolometer Mixers: IF Impedance Characterisation and Modeling", IEEE Trans. Appl. Supercond. **26**, 2300105 (2016).

(5) M. D. Birowosuto, M. Takiguchi, A. Olivier, L. Y. Tobing, E. Kuramochi, A. Yokoo, W. Hong, and M. Notomi, "Temperature-dependent Spontaneous Emission of PbS Quantum Dots inside Photonic Nanostructures at Telecommunication Wavelength", Opt. Commun. **383**, 555 (2017).

(6) N. P. Breznay, I. M. Hayes, B. J. Ramshaw, R. D. McDonald, Y. Krockenberger, A. Ikeda, H. Irie, H. Yamamoto, and J. G. Analytis, "Shubnikov-de Haas Quantum Oscillations Reveal a Reconstructed Fermi Surface Near Optimal Doping in a Thin Film of the Cuprate Superconductor $Pr_{1.86}Ce_{0.14}CuO_{4\pm\delta}$", Phys. Rev. B **94**, 104514 (2016).

(7) A. Browning, N. Kumada, Y. Sekine, H. Irie, K. Muraki, and H. Yamamoto, "Evaluation of Disorder Introduced by Electrolyte Gating through Transport Measurements in Graphene", Appl. Phys. Express **9**, 065102 (2016).

(8) R. J. Collins, R. Amiri, M. Fujiwara, T. Honjo, K. Shimizu, K. Tamaki, M. Takeoka, E. Andersson, G. S. Buller, and M. Sasaki, "Experimental Transmission of Quantum Digital Signatures over 90 km of Installed Optical Fiber Using a Differential Phase Shift Quantum Key Distribution System", Opt. Lett. **41**, 4883 (2016).

(9) F. Couedo, H. Irie, K. Suzuki, K. Onomitsu, and K. Muraki, "Single-edge Transport in an InAs/GaSb Quantum Spin Hall Insulator", Phys. Rev. B **94**, 035301 (2016).

(10) S. Dooley, W. J. Munro, and K. Nemoto, "Quantum Metrology Including State Preparation and Readout Times", Phys. Rev. A **94**, 052320 (2016).

(11) S. Dooley, E. Yukawa, Y. Matsuzaki, G. C. Knee, W. J. Munro, and K. Nemoto, "A Hybrid-systems Approach to Spin Squeezing Using a Highly Dissipative Ancillary System", New J. Phys. **18**, 053011 (2016).

(12) S. N. A. Duffus, K. N. Bjergstrom, V. M. Dwyer, J. H. Samson, T. P. Spiller, A. M. Zagoskin, W. J. Munro, K. Nemoto, and M. J. Everitt, "Some Implications of Superconducting Quantum Interference to the Application of Master Equations in Engineering Quantum Technologies", Phys. Rev. B **94**, 064518 (2016).

(13) K. Furukawa, Y. Ueno, M. Takamura, and H. Hibino, "Graphene FRET Aptasensor", ACS Sens. **1**, 710 (2016).

(14) T. Goto, N. Kasai, R. Lu, R. Filip, and K. Sumitomo, "Scanning Electron Microscopy Observation of Interface Between Single Neurons and Conductive Surfaces", J. Nanosci. Nanotechnol. **16**, 3383 (2016).

(15) R. Hamerly, K. Inaba, T. Inagaki, H. Takesue, Y. Yamamoto, and H. Mabuchi, "Topological Defect Formation in 1D and 2D Spin Chains Realized by Network of Optical Parametric Oscillators", Int. J. Mod. Phys. B **30**, 1630014 (2016).

(16) K. Hirama, Y. Taniyasu, S. Karimoto, H. Yamamoto and K. Kumakura, "Heteroepitaxial Growth of Single-domain Cubic Boron Nitride Films", Appl. Phys. Express **10**, 035501 (2017).

(17) H. Hibino, S. Wang, C. M. Orofeo, and H. Kageshima, "Growth and Low-energy Electron Microscopy Characterizations of Graphene and Hexagonal Boron Nitride", Prog. Cryst. Growth Charact. Mater. **62**, 155 (2016).

(18) M. Hiroki, K. Kumakura, and H. Yamamoto, "Enhancement of Performance of AlGaN/GaN High-electron-mobility Transistors by Transfer from Sapphire to a Copper Plate", Jpn. J. Appl. Phys. **55**, 05FH07 (2016).

(19) A. Ikeda, H. Irie, H. Yamamoto, and Y. Krockenberger, "Clean Superconductivity in Electron Doped $Pr_{2-x}Ce_xCuO_{4+\delta}$ Thin Films Hetero-epitaxially Grown on $SrTiO_3$ by Reactive Molecular Beam Epitaxy", J. Mater. Res. **31**, 3522 (2016).

(20) A. Ikeda, H. Irie, H. Yamamoto, and Y. Krockenberger, "Incommensurate Defect-driven Electron Correlations in $Pr_{1.85}Ce_{0.15}CuO_{4+\delta}$", Phys. Rev. B **94**, 054513 (2016).

(21) A. Ikeda, Y. Krockenberger, H. Irie, M. Naito, and H. Yamamoto, "Direct Observation of Infinite NiO_2 Planes in $LaNiO_2$ Films", Appl. Phys. Express **9**, 061101 (2016).

(22) R. Ikuta, T. Kobayashi, K. Matsuki, S. Miki, T. Yamashita, H. Terai, T. Yamamoto, M. Koashi, T. Mukai, and N. Imoto, "Heralded Single Excitation of Atomic Ensemble via Solid-state-based Telecom Photon Detection", Optica **3**, 1279 (2016).

(23) T. Ikuta and H. Takesue, "Implementation of Quantum State Tomography for Time-bin Qudits", New J. Phys. **19**, 013039 (2017).

(24) K. Inaba and M. Yamashita, "Theoretical Analysis of the Spectroscopy of Atomic Bose-Hubbard Systems", Phys. Rev. A **93**, 043608 (2016).

(25) T. Inagaki, Y. Haribara, K. Igarashi, T. Sonobe, S. Tamate, T. Honjo, A. Marandi, P. L. McMahon, T. Umeki, K. Enbutsu, O. Tadanaga, H. Takenouchi, K. Aihara, K. Kawarabayashi, K. Inoue, S. Utsunomiya, and H. Takesue, "A Coherent Ising Machine for 2000-Node Optimization Problems", Science **354**, 603 (2016).

(26) T. Inagaki, K. Inaba, R. Hamerly, K. Inoue, Y. Yamamoto, and H. Takesue, "Large-scale Ising Spin Network Based on Degenerate Optical Parametric Oscillators", Nature Photon. **10**, 415 (2016).

(27) H. Irie, C. Todt, N. Kumada, Y. Harada, H. Sugiyama, T. Akazaki, and K. Muraki, "Andreev Reflection and Bound State Formation in a Ballistic Two-dimensional Electron Gas Probed by a Quantum Point Contact", Phys. Rev. B **94**, 155305 (2016).

(28) A. Ishizawa, T. Nishikawa, T. Goto, K. Hitachi, T. Sogawa, and H. Gotoh, "Ultralow-phase-noise Millimetre-wave Signal Generator Assisted with an Electro-optics-modulator-based Optical Frequency Comb", Sci. Rep. **6**, 24621 (2016).

(29) K. Kakuyanagi, Y. Matsuzaki, T. Baba, H. Nakano, S. Saito, and K. Semba, "Characterization and Control of Measurement-induced Dephasing on Superconducting Flux Qubit with a Josephson Bifurcation Amplifier", J. Phys. Soc. Jpn. **85**, 104801 (2016).

(30) K. Kakuyanagi, Y. Matsuzaki, C. Deprez, H. Toida, K. Semba, H. Yamaguchi, W. J. Munro, and S. Saito, "Observation of Collective Coupling Between an Engineered Ensemble of Macroscopic Artificial Atoms and a Superconducting Resonator", Phys. Rev. Lett. **117**, 210503 (2016).

(31) N. Kasai, "Nano-biointerfaces for Detection and Control of Biological Information", Electrochemistry **84**, 688 (2016).

(32) N. Kasai, R. Lu, R. Filip, T. Goto, A. Tanaka, and K. Sumitomo, "Neuronal Growth on a-Si and Au Nanopillars", Electrochemistry **84**, 296 (2016).

(33) M. Kasu, K. Hirama, K. Harada, and T. Oishi, "Study on Capacitance-voltage Characteristics of Diamond Field-effect Transistors with NO_2 Hole Doping and Al_2O_3 Gate Insulator Layer", Jpn. J. Appl. Phys. **55**, 041301 (2016).

(34) S. Kato, K. Inaba, S. Sugawa, K. Shibata, R. Yamamoto, M. Yamashita, and Y. Takahashi, "Laser Spectroscopic Probing of Coexisting Superfluid and Insulating States of an Atomic Bose-Hubbard System", Nature Commun. **7**, 11341 (2016).

(35) G. Kato and K. Tamaki, "Security of Six-state Quantum Key Distribution Protocol with Threshold Detectors", Sci. Rep. **6**, 30044 (2016).

(36) S. Kita, K. Takata, M. Ono, K. Nozaki, E. Kuramochi, K. Takeda, and M. Notomi, "Coherent Control of High Efficiency Metasurface Beam Deflector with a Back Partial Reflector", APL Photonics **2**, 046104 (2017).

(37) G. C. Knee, K. Kakuyanagi, M. C. Yeh, Y. Matsuzaki, H. Toida, H. Yamaguchi, S. Saito, A. J. Leggett, and W. J. Munro, "A Strict Experimental Test of Macroscopic Realism in a Superconducting Flux Qubit", Nature Commun. **7**, 13253 (2016).

(38) P. A. Knott, W. J. Munro, and J. A. Dunningham, "Correspondence: Enhancing a Phase Measurement by Sequentially Probing a Solid-state System", Nature Commun. **7**, 11520 (2016).

(39) R. Kou, Y. Hori, T. Tsuchizawa, K. Warabi, Y. Kobayashi, Y. Harada, H. Hibino, T. Yamamoto, H. Nakajima, and K. Yamada, "Ultra-fine Metal Gate Operated Graphene Optical Intensity Modulator", Appl. Phys. Lett. **109**, 251101 (2016).

(40) E. Kuramochi, "Manipulating and Trapping Light with Photonic Crystals from Fundamental Studies to Practical Applications", J. Mater. Chem. C **4**, 11032 (2016).

(41) N. Lambert, K. Debnath, A. F. Kockum, G. C. Knee, W. J. Munro, and F. Nori, "Leggett-Garg Inequality Violations with a Large Ensemble of Qubits", Phys. Rev. A **94**, 012105 (2016).

(42) N. Lambert, Y. Matsuzaki, K. Kakuyanagi, N. Ishida, S. Saito, and F. Nori, "Superradiance with an Ensemble of Superconducting Flux Qubits", Phys. Rev. B **94**, 224510 (2016).

(43) C. H. Lin, T. Akasaka, and H. Yamamoto, "N-Face GaN(000$\bar{1}$) Films with Hillock-free Smooth Surfaces Grown by Group-III-source Flow-rate Modulation Epitaxy", Jpn. J. Appl. Phys. **55**, 04EJ01 (2016).

(44) I. Mahboob, R. Dupuy, K. Nishiguchi, A. Fujiwara, and H. Yamaguchi, "Hopf and Period-doubling Bifurcations in an Electromechanical Resonator", Appl. Phys. Lett. **109**, 073101 (2016).

(45) I. Mahboob, H. Okamoto, and H. Yamaguchi, "An Electromechanical Ising Hamiltonian", Sci. Adv. **2**, E1600236 (2016).

(46) I. Mahboob, H. Okamoto, and H. Yamaguchi, "Enhanced Visibility of Two-mode Thermal Squeezed States via Degenerate Parametric Amplification and Resonance", New J. Phys. **18**, 083009 (2016).

(47) I. Mahboob, M. Villiers, K. Nishiguchi, D. Hatanaka, A. Fujiwara, and H. Yamaguchi , "A Correlated Electromechanical System", New J. Phys. **19**, 033026 (2017).

(48) H. Mashiko, K. Oguri, T. Yamaguchi, A. Suda, and H. Gotoh, "Petahertz Optical Drive with Wide-bandgap Semiconductor", Nature Phys. **12**, 741 (2016).

(49) N. Matsuda and H. Takesue, "Generation and Manipulation of Entangled Photons on Silicon Chips", Nanophotonics **5**, 440 (2016).

(50) Y. Matsuzaki, H. Morishita, T. Shimooka, T. Tashima, K. Kakuyanagi, K. Semba, W. J. Munro, H. Yamaguchi, N. Mizuochi, and S. Saito, "Optically Detected Magnetic Resonance of High-density Ensemble of NV Centers in Diamond", J. Phys. : Condens. Matter **28**, 275302 (2016).

(51) Y. Matsuzaki, T. Shimo-Oka, H. Tanaka, Y. Tokura, K. Semba, and N. Mizuochi, "Hybrid Quantum Magnetic-field Sensor with an Electron Spin and a Nuclear Spin in Diamond", Phys. Rev. A **94**, 052330 (2016).

(52) Y. Matsuzaki and S. Benjamin, "Magnetic-field Sensing with Quantum Error Detection under the Effect of Energy Relaxation", Phys. Rev. A **95**, 032303 (2017).

(53) P. L. McMahon, A. Marandi, Y. Haribara, R. Hamerly, C. Langrock, S. Tamate, T. Inagaki, H. Takesue, S. Utsunomiya, K. Aihara, R. L. Byer, M. M. Fejer, H. Mabuchi, and Y. Yamamoto, "A Fully Programmable 100-spin Coherent Ising Machine with All-to-all Connections", Science **354**, 614 (2016).

(54) A. Morinaga, M. Murakami, K. Nakamura, and H. Imai, "Scalar Aharonov-Bohm Phase in Ramsey Atom Interferometry under Time-varying Potential", Atoms **4**, 23 (2016).

(55) D. Morita, T. Kubo, Y. Tokura, and M. Yamashita, "Spin-1 Quantum Walks", Phys. Rev. A **93**, 063625 (2016).

(56) W. J. Munro and K. Nemoto, "Optical Circulators Reach the Quantum Level", Science **354**, 1532 (2016).

(57) Y. Nagamatsu, A. Mizutani, R. Ikuta, T. Yamamoto, N. Imoto, and K. Tamaki, "Security of Quantum Key Distribution with Light Sources that are Not Independently and Identically Distributed", Phys. Rev. A **93**, 042325 (2016).

(58) M. Naito, Y. Krockenberger, A. Ikeda, and H. Yamamoto, "Reassessment of the Electronic State, Magnetism, and Superconductivity in High-T_C Cuprates with the Nd_2CuO_4 Structure", Physica C **523**, 28 (2016).

(59) K. Nemoto, M. Trupke, S. J. Devitt, B. Scharfenberger, K. Buczak, J. Schmiedmayer, and W. J. Munro, "Photonic Quantum Networks Formed from NV-centers", Sci Rep. **6**, 26284 (2016).

(60) H. Nishi, T. Fujii, K. Takeda, K. Hasebe, T. Kakitsuka, T. Tsuchizawa, T. Yamamoto, K. Yamada, and S. Matsuo, "Membrane Distributed-reflector Laser Integrated with SiO_x -based Spot-Size Converter on Si Substrate", Opt. Express **24**, 18346 (2016).

(61) K. Nishiguchi, D. Yoshizumi, Y. Sekine, K. Furukawa, A. Fujiwara, and M. Nagase, "Planar Cold Cathode Based on a Multilayer-graphene/SiO_2/Si Heterodevice", Appl. Phys. Express **9**, 105101 (2016).

(62) J. Nishinaka, Y. Taniyasu, T. Akasaka, and K. Kumakura, "Surface Morphology Control of Nonpolar M-plane AlN Homoepitaxial Layers by Flow-rate Modulation Epitaxy", Phys. Status Solidi B **254**, 1600545 (2017).

(63) M. Y. Niu, F. H. Xu, J. H. Shapiro, and F. Furrer, "Finite-key Analysis for Time-energy High-dimensional Quantum Key Distribution", Phys. Rev. A **94**, 052323 (2016).

(64) K. Nozaki, S. Matsuo, T. Fujii, K. Takeda, M. Ono, A. Shakoor, E. Kuramochi, and M. Notomi, "Photonic-crystal Nano-photodetector with Ultrasmall Capacitance for On-chip Light-to-voltage Conversion without an Amplifier", Optica **3**, 483 (2016).

(65) R. Ohsugi, Y. Kunihashi, H. Sanada, M. Kohda, H. Gotoh, T. Sogawa, and J. Nitta, "Bias Dependence of Spin Injection/transport Properties of a Perpendicularly Magnetized FePt/MgO/GaAs Structure", Appl. Phys. Express **9**, 043002 (2016).

(66) R. Ohta, H. Okamoto, and H. Yamaguchi, "Feedback Control of Multiple Mechanical Modes in Coupled Micromechanical Resonators", Appl. Phys. Lett. **110**, 053106 (2017).

(67) R. Ohta, Y. Ueno, and K. Ajito, "Raman Spectroscopy of Pharmaceutical Cocrystals in Nanosized Pores of Mesoporous Silica", Anal. Sci. **33**, 47 (2017).

(68) M. Ohtomo, Y. Sekine, S. N. Wang, H. Hibino, and H. Yamamoto, "Etchant-free Graphene Transfer Using Facile Intercalation of Alkanethiol Self-assembled Molecules at Graphene/metal Interfaces", Nanoscale **8**, 11503 (2016).

(69) H. Okamoto, R. Schilling, H. Schutz, V. Sudhir, D. J. Wilson, H. Yamaguchi, and T. J. Kippenberg, "A Strongly Coupled Λ-type Micromechanical System", Appl. Phys. Lett. **108**, 153105 (2016).

(70) Y. Okazaki, I. Mahboob, K. Onomitsu, S. Sasaki, and H. Yamaguchi, "Gate-controlled Electromechanical Backaction Induced by a Quantum Dot", Nature Commun. **7**, 11132 (2016).

(71) M. Ono, E. Kuramochi, G. Q. Zhang, H. Sumikura, Y. Harada, D. Cox, and M. Notomi, "Nanowire-nanoantenna Coupled System Fabricated by Nanomanipulation", Opt. Express **24**, 8647 (2016).

(72) M. Ono, H. Taniyama, H. Xu, M. Tsunekawa, E. Kuramochi, K. Nozaki, and M. Notomi, "Deep-subwavelength Plasmonic Mode Converter with Large Size Reduction for Si-wire Waveguide", Optica **3**, 999 (2016).

(73) K. Onomitsu, A. Krajewska, R. A. E. Neufeld, F. Maeda, K. Kumakura, and H. Yamamoto, "Epitaxial Growth of Monolayer $MoSe_2$ on GaAs", Appl. Phys. Express **9**, 115501 (2016).

(74) F. D. Parmentier, T. Cazimajou, Y. Sekine, H. Hibino, H. Irie, D. C. Glattli, N. Kumada, and P. Roulleau, "Quantum Hall Effect in Epitaxial Graphene with Permanent Magnets", Sci. Rep. **6**, 38393 (2016).

(75) N. L. Piparo, M. Razavi, and W. J. Munro, "Measurement-device-independent Quantum Key Distribution with Nitrogen Vacancy Centers in Diamond", Phys. Rev. A **95**, 022338 (2017).

(76) S. Punniyakoti, R. Sivakumarasamy, F. Vaurette, P. Joseph, K. Nishiguchi, A. Fujiwara, and N. Clement, "Hydrogen Silsesquioxane-based Nanofluidics", Adv. Mater. Interf. 1601155 (2017).

(77) S. Putz, A. Angerer, D. O. Krimer, R. Glattauer, W. J. Munro, S. Rotter, J. Schmiedmayer, and J. Majer, "Spectral Hole Burning and Its Application in Microwave Photonics", Nature Photon. **11**, 36 (2017).

(78) K. Sasaki, S. Murakami, and H. Yamamoto, "Theory of Intraband Plasmons in Doped Carbon Nanotubes: Rolled Surface-Plasmons of Graphene", Appl. Phys. Lett. **108**, 163109 (2016).

(79) S. Sergent, M. Takiguchi, H. Taniyama, A. Shinya, E. Kuramochi, and M. Notomi, "Design of Nanowire-Induced Nanocavities in Grooved 1D and 2D SiN Photonic Crystals for the Ultra-Violet and Visible Ranges", Opt. Express **24**, 26792 (2016).

(80) A. Srinivasan, K. L. Hudson, D. Miserev, L. A. Yeoh, O. Klochan, K. Muraki, Y. Hirayama, O. P. Sushkov, and A. R. Hamilton, "Electrical Control of the Sign of the g Factor in a GaAs Hole Quantum Point Contact", Phys. Rev. B **94**, 041406 (2016).

(81) H. Sumikura, E. Kuramochi, H. Taniyama, and M. Notomi, "Purcell Enhancement of Fast-dephasing Spontaneous Emission from Electron-hole Droplets in High-Q Silicon Photonic Crystal Nanocavities", Phys. Rev. B **94**, 195314 (2016).

(82) S. Suzuki, M. Takamura, and H. Yamamoto, "Transmission, Reflection, and Absorption Spectroscopy of Graphene Microribbons in the Terahertz Region", Jpn. J. Appl. Phys. **55**, 06GF08 (2016).

(83) M. Taguchi, S. Nakajima, T. Kubo, and Y. Tokura, "Quantum Adiabatic Pumping by Modulating Tunnel Phase in Quantum Dots", J. Phys. Soc. Jpn. **85**, 084704 (2016).

(84) M. Takamura, H. Hibino, and H. Yamamoto, "Applying Strain into Graphene by SU-8 Resist Shrinkage", J. Phys. D-Appl. Phys. **49**, 285303 (2016).

(85) M. Takamura, H. Okamoto, K. Furukawa, H. Yamaguchi, and H. Hibino, "Energy Dissipation in Graphene Mechanical Resonators with and without Free Edges", Micromachines **7**, 158 (2016).

(86) Y. Takesaki, K. Kawahara, H. Hibino, S. Okada, M. Tsuji, and H. Ago, "Highly Uniform Bilayer Graphene on Epitaxial Cu-Ni(111) Alloy", Chem. Mat. **28**, 4583 (2016).

(87) H. Takesue and T. Inagaki, "10 GHz Clock Time-multiplexed Degenerate Optical Parametric Oscillators for a Photonic Ising Spin Network", Opt. Lett. **41**, 4273 (2016).

(88) M. Takiguchi, A. Yokoo, K. Nozaki, M. D. Birowosuto, K. Tateno, G. Zhang, E. Kuramochi, A. Shinya, and M. Notomi, "Continuous-wave Operation and 10-Gb/s Direct Modulation of InAsP/InP Sub-wavelength Nanowire Laser on Silicon Photonic Crystal", APL Photonics **2**, 046106 (2017).

(89) K. Tamaki, M. Curty, and M. Lucamarini, "Decoy-State Quantum Key Distribution with a Leaky Source", New J. Phys. **18**, 065008 (2016).

(90) T. Tawara, Y. Kawakami, H. Omi, R. Kaji, S. Adachi, and H. Gotoh, "Mechanism of Concentration Quenching in Epitaxial $(Er_xSc_{1-x})_2O_3$ Thin Layers", Opt. Mat. Express **7**, 1097 (2017).

(91) T. Tawara, G. Mariani, K. Shimizu, H. Omi, S. Adachi, and H. Gotoh, "Effect of Isotopic Purification on Spectral-hole Narrowing in $^{167}Er^{3+}$ Hyperfine Transitions", Appl. Phys. Express **10**, 042801 (2017).

(92) T. Teshima, H. Nakashima, N. Kasai, S. Sasaki, A. Tanaka, S. Tsukada, and K. Sumitomo, "Mobile Silk Fibroin Electrode for Manipulation and Electrical Stimulation of Adherent Cells", Adv. Funct. Mater. **26**, 8185 (2016).

(93) A. M. D. Thomasen, T. Mukai, and T. Byrnes, "Ultrafast Coherent Control of Spinor Bose-Einstein Condensates Using Stimulated Raman Adiabatic Passage", Phys. Rev. A **94**, 053636 (2016).

(94) F. Tian, H. Sumikura, E. Kuramochi, H. Taniyama, M. Takiguchi, and M. Notomi, "Optomechanical Oscillator Pumped and Probed by Optically Two Isolated Photonic Crystal Cavity Systems", Opt. Express **24**, 28039 (2016).

(95) T. Tilma, M. J. Everitt, J. H. Samson, W. J. Munro, and K. Nemoto, "Wigner Functions for Arbitrary Quantum Systems", Phys. Rev. Lett. **117**, 180401 (2016).

(96) J. Trasobares, D. Vuillaume, D. Theron, and N. Clement, "A 17 GHz Molecular Rectifier", Nature Commun. **7**, 12850 (2016).

(97) T. Uchida, M. Jo, A. Tsurumaki-Fukuchi, M. Arita, A. Fujiwara, and Y. Takahashi, "Capacitance Evaluation of Compact Silicon Triple Quantum Dots by Simultaneous Gate Voltage Sweeping", J. Appl. Phys. **120**, 234502 (2016).

(98) M. Villiers, I. Mahboob, K. Nishiguchi, D. Hatanaka, A. Fujiwara, and H. Yamaguchi, "An Electromechanical Displacement Transducer", Appl. Phys. Express **9**, 086701 (2016).

(99) S. N. Wang, H. Hibino, S. Suzuki, and H. Yamamoto, "Atmospheric Pressure Chemical Vapor Deposition Growth of Millimeter-scale Single-crystalline Graphene on the Copper Surface with a Native Oxide Layer", Chem. Mat. **28**, 4893 (2016).

(100) T. Watanabe, M. Hori, T. Tsuchiya, A. Fujiwara, and Y. Ono, "Time-domain Charge Pumping on Silicon-on-insulator MOS Devices", Jpn. J. Appl. Phys. **56**, 011303 (2017).

(101) G. Yamahata, S. P. Giblin, M. Kataoka, T. Karasawa, and A. Fujiwara, "Gigahertz Single-electron Pumping in Silicon with an Accuracy Better than 9.2 Parts in 10^7", Appl. Phys. Lett. **109**, 013101 (2016).

(102) G. Yamahata, S. P. Giblin, M. Kataoka, T. Karasawa, and A. Fujiwara, "High-accuracy Current Generation in the Nanoampere Regime from a Silicon Single-trap Electron Pump", Sci. Rep. **7**, 45137 (2017).

(103) A. Yokoo, M. Takiguchi, M. D. Birowosuto, K. Tateno, G. Zhang, E. Kuramochi, A. Shinya, H. Taniyama, and M. Notomi, "Subwavelength Nanowire Lasers on a Silicon Photonic Crystal Operating at Telecom Wavelengths", ACS Photonics **4**, 355 (2017).

(104) F. Yoshihara, T. Fuse, S. Ashhab, K. Kakuyanagi, S. Saito, and K. Semba, "Superconducting Qubit-oscillator Circuit beyond the Ultrastrong-coupling Regime", Nature Phys. **13**, 44 (2017).

List of Invited Talks

Ⅰ. Materials Science Laboratory

(1)	M. Hiroki, K. Kumakura, and H. Yamamoto, "Improvement in Thermal Resistance of Substrate-transferred GaN-HEMT Using Layered h-BN", 7th International Symposium on Control of Semiconductor Interfaces (ISCSI-VII), Nagoya, Japan (June 2016).
(2)	H. Hibino, "Structural analysis of heterostructures of 2D materials by low-energy electron microscopy and diffraction," 18th International Conference on Crystal Growth and Epitaxy (ICCGE-18), Nagoya, Aichi, Japan (Aug. 2016).
(3)	Y. Ueno and K. Furukawa, "On-chip FRET Aptasensor Built on the Graphene-biomolecular-interface", RSC Tokyo International Conference 2016, Chiba, Japan (Sep. 2016).
(4)	H. Hibino, "Structural analysis of 2D materials and heterostructures using low-energy electron microscopy and diffraction," 7th International Symposium on Practical Surface Analysis (PSA-16), Daejeon, South Korea (Oct. 2016).
(5)	Y. Ueno and K. Furukawa, "On-chip FRET Aptasensor Built on the Graphene-biomolecular-interface", 29th International Microprocesses and Nanotechnology Conferences (NMC), Kyoto, Japan (Nov. 2016).
(6)	H. Omi and T. Tawara, "Molecular Beam Epitaxy of $Er_xSc_{2-x}O_3$ on Si(111) and Optical Properties of the Films", 2016 Materials Research Society Fall Meeting (MRS Meeting), Boston, U.S.A. (Nov. 2016).

Ⅱ. Physical Science Laboratory

(1)	K. Muraki, "NMR Probing of Density-modulated Phases in the Third Landau Level", Recent Developments in 2D systems, Okinawa, Japan (Apr. 2016).
(2)	M. Hashisaka, N. Hiyama, T. Akiho, K. Muraki, and T. Fujisawa, "Time-domain Observation of Spin-and Charge-wave Packet Separation in Chiral One-dimensionalchannels", EMN Optoelectronics Meeting 2016, Phuket, Thailand (Apr. 2016).
(3)	H. Yamaguchi, I. Mahboob, H. Okamoto, and D. Hatanaka, "Phonon Confinement, Transport, and Piezoelectric Manipulation in Nonlinear Electromechanical Resonators", The 11th Annual IEEE International Conference on Nano/Micro Engineered and Molecular Systems (IEEE-NEMS 2016), Sendai, Japan (Apr. 2016).
(4)	H. Yamaguchi, D. Hatanaka, Y. Okazaki, and I. Mahboob, "Piezoelectric Phonon Manipulation in Electromechanical Resonators and Waveguides", SPICE Workshop: Quantum Acoustics - Surface Acoustic Waves meets Solid State Qubits, Mainz, Germany (May 2016).
(5)	Y. Sato, J. C. H. Chen, R. Kosaka, M. Hashisaka, K. Muraki and T. Fujisawa, "Enhanced Transition Between Charge States and Spin States of a Double Quantum Dot in a Surface Acoustic Wave Cavity", Quantum Acoustics, Mainz, Germany (May 2016).
(6)	H. Okamoto, T. Watanabe, R. Ohta, K. Onomitsu, H. Gotoh, T. Sogawa, and H. Yamaguchi, "Excitonic Optomechanics in a GaAs System", Frontiers in Quantum Materials & Devices Workshop 2016, Saitama, Japan (June 2016).

(7)	S. Sasaki, "InAs/InP Core-shell Nanowire Transistors with Outstanding Device Performance", The 28th International Conference on Indium Phosphide and Related Materials (IPRM2016), Toyama, Japan (June 2016).
(8)	H. Yamaguchi, I. Mahboob, and H. Okamoto, "Multi-mode Nonlinear Electromechanics", OPTO-And Electro-mechanical Technologies 2016 (OET2016), Monte Verita, Switzerland (July 2016).
(9)	A. Fujiwara, G. Yamahata, K. Nishiguchi, S. P. Giblin, and S. Kataoka, "Gigahertz Single-electron Pump for Quantum Current Standard", 33rd International Conference on the Physics of Semiconductors (ICPS), Beijing, China (July 2016).
(10)	D. Hatanaka, I. Mahboob, K. Onomitsu, and H. Yamaguchi, "An Electromechanical Phononic Crystal", 20th International Vacuum Congress (IVC-20), Busan, Korea (Aug. 2016).
(11)	K. Muraki, "Engineering a Quantum Spin Hall Insulator with InAs/GaSb Type-II Quantum Wells", Topological Material Science TopoMat Meeting 2016, Stuttgart, Germany (Sep. 2016).
(12)	K. Muraki, "Engineering a Two-dimensional Topological Insulator with III-V Semiconductor Heterostructures", International Symposium on Revolutionary Atomic-layer Materials, Sendai, Japan (Oct. 2016).
(13)	H. Yamaguchi, "Mechanical Resonators Hybridized with Semiconductor Quantum Structures", German-Japanese Meeting on the Science of Hybrid Quantum Systems, Berlin, Germany (Nov. 2016).
(14)	N. Clement and A. Fujiwara, "10-nm-scale Nanotechnology: from Nanoarrays to 0D Nanotransistor Biosensors", The 18th Takayanagi Kenjiro Memorial Symposium, Shizuoka, Japan (Nov. 2016).
(15)	S. Saito, "Superconducting Quantum Circuits and Electron Spin Ensembles", 6th Atom Chip Workshop, Pangkil Island, Indonesia (Dec. 2016).
(16)	H. Yamaguchi, I. Mahboob, H. Okamoto, and D. Hatanaka, "Parametric Coupling and Correlated Fluctuation in Multimode Electromechanical Resonators", Frontiers of Nanomechanical Systems (FNS2017), La Thuile, Italy (Feb. 2017).
(17)	K. Muraki, "Engineering Quantum Spin Hall Insulators with InAs/(In,Ga)Sb Quantum Wells: A Status Report", International School on Topological Science and Topological Matters, Kyoto, Japan (Feb. 2017).
(18)	K. Kakuyanagi, G. Knee, M. C. Yeh, Y. Matsuzaki, H. Toida, H. Yamaguchi, S. Saito, A. J. Leggett, and W. J. Munro, "Violation of Macroscopic Realism by Using a Superconducting Flux Qubit", Interdisciplinary Workshop on Quantum Device (IWQD 2017), Tokyo, Japan (Mar. 2017).
(19)	S. Saito, "Collective Coupling in Hybrid Superconducting Circuits", APS March Meeting 2017, New Orleans, U.S.A. (Mar. 2017).

Ⅲ. Optical Science Laboratory

(1)	H. Sanada, Y. Kunihashi, H. Gotoh, K. Onomitsu, M. Kohda, J. Nitta, P. V. Santos, and T. Sogawa "Acoustic Transport and Manipulation of Electron Spins in Semiconductors", SPICE Workshop: Quantum Acoustics – Surface Acoustic Waves meets Solid State Qubits, Mainz, Germany (May 2016).
(2)	K. Oguri, H. Mashiko, T. Yamaguchi, A. Suda, and H. Gotoh, "Observation of Petaherz Electronic Oscillation Based on Attosecond Spectroscopy", Shanghai-Tokyo Advanced Research Symposium on Ultrafast Intense Laser Science (STAR7), Kanagawa, Japan (May 2016).

(3)	H. Takesue, T. Sasaki, K. Tamaki, and M. Koashi, "Round-robin Differential Phase Shift Quantum Key Distribution Experiment", Trustworthy Quantum Information 2016, Shanghai, China (June 2016).
(4)	K. Azuma, "All-photonic Measurement-device-independent Quantum Repeaters", Trustworthy Quantum Information 2016, Shanghai, China (June 2016).
(5)	W. J. Munro, "Quantum @ NTT", International Conference on Quantum Communication, Measurement and Computing (QCMC 2016), Singapore, Singapore (July 2016).
(6)	W. J. Munro, K. Azuma, and K. Tamaki, "Intercity Quantum Networking without Repeaters", SPIE 2016 Optics+Photonics, San Diego, U.S.A. (Aug. 2016).
(7)	W. J. Munro, "Quantum Communication for Tomorrow", Photonics Conference (IPC2016), Hawaii, U.S.A. (Oct. 2016).
(8)	K. Oguri, H. Mashiko, T. Yamaguchi, A. Suda, and H. Gotoh, "Light-induced Electron Dynamics in Semiconductor from Femtosecond to Attosecond Regime", International Symposium on Ultrafast Intense Laser Science (ISUILS15), Cassis, France (Oct. 2016).
(9)	N. Matsuda, "Spectral and Spatial Manipulation of Single Photons Using Optical Waveguides", The 3rd UK-Japan Quantum Technology Workshop, Tokyo, Japan (Oct. 2016).
(10)	K. Azuma, "Theory of the Quantum Internet", Quantum Science Symposium Europe-2016, Cambridge, U.K. (Nov. 2016).
(11)	K. Oguri, H. Mashiko, T. Yamaguchi, A. Suda, and H. Gotoh, "Petaherz Electronic Response in Semiconductor", The 9th Asian Symposium on Intense Laser Science (ASILS 9), Ninh Binh, Vietnam (Nov. 2016).
(12)	G. Zhang and H. Gotoh, "InP/InAs Heterostructure Nanowires Grown by Indium-particle-assisted Vapor-liquid-solid Mode", 31st DGKK Workshop: Epitaxy of III/V Semiconductor, Duisburg, Germany (Dec. 2016).
(13)	W. J. Munro, "Quantum Communication: A primer", Mini-School on Quantum Information Science, Taipei, Taiwan (Dec. 2016).
(14)	W. J. Munro, "Quantum Hybridization: Why One Plus One is Now Greater than Two", 8th International Workshop on Solid State Quantum Computing, Taipei, Taiwan (Dec. 2016).
(15)	W. J. Munro, "New Century Engineering Using the Age Old Principles of Quantum Mechanics", Conference on 90 Years of Quantum Mechanics (QM90), Singapore, Singapore (Jan. 2017).
(16)	H. Takesue, T. Inagaki, K. Inaba, R. Hamerly, K. Inoue, and Y. Yamamoto, "Large-scale Artificial Spin Network Based on Time-multiplexed Degenerate Optical Parametric Oscillators for Coherent Ising Machine", SPIE Photonics West 2017, San Francisco, U.S.A. (Jan. 2017).
(17)	N. Matsuda, "Spectral and Spatial Manipulation of Single Photons", The JSAP Workshop on Quantum Information and Related Fields, Tokyo, Japan (Mar. 2017).
(18)	K. Oguri, H. Mashiko, and H. Gotoh, "Petahertz Semiconductor Drive Characterized by Isolated Attosecond Pulse", The 8th Asian Workshop on Generation and Application of Coherent XUV and X-ray Radiation (8th AWCXR), Hsinchu, Taiwan (Mar. 2017).

Ⅳ. Nanophotonics Center

(1)	M. Notomi, "Nanomaterial-nanophotonics Hybrid Systems for Novel Photonic Platform", SPIE Photonics Europe 2016, Brussel, Belgium (Apr. 2016).
(2)	K. Takeda, T. Fujii, A. Shinya, E. Kuramochi, M. Notomi, K. Hasebe, T. Kakitsuka, and S. Matsuo, "Electrically Driven Nanocavity Lasers on Silicon with Photonic-crystal Cavity and Ultrasmall Buried Heterostructure", International Nanotechnology Conference & Expo (Nanotech 2016), Baltimore, U.S.A. (Apr. 2016).
(3)	M. Notomi, "Hybrid Nanophotonics-nanomaterial Platforms with III/V Semiconductor Nanowires on Si", 5th International Conference on Smart and Multifunctional Materials Structures & Systems (CIMTEC 2016), Perugia, Italy (June 2016).
(4)	S. Matsuo, K. Takeda, and T. Fujii, "Heterogeneously Integrated Photonic Crystal Laser on Si", 2016 - the Premier International Laser and Electro-Optics Event (CLEO/QELS), San Jose, U.S.A. (June 2016).
(5)	R. Nakao, M. Arai, T. Kobayashi, T. Kakitsuka, T. Yamamoto, and S. Matsuo, "Epitaxial Growth on Lattice-mismatched Substrate for High-performance Lasers", The 43rd International Symposium on Compound Semiconductors (ISCS), Toyama, Japan (June 2016).
(6)	M. Notomi, "Integrated Nanophotonics for Optical Computation in a Chip", 18th International Conference on Tranparent Optical Networks (ICTON 2016), Torento, Italy (July 2016).
(7)	A. Shinya, "Nanophotonics for Low-latency Optical Passgate Logic Circuits", 16th International Forum on MPSoC for Software-defined Hardware (MP SOC), Nara, Japan (July 2016).
(8)	S. Matsuo, K. Takeda, T. Fujii, H. Nishi, and T. Kakitsuka, "Directly Modulated Membrane DFB Lasers and Photonic Crystal Lasers", 2016 IEEE Photonics Society Summer Topical Meeting Series (SUM), Newport Beach, U.S.A. (July 2016).
(9)	M. Notomi, "Impact of Capacitance and Latency on Integrated Nanophotonics", The 12th International Symposium on Photonic and Electromagnetic Crystal Structures (PECS-XII), York, U.K. (July 2016).
(10)	S. Matsuo, K. Takeda, T. Fujii, H. Nishi, and T. Kakitsuka, "Membrane DFB and Photonic Crystal Lasers on Si", The 25th International Semiconductor Laser Conference (ISLC2016), Kobe, Japan (Sep. 2016).
(11)	S. Matsuo, "Applications of Photonic Crystal and Heterogeneous Integration to Ultra-low-energy Lasers for Optical Interconnects and Datacenter Networks", 42nd European Conference and Exhibition on Optical Communication (ECOC), Dusseldorf, Germany (Sep. 2016).
(12)	S. Matsuo, K. Takeda, and T. Fujii, "Directly Modulated Photonic Crystal Lasers for Extremely Short Optical Links", 2016 IEEE Photonics Conference (IPC), Hawaii, U.S.A. (Oct. 2016).
(13)	H. Nishi, T. Tsuchizawa, T. Kakitsuka, K. Hasebe, K. Takeda, T. Hiraki, T. Fujii, T. Yamamoto, and S. Matsuo, "SiO_xN_y Back-end Photonics Platform for Si-Ge-InP Integration", Pacific Rim Meeting on Electrochemical and Solid-State Science (PRiME 2016), Hawaii, U.S.A. (Oct. 2016).
(14)	M. Notomi, "Hybrid Nanoemitterd with Nanomaterials and Nanophotonic Platforms", Workshop on Coherence and Quantum Phenomena in Small and Single-Photon Sources (CohQuantSSPhS), Nice, France (Oct. 2016).
(15)	A. Ishihara, A. Shinya, K. Inoue, K. Nozaki, and M. Notomi, "An Integrated Optical Parallel Adder as a First Step Towards Light Speed Data Processing", 13th International SoC Design Conference (ISOCC 2016), Jeju, Korea (Oct. 2016).

(16)	T. Kakitsuka, T. Fujii, K. Takeda, H. Nishi, and S. Matsuo, "III-V Membrane Lasers on Silicon for Datacom and Computercom Applications", Photonics 2017 (in IEEE Symposium on HPCA), Austin, U.S.A. (Feb. 2017).
(17)	S. Matsuo, "High-performance Lasers on InP-SOI Platform", The Future of Optical Networking and Communication (OFC), Los Angeles, U.S.A. (Mar. 2017).
(18)	A. Ishihara, A. Shinya, K. Inoue, K. Nozaki and M. Notomi, "An Optical Parallel Adder towards Light Speed Data Processing", Design, Automation and Test in Europe (DATE 2017), Lausanne, Switzerland (Mar. 2017).

Data

Research Activities in NTT-BRL
Editorial Committee

NTT Basic Research Laboratories
3-1 Morinosato Wakamiya, Atsugi
Kanagawa, 243-0198 Japan
URL: http://www.brl.ntt.co.jp/