Research Activities in NTT Basic Research Laboratories

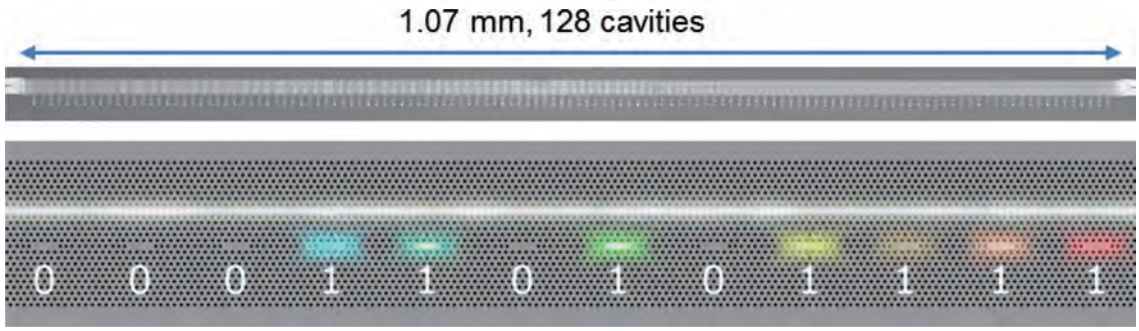
Fiscal 2014

VOL. 25

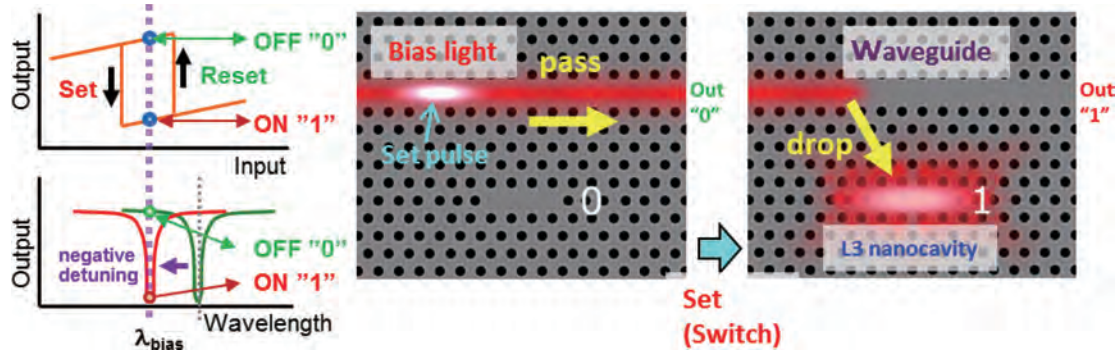
NTT Basic Research Laboratories,
Nippon Telegraph and Telephone Corporation
http://www.brl.ntt.co.jp/

Cover Photograph: Over-100-bit Photonic Crystal Optical-RAM Chip

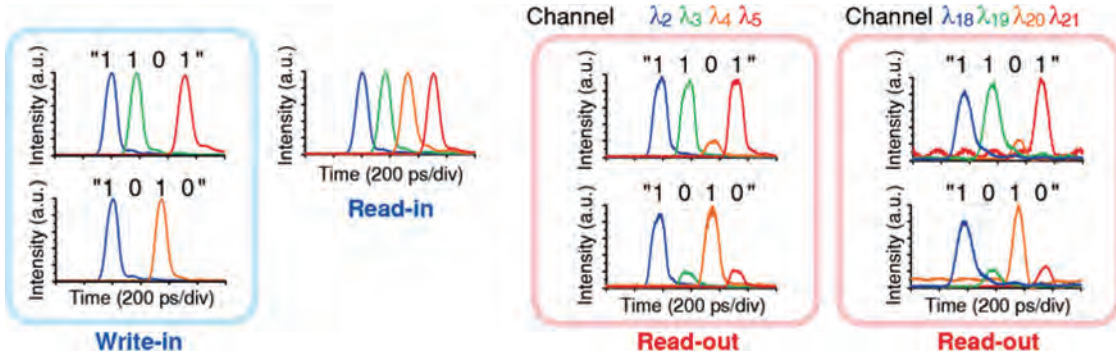
We are working on large-scale integration of optical-memory (o-RAM) by photonic crystal technology which can break through the limit of size and power consumption in conventional o-RAMs. Here we fabricated a 1.1-mm silicon photonic crystal chip in which over 100 nanocavities were integrated and realized successfully over-100-bit o-RAM operation with low power for the first time (See page 45).



Microscope image of 128 nanocavities integrated in a silicon chip. Lower: Schematic of multi-bit o-RAM action with wavelength division multiplexing.



Principal of o-RAM operation. A bistable memory that holds/switches “0” and “1” states is realized by fast carrier-plasma effect greatly enhanced in a high quality factor nanocavity.



Write and read-out operations of 4-bit random pulses in two different sets of sequential 4 o-RAMs (demonstrated in a similar integrated o-RAM chip in an InP-based photonic crystal).

Message from the Director

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

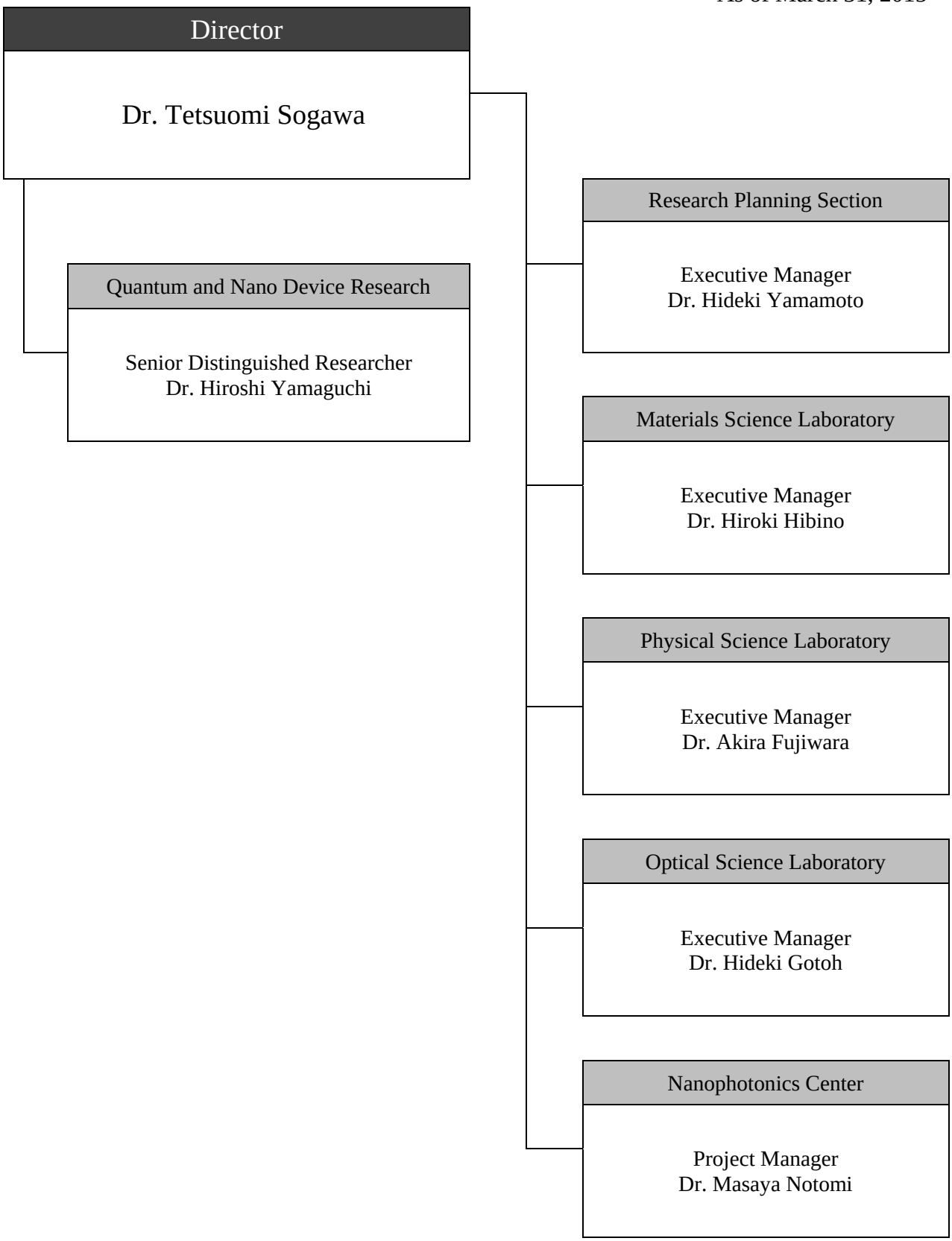
July, 2015

Tetsuomi Sogawa
Director
NTT Basic Research Laboratories

Contents

NTT Basic Research Laboratories Organogram

As of March 31, 2015



Member List

As of March 31, 2015
(*/ left NTT BRL 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**

Research Planning Section

Senior Research Scientist, Supervisor **Dr. Hideki Yamamoto**

Senior Research Scientist, Supervisor Dr. Hiroshi Nakashima

Senior Research Scientist, Supervisor Dr. Shiro Saito

NTT Research Professor **Prof. Yasuhiro Tokura** (University of Tsukuba)

Materials Science Laboratory

Executive Manager **Dr. Hiroki Hibino**

Dr. Fumihiko Maeda

Thin-Film Materials Research Group:

Dr. Hideki Yamamoto (Group Leader)

Dr. Kazuhide Kumakura	Dr. Hisashi Sato	Dr. Tetsuya Akasaka
Dr. Yoshitaka Taniyasu	Dr. Koji Onomitsu	Dr. Yoshiharu Krockenberger
Dr. Masanobu Hiroki	Dr. Shin-ichi Karimoto	Dr. Kazuyuki Hirama
Dr. Junichi Nishinaka	Dr. Ryan G. Banal*	Dr. Hironori Okumura

Low-Dimensional Nanomaterials Research Group:

Dr. Hiroki Hibino (Group Leader)

Dr. Fumihiko Maeda	Dr. Yuko Ueno	Dr. Kazuaki Furukawa
Dr. Satoru Suzuki	Dr. Hiroo Omi	Dr. Ken-ichi Sasaki
Dr. Yoshiaki Sekine	Dr. Makoto Takamura	Dr. Shengnan Wang
Dr. Carlo M. Orofeo*	Dr. Adel Najar	Dr. Manabu Ohtomo

Molecular and Bio Science Research Group:

Dr. Koji Sumitomo (Group Leader)

Dr. Shingo Tsukada	Dr. Nahoko Kasai	Dr. Yoshiaki Kashimura
Dr. Toichiro Goto	Dr. Aya Tanaka	Dr. Azusa Oshima
Dr. Tetsuhiko Teshima		

Physical Science Laboratory

Executive Manager **Dr. Akira Fujiwara**

Dr. Toshiaki Hayashi

Takeshi Karasawa

Nanodevices Research Group:

Dr. Akira Fujiwara (Group Leader)

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

Hybrid Nanostructure Physics Research Group:

Dr. Hiroshi Yamaguchi (Group Leader)

Dr. Yuichi Harada	Dr. Kenji Yamazaki	Dr. Imran Mahboob
Dr. Hajime Okamoto	Dr. Kosuke Kakuyanagi	Dr. Yuichiro Matsuzaki
Daiki Hatanaka	Dr. Hiraku Toida	Dr. Ryuichi Ota

Quantum Solid State Physics Research Group:

Dr. Koji Muraki (Group Leader)

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

Optical Science Laboratory

Executive Manager **Dr. Hideki Gotoh**

Dr. Tetsuya Mukai

Quantum Optical State Control Research Group:

Dr. Kaoru Shimizu (Group Leader)

Dr. Hiroki Takesue	Kazuhiro Igeta	Dr. Hiroyuki Shibata
Dr. Makoto Yamashita	Dr. Tetsuya Mukai	Dr. Kensuke Inaba
Dr. Nobuyuki Matsuda	Daisuke Hashimoto	Dr. Hiromitsu Imai
Dr. Takahiro Inagaki	Dr. Kazuto Noda	

Theoretical Quantum Physics Research Group:

Dr. William John Munro (Group Leader)

Dr. Kiyoshi Tamaki	Dr. Fumiaki Morikoshi	Dr. Koji Azuma
Dr. George Knee	Dr. Fabian Furrer	

Quantum Optical Physics Research Group:

Dr. Hideki Gotoh (Group Leader)

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

Photonic Nano-Structure Research Group:

Dr. Masaya Notomi (Group Leader)

Dr. Akihiko Shinya	Dr. Atsushi Yokoo	Dr. Eiichi Kuramochi
Dr. Hideaki Taniyama	Dr. Hisashi Sumikura	Dr. Kengo Nozaki
Dr. Masato Takiguchi	Dr. Masaaki Ono	Dr. Abdul Shakoor*
Dr. Devin Smith	Dr. Feng Tian	

Nanophotonics Center

Project Manager **Dr. Masaya Notomi**

Photonic Nano-Structure Research Team:

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

Nanostructured Device Research Team:

Dr. Shinji Matsuo	Dr. Koji Yamada	Dr. Tai Tsuchizawa
Dr. Takaaki Kakitsuka	Dr. Masakazu Arai	Dr. Tomonari Sato*
Dr. Koichi Hasebe	Dr. Koji Takeda	Hidetaka Nishi
Rai Kou (Rai Takahashi)	Dr. Kotaro Takeda	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 Researcher 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 is serving as a member of National University Corporation Evaluation Committee in the Japanese government. He is also a member of the Japan Society of Applied Physics, APS, IEEE, and OSA.

Hiroshi YAMAGUCHI received his B.E., M.S. in physics and Ph.D. degrees in engineering from Osaka University in 1984, 1986, and 1993, respectively. He joined NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corporation in 1986 and has been engaged in the study of compound semiconductor surfaces using electron diffraction and scanning tunneling microscopy. His current interests are micro/nanomechanical devices using semiconductor heterostructures. He was a visiting research fellow in Imperial College, University of London, U.K. during 1995-1996 and a visiting research staff in Paul Drude Institute, Germany in 2003. He is a guest professor in Tohoku University from 2006 and a director of the Japanese Society of Applied Physics (JSAP) in 2008 and 2009. He served as more than 40 committee members of academic societies and international conferences. He was appointed as Senior Distinguished Researcher of NTT since 2011. He is currently an executive manager of Quantum and Nano Device Research and a group leader of Hybrid Nano-Structure Physics Research Group. He received the Paper Awards of Japan Society of Applied Physics in 1989, 2004, and 2010, MNC2008 Outstanding Paper Award in 2009, SSDM2009 Paper Award in 2010, Inoue Prize for Science in 2012, and Commendation for Science and Technology by MEXT in 2013. He was made a Fellowship of Institute of Physics (IOP) in 2011 and JSAP in 2013. He is a member of JSAP, the Physical Society of Japan, Institute of Physics (IOP), American Physical Society (APS), and IEEE.

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

Distinguished Researchers

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

Yoshitaka TANIYASU received his B.E., M.E., and Dr. Eng. degrees in electrical engineering from Chiba University, Chiba, Japan in 1996, 1998, and 2001, respectively. He joined NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corporation in 2001. Since then, he has been engaged in research on wide-bandgap nitride semiconductors. He was a visiting researcher at Ecole polytechnique fédérale de Lausanne (EPFL) during 2011-2012. He was appointed as Distinguished Researcher of NTT in 2010. He is currently a member of Thin-Film materials Research Group. He received the Young Scientist Presentation Award at the Japan Society of Applied Physics (JSAP) in 2001, the Young Scientist Award at the 14th Semiconducting and Insulating Materials Conference in 2007, the Young Scientists' Prize from the Minister of Education, Culture, Sports, Science and Technology, the Young Scientist Award at the 38th International Symposium on Compound Semiconductors in 2011, and the Best Paper Award at the International Workshop on Nitride Semiconductors in 2012. He is a member of the Japan Society of Applied Physics.

Norio KUMADA received his B.S., M.S., and Ph.D. degrees in physics from Tohoku University, Japan, in 1998, 2000, and 2003, respectively. He joined NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corporation in 2003. Since then, he has been engaged in the study of highly correlated electronic states in semiconductor heterostructures. He was a visiting researcher at CEA Saclay during 2013-2014. He was appointed as Distinguished Researcher 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 Researcher of NTT in 2011. He is currently a member of Nanodevices Research Group. He received IUPAP Young Author Best Paper Award at the International Conference on Physics of Semiconductors 2000, Graduate Student Award Silver at the Materials Research Society 2000 Fall Meeting, Young Scientist Award at the Japan Society of Applied Physics Spring Meeting in 2000, JSAP Outstanding Paper Award 2013, and The Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology of Japan (the Young Scientists' Prize) in 2013. He is a member of the Japan Society of Applied Physics.

Shiro SAITO received his B.S., M.S., and Dr. Eng. degrees in applied physics from The University of Tokyo, Japan, in 1995, 1997, and 2000, respectively. He joined NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corporation in 2000. Since then, he has been engaged in quantum information processing using superconducting circuits. He was a guest researcher at Delft University of Technology, Delft, the Netherlands during 2005-2006. He is a guest associate professor in Tokyo University of Science from 2012. He was appointed as Distinguished Researcher 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 optical access networks using wavelength division multiplexing and experimental quantum optics and quantum communications. He was appointed as Distinguished Researcher 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 in 2008 and The Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology of Japan (the Young Scientists' Prize) in 2010. He was a Visiting Scholar at Stanford University, Stanford, CA from 2003 to 2004, and a guest researcher at the National Institute of Standards and Technology (NIST), Boulder, CO in 2014. He is a member of IEEE and the Japan Society of Applied Physics.

Imran MAHBOOB received a combined B.Sc. and M.Sc. degree in Theoretical Physics from The University of Sheffield, U.K., in 2001 and Ph.D. degree in Physics studying the electronic properties of nitride semiconductors from The University of Warwick, U.K., in 2004, respectively. He joined NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corporation in 2005 as a Research Associate, from 2008 as a Research Specialist, and from 2012 as a Senior Research Scientist. His current interests are developing electromechanical resonators for digital signal processing applications and to study their non-linear dynamics. He was appointed as Distinguished Researcher 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 Researcher of NTT in 2014. He is currently a member of Quantum Optical Physics Research Group. He received the Young Scientist Presentation Award at the Japan Society of Applied Physics (JSAP) Autumn Meeting in 2004, the SSDM Paper Award in 2010, and the RIEC Award from Tohoku University in 2014. He is a member of the Japan Society of Applied Physics.

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

Advisory Board

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

Invited / Guest Scientists

Name	Affiliation	Period
Prof. Christos Flytzanis	École Normale Supérieure / The Centre National de la Recherche Scientifique (ENS/CNRS), France	June 2014 - July 2014
Dr. Paulo Santos	Paul Drude Institute for Solid State Electronics, Germany	Oct. 2014 - Dec. 2014
Dr. Jason Brown	University of Oxford, U.K.	June 2014 - June 2014

Overseas Trainees

Name	Affiliation	Period
Louise Waterston	University of Edinburgh, U.K.	July 2013 - July 2014
Rick Lu	University of Waterloo, Canada	Sep. 2013 - Apr. 2014
Anna Fomitcheva Khartchenko	University of Barcelona, Spain	Sep. 2013 - Aug. 2014
Jose Alberto Rodriguez Santamaria	University of Burgos, Germany	Sep. 2013 - Aug. 2014
Krzysztof Jan Gibasiewicz	Warsaw University of Technology, Poland	Sep. 2013 - Aug. 2014
Gianfranco D'Ambrosio	Politecnico di Milano, Italy	Sep. 2013 - Aug. 2014
Logan G. Blackstad	Geogia Institute of Technology, U.S.A.	Sep. 2013 - Aug. 2014
Peter Karkus	Budapest University of Technology and Economics, Hungary	Sep. 2013 - Aug. 2014
Adrian Salmon	Geogia Institute of Technology, U.S.A.	Jan. 2014 - July 2014
Henry Pigot	The University of British Columbia, Canada	Jan. 2014 - Aug. 2014
Ryan Neufeld	University of Waterloo, Canada	Jan. 2014 - Aug. 2014

Name	Affiliation	Period
Andrew Tin	McGill University, Canada	Feb. 2014 - Dec. 2014
Roxana Filip	University of Ottawa, Canada	May 2014 - Dec. 2014
Josh Kuo	The University of British Columbia, Canada	May 2014 - Dec. 2014
Christophe Rainville	McGill University, Canada	May 2014 - Dec. 2014
Shane Dooley	University of Leeds, U.K.	June 2014 - Sep. 2014
Matt Edmonds	University of Bath, U.K.	June 2014 - Dec. 2014
Thomas McManus	University of Bath, U.K.	July 2014 - Dec. 2014
Flore Castellan	ESPCI ParisTech, France	July 2014 - Dec. 2014
Pierre-Alix Carles	ESPCI ParisTech, France	July 2014 - Dec. 2014
Amaury Dodel	ESPCI ParisTech, France	July 2014 - Dec. 2014
Remi Dupuy	ESPCI ParisTech, France	July 2014 - Dec. 2014
Tony Jin	ESPCI ParisTech, France	July 2014 - Dec. 2014
Hadrien Duprez	École Polytechnique de Montreal, Canada	May 2014 -
Sophia Chan	University of Edinburgh, U.K.	June 2014 -
Aleksandra Krajewska	University of Edinburgh, U.K.	July 2014 -
Clemens Todt	Technical University Dresden, Germany	Sep. 2014 -
Aleix Llenas	Polytechnic University of Catalonia Barcelona Tech, Spain	Sep. 2014 -
Dorota Kowalczyk	Gdansk University of Technology, Poland	Sep. 2014 -
Silviu Dinulescu	University Politehnica of Bucharest, Romania	Sep. 2014 -
Akie Watanabe	The University of British Columbia, Canada	Jan. 2015 -
Mats Powlowski	Corcodia University, Canada	Jan. 2015 -

Domestic Trainees (Fiscal 2014)

Name	Affiliation	Period
Han Cai	Tohoku University	Apr. 2014 - Mar. 2015
Ahmad Yoshinari	Tokyo University of Science	Apr. 2014 - Mar. 2015
Kazuki Moriya	The University of Tokyo	Apr. 2014 - Mar. 2015
Kosuke Sato	Kyoto University	Apr. 2014 - Mar. 2015
Toru Tanaka	Waseda University	Apr. 2014 - Mar. 2015
Takahiko Sato	The University of Tokyo	Apr. 2014 - Mar. 2015
Saki Tanaka	Keio University	Apr. 2014 - Mar. 2015
Rento Osugi	Tohoku University	Apr. 2014 - Mar. 2015
Tomohiro Tamaki	Toyo University	Apr. 2014 - Mar. 2015
Takahiro Goto	Tokyo Denki University	Apr. 2014 - Mar. 2015
Ken-ichi Suzuki	Tokyo Denki University	Apr. 2014 - Mar. 2015
Tomohiko Yamaguchi	Tokyo University of Science	Apr. 2014 - Mar. 2015
Masato Tsunekawa	Tokyo Institute of Technology	Apr. 2014 - Mar. 2015
Keisuke Noguchi	Tokyo Institute of Technology	Apr. 2014 - Mar. 2015
Akihiro Fushimi	Keio University	Apr. 2014 - Mar. 2015
Takuya Ohrai	Tokyo University of Science	May 2014 - Mar. 2015
Yamato Ashikawa	Tohoku University	Aug. 2014 - Mar. 2015
Masafumi Horio	The University of Tokyo	Sep. 2014 - Nov. 2014
Ayumi Ishijima	Kyushu University	Aug. 2014 - Sep. 2014
Kohei Nakanishi	Mie University	Aug. 2014 - Sep. 2014
Ryousuke Tanaka	Hokkaido University	Aug. 2014 - Sep. 2014
Daichi Morita	University of Tsukuba	Aug. 2014 - Sep. 2014
Takuya Aritsuki	Tokushima University	Aug. 2014 - Sep. 2014
Asahiko Sakai	Nagaoka University of Technology	Oct. 2014 - Feb. 2015
Tran Minh Tien	Nagaoka University of Technology	Oct. 2014 - Feb. 2015
Masafumi Horio	The University of Tokyo	Dec. 2014 - Mar. 2015
Ryousaku Sakamoto	Toyohashi University of Technology	Jan. 2015 - Feb. 2015
Takaya Nakane	Toyohashi University of Technology	Jan. 2015 - Feb. 2015
Motoki Itoh	Toyohashi University of Technology	Jan. 2015 - Feb. 2015
Takeshi Kamiya	Osaka University	Jan. 2015 - Mar. 2015
Suguru Endo	Keio University	Jan. 2015 - Mar. 2015
Yuki Nagakubo	The University of Tokyo	Feb. 2015 - Feb. 2015

Ⅰ. Research Topics

Overview of Research in Laboratories

Materials Science Laboratory

Hiroki Hibino

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

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

This year, we succeeded in the CVD growth of single-layer graphene composed of mm-sized single-crystalline domains. The self-heating effect has been suppressed in GaN-based electronic devices by transferring them to thermally conductive materials using our original epitaxial lift-off technique based on the cleavable nature of *h*-BN. In addition, the sensing fabric “hitoe”, which was developed last year in collaboration with Toray Industries, Inc., has been marketed by GOLDWIN Co. Ltd.

Physical Science Laboratory

Akira Fujiwara

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

This year we realized the dynamic control of one-dimensional phononic crystals, observed Wigner solids in high magnetic fields, achieved high-speed single-electron transfer via a single-trap level in silicon, and observed dark states in a superconductor diamond quantum hybrid system. Progress was also made in the research on two-mode squeezing in an electromechanical resonator, the electric tuning of direct/indirect optical transitions in silicon, and resonant edge magnetoplasmons in graphene.

Optical Science Laboratory Hideki Gotoh

The aims of this laboratory are to develop innovative core technologies for optical communications and optical signal processing, and to make fundamental scientific progress.

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

This year, we have succeeded in monitoring inner-shell electron motion with an ultrafast strobe light source using attosecond optical pulse creation techniques. We have also made progress on quantum key distribution employing superconducting detectors with an ultra-low-dark count rate and undertaken theoretical studies on quantum cryptography assuming realistic environments. In addition, we have clarified the quantum optical properties of silicon integrated optical circuits, revealed energy transfer processes in Er oxides, and fabricated a new type of semiconductor hetero-nanowire exploiting original self-catalyst growth techniques.

Nanophotonics Center Masaya Notomi

The Nanophotonics Center was established in April 2012, and is now composed of several nanophotonics-related research groups from NTT Basic Research Laboratories and NTT Device Technology Laboratories. Our aim is to develop a full-fledged large-scale photonic integration technology that will allow us to densely integrate a large number of nano-scale photonic devices with various functions in a single chip. Furthermore, we are targeting an extreme reduction in energy consumption for photonic information processing by taking advantage of nanophotonics technology.

This year, we demonstrated an optical random access memory of over 100 bits based on ultrasmall integrated photonic crystal nanocavities. As a novel step, we realized InP nanowire and plasmonic nanoantenna coupled systems that showed substantial light emission enhancement. We also achieved large Raman enhancement in Si photonic crystal nanocavities with carbon nanotubes. As regards device applications, we achieved the room-temperature operation of on-Si photonic crystal nanolasers by employing a wafer-bonding technique, and demonstrated a spatial mode multiplexer/demultiplexer based on 3D multi-layer waveguides.

Suppression of Self-Heating Effect in AlGaN/GaN HEMTs by Mechanical Transfer Using an *h*-BN Release Layer

Masanobu Hiroki, Kazuhide Kumakura, Yasuyuki Kobayashi*, Tetsuya Akasaka, Toshiki Makimoto**, and Hideki Yamamoto
Materials Science Laboratory

III-nitride semiconductor materials have potential for high-power device applications by exploiting their high critical electric field. Under high-current operation, however, power performance is limited because of the generation of Joule heat (the so-called self-heating effect). Therefore, thermal management in the GaN-based devices is necessary to further improve high-power performance. One approach to overcome this problem is to grow device structures on highly thermal conductive substrate. However, the lattice mismatch or the difference in thermal expansion coefficients between substrates and GaN often limit the crystal quality and thickness of the layers. We propose a different approach, where the devices are transferred to foreign materials with high thermal conductivity. Recently, we have developed a mechanical transfer technique using release layer (MeTRe mothod), in which *h*-BN is inserted between a GaN layer and sapphire substrate as a release layer [1]. Using this method, we have demonstrated strong emission from transferred InGaN/GaN multiple quantum well light emitting diodes (LEDs) [2]. In this study, we applied the same approach to electronic devices [3]. We fabricated AlGaN/GaN high-electron-mobility transistors (HEMTs) on *h*-BN/sapphire substrates and transferred them to copper plates, which led to an improvement of device performance due to enhanced heat dissipation.

Figure 1 shows typical *I*-*V* characteristics of an AlGaN/GaN HEMT before release from the substrate and after transfer to the copper plate. We obtained good pinch-off and saturation characteristics before release and after transfer. Before release, a large reduction in drain current I_d with increasing V_{ds}, i.e., negative differential resistance, is observed in the saturation region. In contrast, the negative resistance is reduced for the transferred HEMT. The negative resistance is commonly attributed to the self-heating effect. Transfer from sapphire (thermal conductivity κ = 40 W/m K) to the copper plate (κ = 390 W/m K) improves the heat dissipation efficiency. We took temperature images of devices during operation with 1-W power dissipation (Fig. 2). Before release, a hot spot with a temperature of about 50°C is observed. In contrast, the temperature is as low as 30°C for the transferred HEMT. Our results indicate that the transfer technique using the *h*-BN release layer can enhance the heat dissipation and significantly improve the power performance of GaN-based devises.

Present address:* Hirosaki University, ** Waseda University

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[2] T. Makimoto et al., Appl. Phys. Express **5**, 07102 (2012).

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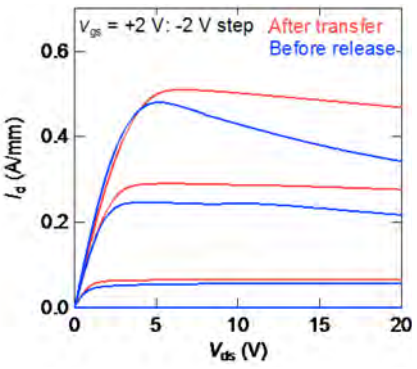

Fig. 1. *I*-*V* characteristics of HEMT before release and after transfer.

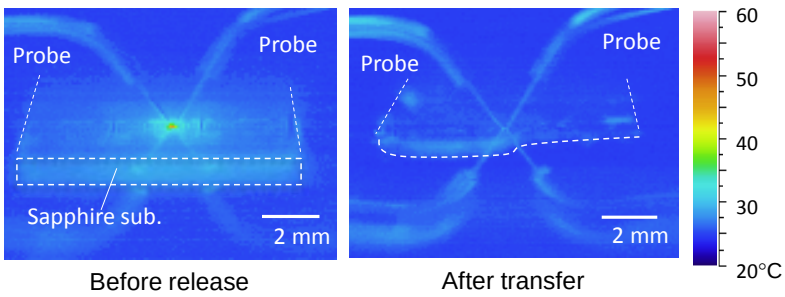

Fig. 2. Temperature map of devices before release and after transfer.

MBE Growth of Transition Metal Dichalcogenide Thin Films

Koji Onomitsu, Aleksandra Krajewska, Ryan Neufeld, Fumihiko Maeda,
Kazuhide Kumakura, and Hideki Yamamoto
Materials Science Laboratory

Transition metal dichalcogenides (TX_2) belong to a family of two-dimensional layered materials, where adjacent layers are weakly bound by van der Waals forces, like in graphite. These materials offer a large variety of properties, from insulating/semiconducting to metallic ones, depending on the combination of T and X. Among them, we have been focusing on semiconducting $MoSe_2$.

We grew wafer-scale $MoSe_2$ thin films on Se terminated GaAs(111)B substrates using the molecular beam epitaxy (MBE) method. The Scanning transmission electron microscope (STEM) image in Fig. 1 shows that two-monolayer (2L)-thick $MoSe_2$ is grown in a layer-by-layer manner. It also indicates that the $MoSe_2$ layers can climb over the monolayer step of GaAs. Though Fig. 1 shows an STEM image for a double-layer $MoSe_2$, it should be noted that the layer number can be varied with growth time. We carried out Raman spectroscopy measurements and investigated layer number dependence. Figure 2 shows Raman spectra around the A_{1g} peak for single-layer (1L), double-layer (2L), and more-than-four-layer (> 4L) $MoSe_2$ thin films. The spectrum for Se-terminated GaAs is also shown as a reference. According to a previous report on $MoSe_2$ mechanically cleaved from bulk crystal [1], the A_{1g} peak shifts to a higher wavenumber with an increasing number of layers because of multiple interlayer interactions. The A_{1g} peaks in our $MoSe_2$ thin films also show the blue shift (Fig. 2) when the layer number increases. The layer number of our films estimated from the positions of A_{1g} peaks, using reported values for cleaved samples as references [1], well coincides with that directly determined by STEM observation. On the other hand, splitting of the A_{1g} peak is not clearly observed in our film samples, which is in contrast to the cleaved ones with thicknesses of > 3L [1]. The peak splitting originates from the minute difference in vibration frequencies between the in-phase and out-of-phase vibrations and is very sensitive to the layer number [1]. Therefore, the absence of the peak splitting in our films likely stems from a fluctuation of the layer number (±1 layer) due to partial formation of growth nuclei on atomically flat surfaces.

Our results indicate that wafer-scale $MoSe_2$ thin films with a controlled layer number can be prepared by MBE, which is widely used for growth of high-quality thin films of conventional semiconductors. Application of this technique to other TX_2 materials may allow fabrication of heterostructures consisting of various TX_2 materials.

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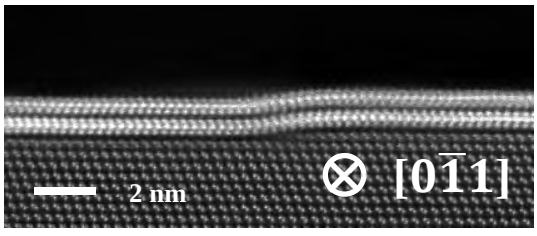

Fig. 1. Cross-sectional STEM image of $MoSe_2$ around a GaAs step. Incident electron beam is parallel to [0$\bar{1}$1] direction. $MoSe_2$ is epitaxially grown on the GaAs(111)B surface.

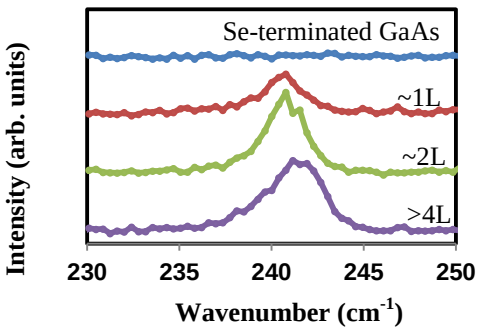

Fig. 2. Layer number dependence of Raman spectra around A_{1g} peak.

Superconducting and Insulating Ground States in La_2CuO_4 Structural Isomers

Yoshiharu Krockenberger and Hideki Yamamoto
Materials Science Laboratory

Superconductivity in cuprate superconductors is associated to a doped Mott insulator scenario and this antiferromagnetic insulating state is considered to be universal. The phase diagram of cuprate superconductors aims at the fundamental comparison of hole- and electron doping into CuO_2 planes. While these CuO_2 planes are, indeed, common among all cuprate superconductors, variations of the coordination of the Cu^{2+} ions are entirely ignored. It is well established that superconductivity is induced by hole doping to the CuO_2 planes with 5- or 6-fold coordinated copper. The induction of superconductivity in cuprates with 4-fold coordinated copper is – against common understanding – not associated to doping but to elimination of defects. Cuprates with 4-fold coordinated copper are metals *per se* and this fact has not been recognized [1]. It would therefore be revealing if one could alter the copper coordination by keeping chemical elements as well as their stoichiometry constant while solely varying the coordination of copper. That is what we did using La_2CuO_4. Molecular beam epitaxy allows to explore thermodynamic synthesis conditions entirely inaccessible by other synthesis methods. In particular, low synthesis temperatures are key. We synthesized La_2CuO_4 with three different copper coordination: 6-fold coordination (T-phase), 5-fold coordination (T*-phase), and 4-fold coordination (T'-phase). All three phases were grown coherently onto $SrLaAlO_4$, $DyScO_3$, and $PrScO_3$ substrates, respectively. Among the three isomers of La_2CuO_4 the T-phase (6-fold coordinated copper) is the thermodynamically stable polymorph and its electronic response is well known. So, it is not surprising that T-La_2CuO_4 is insulating [Fig. 1(a)]. The T*-phase of La_2CuO_4 is, however, a new material as it is not a thermodynamic stable polymorph. So far we shed some light on its electronic response (it is insulating) and magnetic ordering phenomena are currently investigated by low-energy muon spin resonance spectroscopy. The T'-phase of La_2CuO_4 is also only accessible by low-temperature synthesis methods and its electronic response strongly deviates from its isomers. T'-La_2CuO_4 is a superconductor [2, 3].

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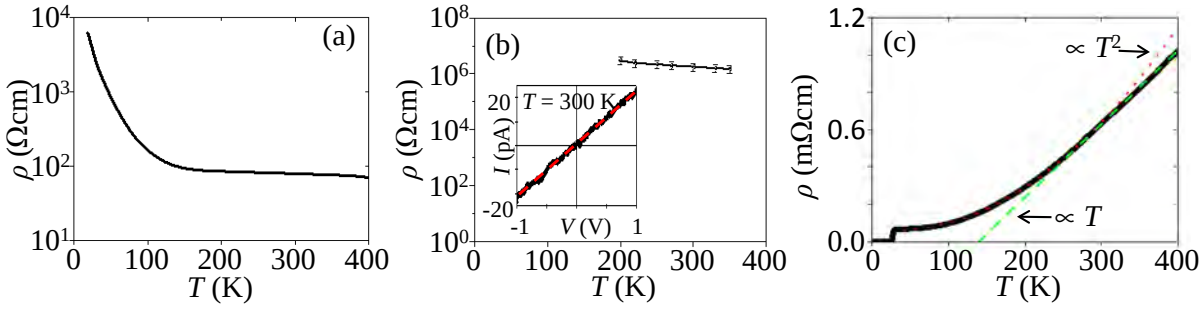

Fig. 1. Temperature dependent resistivity. (a) T-phase La_2CuO_4. (b) T*-phase La_2CuO_4. (c) T'-phase.

Simultaneous Light Emissions from Erbium-Thulium Silicates on Silicon in the Second and Third Telecommunications Bands

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

The increasing demand for small-footprint and cost-effective devices in fiber optical communications links has prompted significant research activity into developing efficient silicon-based lasers. The operating wavelengths of interest are in and neighboring the C-band lines (1530-1565 nm). Some effort has been focused on combining the function of two lasers into one by achieving dual-wavelength emission from separate dopant ions. Dual-band lasers using the emissions of erbium (Er) and other neighboring ions such as Tm, Nd, Yb and Ho in glasses have been reported. However, there are few reports on the co-doping of Er and Tm into crystalline hosts for realization of broadband optical waveguide amplifiers and dual-wavelength light emitters on silicon in the telecommunications bands.

We succeeded in observing sharp light emissions from Tm^{3+} ions in the wavelength regions of 1300 and 1470 nm and from Er^{3+} ions at 1530 nm from a mixture of polycrystalline $Er_{2x}Tm_{2-2x}SiO_5$ and $Er_{2x}Tm_{2-2x}Si_2O_7$ formed on Si [1]. We demonstrated that Er^{3+} ions in the mixed compounds act as not only 1530 nm wavelength light emitters but also as effective sensitizers to the 1300 nm wavelength light emissions from Tm^{3+} ions (Fig.1). The resonant energy transfers between higher energy levels of Er^{3+} and Tm^{3+} ions play an important role in the simultaneous sharp light emissions in O and S+C bands when excited with λ_{exc} = 532 nm (Fig. 2). Additionally, we demonstrated the dual-wavelength sharp light emissions in the S and C bands at λ_{exc} = 785 nm.

A future objective of this work will be the deeper understanding and optimization of the mixture formation on silicon and the lifetime measurements of the light emissions, which is important for obtaining high-quantum-efficiency dual-wavelength light emitters in the telecommunications bands.

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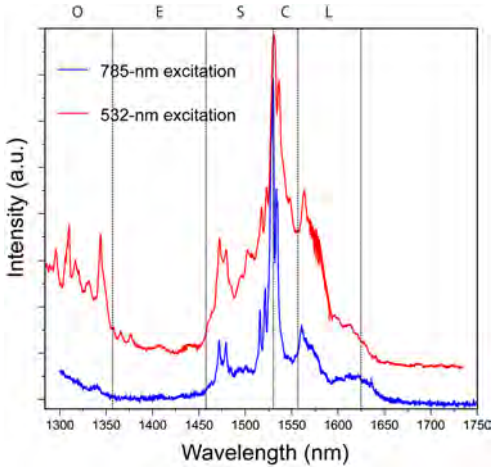

Fig. 1. Wavelength excitation dependence of PL spectra from Er-Tm silicates.

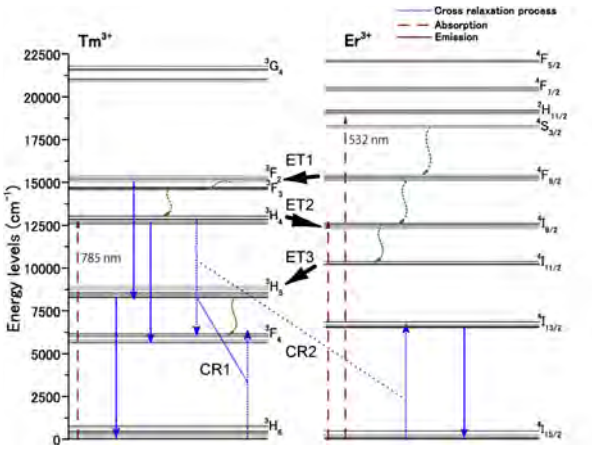

Fig. 2. Energy diagrams and possible transitions between Er^{3+} and Tm^{3+} ions in Er-Tm silicates.

Raman Spectroscopic Visualization of Topological Defects in Chemical Vapor Deposition-Grown Graphene by Isotope Labeling

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

In the past decade, chemical vapor deposition (CVD) growth of graphene has been emerged as a promising route to scale up the fabrication of graphene-based applications [1]. However, the CVD graphene samples are always polycrystalline, composed of single-crystalline domains having various in-plane rotations and related topological defects. These topological defects, especially grain boundaries, dominate the electrical and mechanical performance of large-scale CVD-grown graphene. Thus, an efficient method for elucidating the topological structure in CVD graphene is important for its fundamental research and potential technological applications in nanoelectronics and related fields.

Here, for the first time we demonstrate an isotope labeling method to identify the topological defects in CVD-grown graphene by micro-Raman spectroscopy [2]. In a stepwise CVD process, the hydrogen and isotopic carbon sources are sequentially introduced after the standard growth of full-coverage monolayer graphene. Owing to the dual role of hydrogen in the catalytic reaction of graphene growth, the surface exchange of ^{12}C-^{13}C atoms occurs on a heated copper substrate. Taking the advantages of the distinct phonon energy between ^{12}C and ^{13}C lattice, we observed the coexistence of ^{12}C- and ^{13}C-graphene in an isotope-labeled graphene sample by Raman spectroscopy [Fig. 1(a)]. Moreover, as Fig. 1(b) shows, the ^{13}C-rich regions form a pronounced network-like structure, isolating the ^{12}C-graphene regions into micrometer-sized islands. The Raman characteristics of isotope-labeled graphene indicate that the carbon atom substitution is energetically favored along the grain boundaries of polycrystalline CVD graphene, which is further evidenced by low-energy electron microscopy (LEEM) characterization [Fig. 1(c)]. The carbon isotope labeling method provides a facile and effective way to characterize the topological defects in CVD-grown graphene, and also gives new insight for understanding the growth mechanism of graphene on copper catalyst.

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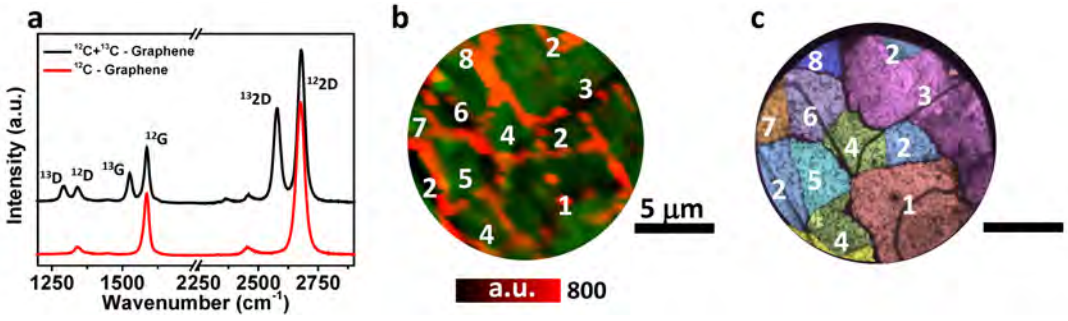

Fig. 1. (a) Raman spectra from coexistence area of ^{12}C- and ^{13}C- graphene and area of pure ^{12}C-graphene in an isotope-labeled graphene sample. (b) Raman ^{13}C-2D intensity mapping of an isotope-labeled graphene sample. (c) Color-coded dark-field LEEM image of the sample in (b). The different color and number shows the various lattice orientations of grains with different shapes.

On-Chip FRET Graphene Aptasensor for Multiple Protein Detection

Yuko Ueno and Kazuaki Furukawa
Materials Science Laboratory

Graphene and its chemical derivatives behave as efficient acceptors for fluorescence resonance energy transfer (FRET) between a graphene surface and dye molecules located close to it. This makes graphene a promising material for realizing a unique type of biomolecular interface for visualizing an invisible biological response to a measurable physical quantity such as fluorescence. We have successfully demonstrated a graphene oxide (GO) aptasensor for selective and highly sensitive protein detection. We realized this sensor by modifying the GO surface with a pyrene-aptamer-dye probe that we developed. The segments work as a linker to the GO surface, a protein recognition part, and a fluorescence detection tag, respectively [Fig. 1 (left)] [1]. The system allows us to perform molecular detection on a solid surface, which is a powerful tool for realizing an on-chip sensor, and especially for forming a multichannel configuration and for micropatterning probes [2, 3]. The on-chip sensor allows us to evaluate the sensor response quantitatively by using one of the channels/patterns as an internal standard.

Aptamers offer many advantages as molecular recognition probes because they are chemically stable and have a wide variety of targets. We confirmed the versatility of the GO aptasensor through the detection of three different proteins, namely, thrombin, prostate specific antigen (PSA), and hemagglutinin, simply by changing the aptamers but with the sensor composition remaining the same. We also demonstrated the simultaneous detection of multiple proteins, thrombin and PSA, on a single chip by using a multichannel linear-array GO aptasensor [Fig. 1 (right)] [3]. Another attractive feature of aptamers is that they can be flexibly designed without loss of activity. We designed a biomolecular probe for highly sensitive protein detection by modifying an aptamer with a DNA spacer. The spacer controls the distance between a fluorescence dye and a quencher, which is crucial for FRET-based sensors. We successfully demonstrated an improvement in the sensitivity of an on-chip GO aptasensor [2]. Our findings will advance the field of on-chip microsensors.

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[2] Y. Ueno et al., Chem. Commun. **49**, 10346 (2013): Featured on cover.
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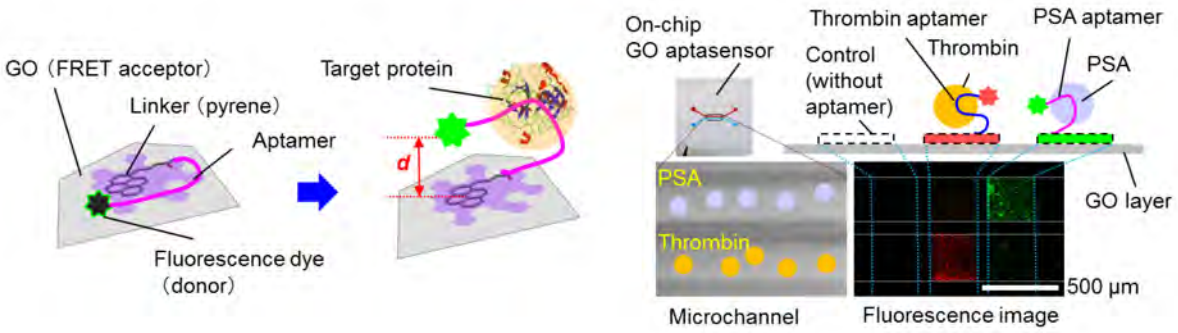

Fig. 1. (Left) Design of a protein recognition system of GO FRET aptasensor.
(Right) Demonstration of multiple protein detection on a single chip.

Formation of a Suspended Lipid Membrane on a Microcavity Covered by a Thin SiO_2 Layer with a Nanohole Array

Aya Tanaka[1], Yoshiaki Kashimura[1], Eiichi Kuramochi[2], and Koji Sumitomo[1]
[1]Materials Science Laboratory, [2]Optical Science Laboratory

By fusing nanotechnology and biotechnology, we aim to fabricate a nanobiodevice that works with membrane proteins on a Si substrate. We succeeded in fabricating a microcavity array sealed with a lipid bilayer on a Si substrate for analyzing ion channel activity [1]. However, it is essential that we improve the lifetime of the nanobiodevice. In this study, we fabricated microcavities on a Si/SiO_2 substrate covered by a thin SiO_2 layer with nanohole arrays that we call a "pepper shaker substrate" [2].

The nanohole arrays were fabricated in a thin SiO_2 layer on a Si substrate using an electron beam lithography and dry etching technique. The Si substrate beneath the SiO_2 overlayer was selectively etched through the nanohole arrays with a KOH aqueous solution, and this resulted in the formation of a microcavity covered by a thin SiO_2 layer with a nanohole array as shown in Fig. 1. The microcavity volume was made comparable to that of a living neuron or synapse by choosing suitable etching conditions. The nanohole diameter (100 nm) was similar to the domain size of a cell membrane supported by cytoskeletons. The total area of the lipid membrane suspended over a nanohole array was kept large enough for the insertion of membrane proteins, although the area of a single nanohole was small. Figure 2 shows fluorescence images of a lipid membrane patch on a pepper shaker substrate. Calcein fluorescence [Fig. 2(b)] was observed at the microcavity where fluorescence from the lipid patch [Fig. 2(a)] was observed (for example, white arrow A). There were more than 100 nanoholes in each microcavity. If even one of the lipid membranes sealing the nanoholes were broken, fluorescent probes would flow out (white arrow B). Nevertheless, the small diameter of the nanoholes makes the suspended lipid membrane more stable, and almost all the microcavities were successfully sealed. This stabilization also increases the lifetime of the nanobiodevice. We confirmed that the green fluorescence was still confined in the microcavities after 10 days.

The stable sealing of the microcavities allows us to reconstitute and analyze membrane proteins embedded in suspended lipid membranes using fluorescence microscopy, AFM, and electrophysiology. We believe that this system could be employed for mimicking and studying the behavior of biological systems.

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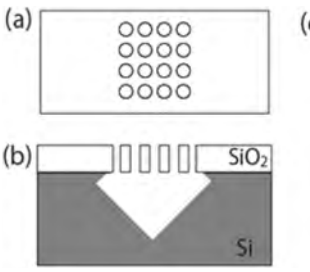
[2] A. Tanaka et al., Appl. Phys. Express **7**, 017001 (2014).



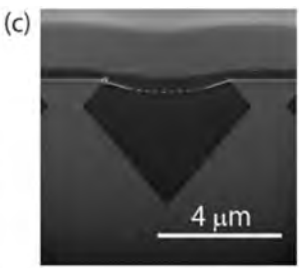


Fig. 1. Schematic illustration of a pepper shaker substrate. (a) Top view and (b) cross-sectional view. (c) SEM image of microcavity cross-section.

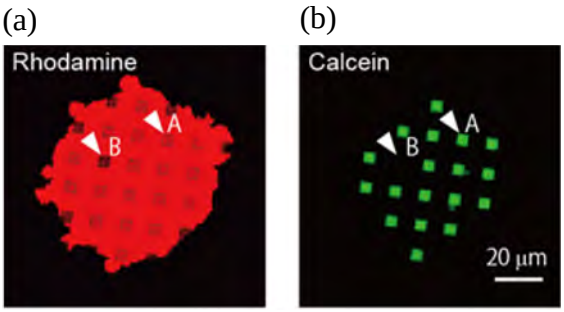


Fig. 2. Fluorescence images of pepper shaker substrate after rupture of GUVs. (a) Lipid membrane. (b) Calcein confined in microwells.

Cross-Sectional SEM Observation of the Interface between a Neuron and a Conductive Material

Toichiro Goto, Nahoko Kasai, and Koji Sumitomo
Materials Science Laboratory

Recently, neuron-nanostructure integrated devices have been attracting a lot of interest in relation to understanding signal transfer mechanisms. In such devices, signals from single neurons, e.g., neuron action potentials, are transmitted extracellularly via conductive materials, and hence the interface between single neurons and conductive materials plays an important role. However, there have been few investigations of this interface because of the difficulty involved in direct and high-resolution observation with conventional optical microscopy. We employed a focused ion beam (FIB)/SEM combined system, which enabled the cross-sectional observation of neurons cultivated on the surfaces of conductive materials. We also examined the relationship between the interface structure and neuron-substrate affinity by using fluorescence microscopy.

Neurons were prepared from rat cortex and cultivated on two types of conductive thin films: indium tin oxide (ITO) and Ti. The cultivated neurons were immunostained and observed with a fluorescent microscope. For the FIB/SEM experiments, the cultivated neurons were dehydrated, fixed and finally freeze-dried. Figures 1 (a) and (b) are fluorescence images of the neurons on ITO and Ti, respectively. On the ITO surface, somas tend to aggregate and dendrites grow linearly, indicating the low affinity between neurons and ITO. In contrast, on a Ti surface, very little soma aggregation or straight dendrite growth is observed, implying a high affinity between neurons and Ti. Figures 1 (c) and (d) are cross-sectional SEM images of single neurons on ITO and Ti surfaces, respectively. Although the neurons hardly make contact with the ITO surface as indicated by the wide interspace between the neurons and the ITO, they come into close contact with the Ti surface. These results obtained in fluorescence and FIB/SEM experiments indicate that Ti has the higher biocompatibility.

Our approach allowed high-resolution observation of the interface between single neurons and substrates, which will provide important implications for the control of neuron growth, leading to a quantitative analysis of the neuronal signals from neuron-nanostructure integrated devices.

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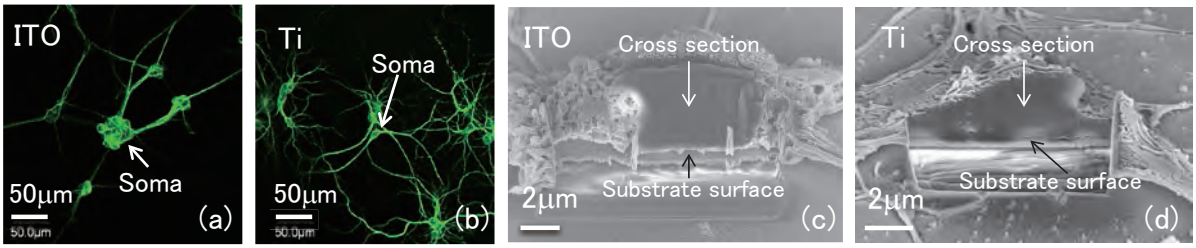

Fig. 1. Fluorescence images of neurons on (a) ITO and (b) Ti thin films. Cross-sectional SEM images of single neurons on (c) ITO and (d) Ti thin films.

Platform for Low Noise Biosensors Using Microwells Sealed with Lipid Bilayers

Yoshiaki Kashimura and Koji Sumitomo
Materials Science Laboratory

A sealed microwell with a lipid bilayer is a promising candidate for constructing artificial cells. If channel proteins can be incorporated into the membrane, their functional properties can be detected using electrophysiological or microscopic techniques. We have fabricated microwell structures sealed with lipid bilayers on a Si substrate, and succeeded in observing Ca^{2+} ion transport through α-hemolysin channels with fluorescent microscopy [1]. However, ion leakage through the water layer between the lipid bilayer and the substrate poses a problem when we try to achieve a low-noise biodevice. Here we present a newly designed microwell structure that uses a self-assembled monolayer (SAM) on a Au surface to prevent ion leakage from/into the microwells [2].

Figure 1 shows the device structure used in this study. We fabricated microwells with a slightly offset Au ring [Fig. 1(a)]. An octadecanethiol SAM was formed on the Au surface. The microwells were filled with calcein or Ca^{2+} indicators (fluo-4) and then sealed with lipid bilayers by rupturing giant unilamellar vesicles. Figure 1(b) shows a fluorescence image of a sealed microwell, in which calcein is confined. There is no fluorescence on the Au ring due to the energy transfer between the dyes and gold. Fluorescence recovery after photobleaching observation revealed that lateral fluidity is maintained across the Au ring. This result supports the structural geometry predicted in Fig. 1(c). Figure 2 shows the time course of the fluorescence intensity of fluo-4 confined in the microwells when $CaCl_2$ solution was added to the outer solution. Unmodified substrates (without a Au ring) caused a significant increase in the fluorescence intensity within 20 min. However, with a modified substrate (with a Au ring), there was no increase in fluorescence intensity during the observation time. By separating the microwells and the outer regions, we can effectively reduce ion diffusion through the water layer. We estimated the membrane resistance with a view to realizing the electrophysiological detection of channel protein activity. The membrane resistances for the modified microwells were one order higher than those of the unmodified microwells, leading to a reduction in the background noise. The improved membrane resistance and background noise for the modified microwells resulted from the reduction in ion leakage. The device structure used in this study has the potential to provide a platform for measuring the very low signal-to-noise ratios of channel proteins.

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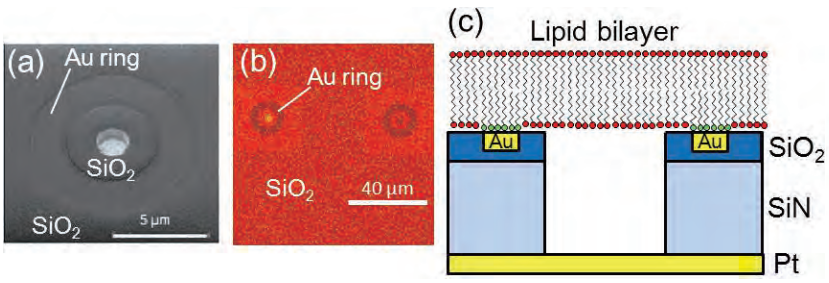

Fig. 1. (a) SEM image of the Au ring substrate. (b) Fluorescence image of a sealed microwell. (c) Schematic illustration of the modified microwell sealed with a lipid bilayer.

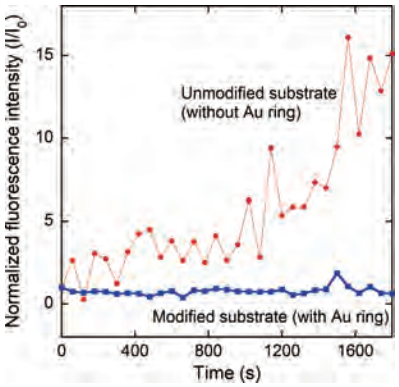

Fig. 2. Change in fluorescence intensity from fluo-4 confined within microwells as a function of time.

Deviation from the Law of Energy Equipartition in a Small Dynamic-Random-Access Memory: Analysis about Thermal Noise with Single-Electron Resolution

Katsuhiko Nishiguchi, Pierre-Alix Carles, and Akira Fujiwara
Physical Science Laboratory

The performance of integrated circuits used in a range of electronic devices has been improved by downsizing transistors in the circuits. Such downsizing, however, increases the noise-related degradation of circuit performance, and the importance of an analysis of noise with single-electron resolution has therefore been growing. Indeed, random telegraph noise originating from single-electron trapping in a transistor gives rise to errors in memory circuits composed of small transistors. In this work, using a dynamic random access memory (DRAM), we demonstrate an analysis of thermal noise, one of the most fundamental noises in electronic devices, with a single-electron resolution.

For the analysis, the DRAM is combined with a charge sensor based on a transistor [Figs. 1(a) and (b)]. Since this sensor has charge sensitivity of single-electron resolution, the number of electrons in the capacitor of the DRAM can be counted. The output signal from the sensor [Fig. 1(c)] indicates that single electrons enter and leave the capacitor randomly and thus the number of electrons in the capacitor fluctuates, which is exactly single-electron thermal noise. Using the characteristics of the sensor, we can convert the fluctuation of the number of electrons into voltage fluctuation. It is well known that according to the law of energy equipartition in which each electron has thermal energy $k_BT/2$ on average, a variance V_{var}^2 of voltage fluctuation can be given by k_BT/C, where k_B is the Boltzmann constant, T temperature, C capacitance. Figure 2 shows the change in V_{var}^2 as a function of C. While V_{var}^2 is close to k_BT/C at C > 10 aF, C smaller than 10 aF causes a deviation between V_{var}^2 and k_BT/C. When charging energy E_C (= $e^2/2C$) for injecting one electron into the capacitor is smaller than thermal energy $k_BT/2$, the thermal energy helps electrons in enter and leave the capacitor, which means that k_BT/C or the law of energy equipartition is satisfied. On the other hand, when $E_C > k_BT/2$ at smaller C, the thermal energy is not large enough to help electrons in enter and leave the capacitor, which leads to smaller V_{var}^2. Additionally, voltage V applied to the DRAM can adjust the energy for injecting and rejecting one electron to be zero. This allows even small thermal energy to help one electron to enter and leave the capacitor, which makes V_{var}^2 larger than k_BT/C. These features at $E_C > k_BT/2$ represent a deviation from the law of energy equipartition. Since our demonstration is carried with DRAM of very small size, our results are very important for all electronic devices with small dimensions.

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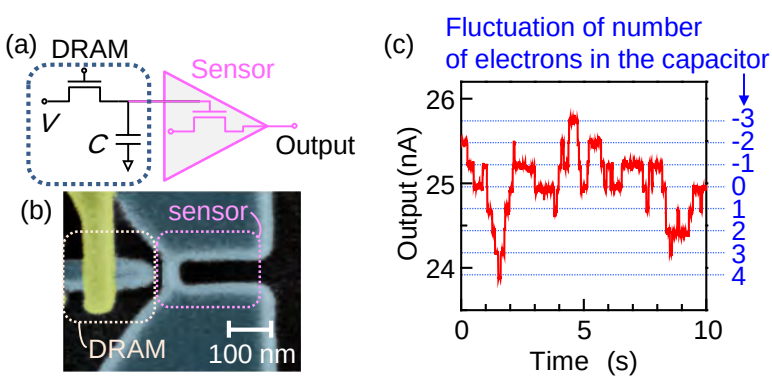

Fig. 1. (a) Equivalent circuit and (b) scanning electron microscope image of the device. (c) Single-electron detection.

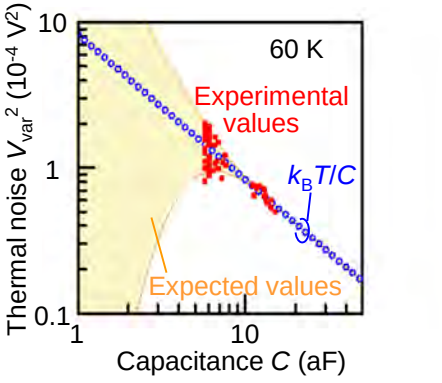

Fig. 2. Change in thermal noise as a function of capacitance C.

Electric Tuning of Direct/Indirect Optical Transitions in Silicon

Jinichiro Noborisaka, Katsuhiko Nishiguchi, and Akira Fujiwara
Physical Science Laboratory

Bulk silicon has an indirect band gap and a multiple degenerate valley structure in the conduction band. Since photons do not carry significant momentum and a dipole transition requires momentum conservation, a direct optical transition is not allowed in bulk silicon. Here we demonstrate electric tuning of direct/indirect optical transitions with specially prepared Si/SiO_2 interfaces [1], where the valley splitting is tuned by a gate electric field and its value is at least one order of the magnitude larger than that at an ordinary metal oxide semiconductor (MOS) interface [2]. For conventional Si MOS interfaces, the valley splitting is well explained by the extended zone effective mass theory [3], where real space confinement causes valley interaction. By extending this theory, it is expected that the valley splitting will lead to phononless direct optical transitions in Si. We therefore anticipate that the direct optical transition is significant and it can be controlled by the gate electric field in the interface with the large valley splitting.

Devices are Si MOS field effect transistors with 4.3- or 6-nm-thick Si quantum well (QW) fabricated on SIMOX (separation by implantation of oxygen) (001) wafer annealed at 1350 °C for 40 hours. It is known that large valley splitting appears when electrons are squeezed to the buried oxide interface of SIMOX. Heavily doped p- and n-type contacts are formed in order to inject holes and electrons into a channel (Fig. 1). The front (FG) and back gate (BG) control the distribution of both carriers in the Si QW. Figure 2 shows typical electroluminescence (EL) spectra at various back-gate voltages (V_{BG}). For $V_{BG} < 0$, an indirect TO phonon mediated optical transition dominates the EL spectra, where the valley splitting (2Δ) is at most several mili-electron volts. In contrast, for $V_{BG} > 0$, the EL intensities of phononless direct optical transition (NP) become dominant with increasing V_{BG}. The intensity ratio of NP to bulk NP (the NP intensity at $V_{BG} = 0$ V for the device with thicker QW) reached 800 at $V_{BG} = 80$ V, where the valley splitting is estimated to be 30 meV. Thus we demonstrate electric tuning of direct/indirect optical transitions in Si just by changing gate voltage.

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

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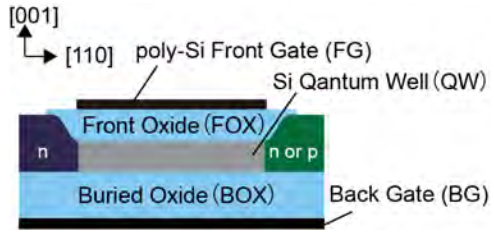

Fig. 1. Device structure.

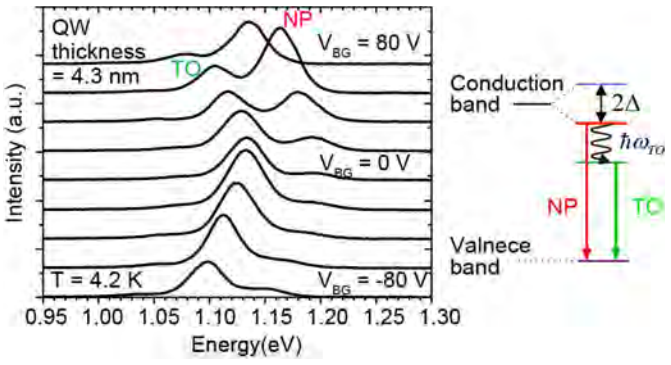

Fig. 2. Electroluminescence spectra.

High-Speed Single-Electron Transfer via a Single Trap Level in Si

Gento Yamahata, Katsuhiko Nishiguchi, and Akira Fujiwara
Physical Science Laboratory

Single-electron (SE) transfer is a technique for accurately conveying an SE in synchronization with a clock signal, which is expected to be applied to a current standard and to low-power-consumption information processing. For the current standard, high-speed operation (more than gigahertz) with an error rate below 10^{-8} is necessary. While SE transfer using an electrically formed quantum dot has been widely studied, SE transfer using a trap level with a large activation energy is expected to have higher accuracy. However, the possibility of high-speed trap-mediated SE transfer is not obvious. Here, we report the achievement of high-speed SE transfer at 3.5 GHz using a trap level in Si [1].

Figure 1(a) shows a schematic of the device. Double-layer polycrystalline-Si gate electrodes on a Si wire with a width of a few ten nanometers were formed using electron beam lithography. Each lower gate (G1, G2) is used to form a potential barrier in the Si wire. The upper gate is used to modulate the potential between G1 and G2. We selected a device that has a single trap level (most likely an interface trap) under the right edge of G1 and measured SE transfer current via the trap level at 17 K. To perform the SE transfer, we modulate a potential barrier by applying a high-frequency signal (frequency f) to G1, with a fixed negative voltage applied to G2 to create another potential barrier [Fig. 1(b)]. An SE is captured by the trap level from the source when the barrier under G1 is low. After that, when the barrier under G1 is high, the captured SE is emitted to the drain. This results in a transfer current level of ef (e is the elementary charge). Detailed measurements reveal that the capture and emission can become fast by lowering the barrier height under G1 during the capture phase and by applying a strong electric field at the trap level during the emission phase, respectively. This can be achieved when the high-frequency signal has a large amplitude. Under this condition, we achieved high-speed operation at 3.5 GHz [Fig. 1(c)], in which the transfer error rate is below the level that can be measured using a commercial current meter (~ 10^{-3}). Theoretically, we found that 1-GHz operation with an error rate below 10^{-8} may be possible. In the future, we will evaluate the absolute accuracy [2] of the trap-mediated SE transfer to realize high-accuracy and high-speed SE transfer toward application to the current standard.

This work was partly supported by the Funding Program for Next Generation World-Leading Researchers of JSPS (GR 103).

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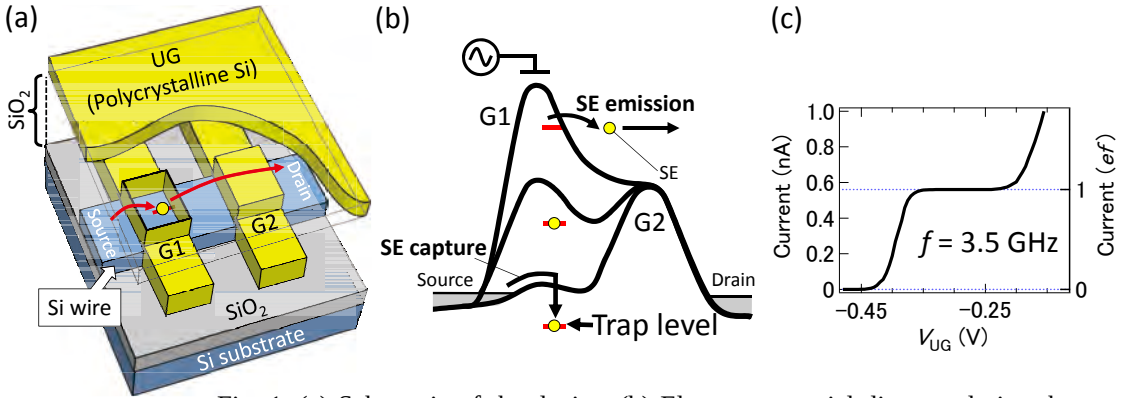

Fig. 1. (a) Schematic of the device. (b) Electron potential diagram during the trap-mediated transfer. (c) High-speed trap-mediated SE transfer (T = 17 K).

Dynamic Control of Phonon Vibrations in a One-Dimensional Phononic Crystal

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[1]Physical Science Laboratory, [2]Materials Science Laboratory

Phononic crystals (PnCs) are one of the most promising candidates for controlling phonon propagation [1]. The periodically modulated elastic structure of the PnC can sustain a phonon bandgap that enables the transmission of phonons such as sound, mechanical vibration, and even heat to be spatially controlled. This ability to control phonons has led to the concept of a novel phononic system in which information signals encoded in phonons can be processed. The key challenge to realizing this tantalizing prospect is the dynamic control of the phonons in the PnC, whereas to date, almost all PnC devices reported have been passive structures. To overcome this limitation, we have developed a unique class of PnCs via electromechanical resonators and have demonstrated dynamically controlled phonon vibrations [2].

The PnC waveguide (WG) consists of a one-dimensional array of GaAs/AlGaAs-based membrane resonators as shown in Fig. 1(a) which are suspended via the periodically arranged air-holes. At the center of the WG, a control mechanical resonator is created by increasing the air-hole separation to the adjacent membranes. Applying an alternating voltage with 5.74 MHz to the electrode on the right edge membrane can piezoelectrically excite phonon waves which travel down to the WG through the control mechanical resonator and are optically measured at the left edge membrane [dashed line in Fig. 1(b)]. Simultaneously, the control mechanical resonator is excited at 1.86 MHz which generates a localized phonon vibration. The strongly confined phonons in the control mechanical resonator induce a nonlinear elastic effect that causes the WG's transmission spectrum to shift to higher frequencies, resulting in the suppression of the phonons at 5.74 MHz [solid line in Fig. 1(b)].

The electromechanical resonator based PnC WG permits the phonon transmission to be dynamically controlled which opens up the possibility of developing highly functional signal processing systems utilizing mobile phonons.

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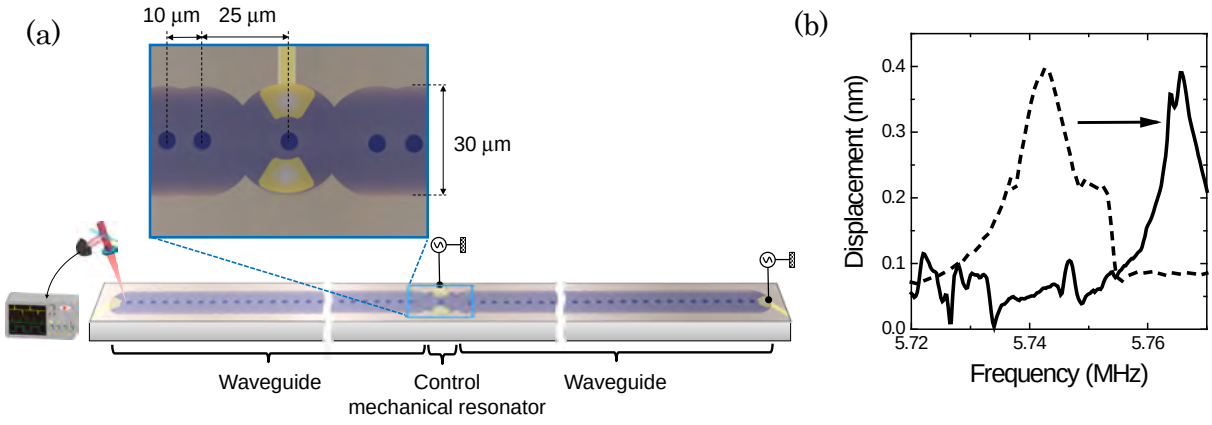

Fig. 1. (a) The control mechanical resonator-embedded one-dimensional PnC measured at room temperature and in a high vacuum. (b) WG's transmission switching via control mechanical resonator.

Two-Mode Squeezing in an Electromechanical Resonator

Imran Mahboob, Hajime Okamoto, and Hiroshi Yamaguchi
Physical Science Laboratory

The widespread availability of quantum entanglement with photons, in the guise of two-mode squeezed states, can be attributed to the phenomenon of parametric down-conversion. A reinterpretation of this effect with macroscopic mechanical objects can offer a route towards a purely mechanical entanglement and the unique possibility of probing the quantum mechanical nature of our everyday classical world. In spite of this prospect, mechanical two-mode squeezed states have remained elusive due to the inability to recreate the nonlinear interaction at the heart of this phenomenon in the mechanical domain.

To address this we have developed a non-degenerate parametric down-converter, in a mechanical resonator integrated with electrical functionality, which enables mechanical nonlinearities to be dynamically engineered to emulate this interaction [1]. In this configuration, phonons are simultaneously generated in pairs in two macroscopic vibration modes which results in the amplification of their motion by more than 20 dB. In parallel, mechanical two-mode squeezed states are also created which exhibit fluctuations 5 dB below the thermal level of their constituent modes as well as harbouring correlations between the modes that become almost perfect as their amplification is increased. This remarkable observation of correlations between two massive phonon ensembles paves the way towards an entangled macroscopic mechanical system at the single phonon level.

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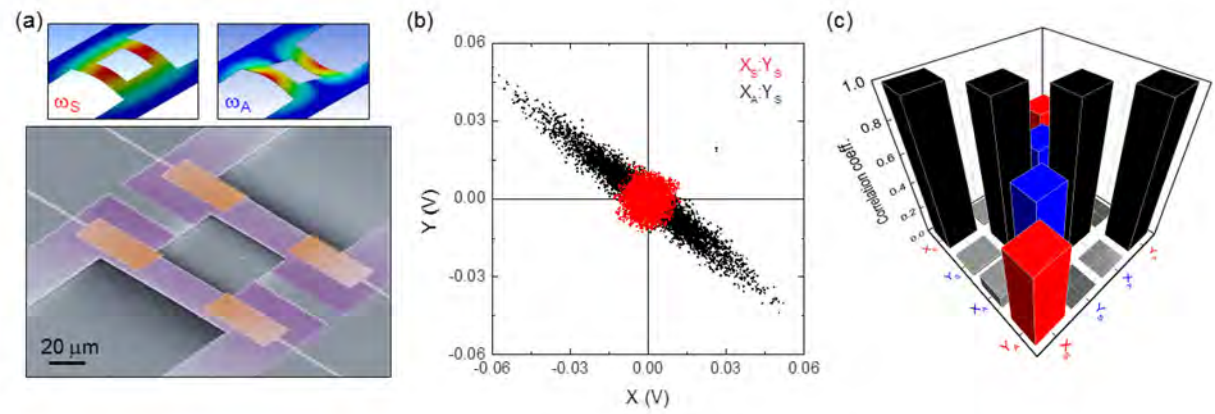

Fig. 1. (a) An electron micrograph of the coupled GaAs based electromechanical resonator, sustaining a symmetric (S) and an asymmetric mode (A), whose profiles extracted from a finite element analysis are also depicted. The mechanical elements are integrated with piezoelectric transducers that can induce tension and parametrically modulate the spring constant. (b) The thermal Langevin force driven motion of the symmetric X_S:Y_S (red points) and asymmetric X_A:Y_A (not shown) modes yield a circular distribution in phase space indicating their uncorrelated random nature. Piezoelectrically activating the non-degenerate parametric down-conversion, at the sum frequency of both modes ($\omega_S+\omega_A$), results in two-mode squeezing which can be observed in the cross-quadratures namely X_A:Y_S (black points) and X_S:Y_A (not shown). (c) The two-mode squeezed state corresponds to the fluctuations in both modes becoming correlated which can be readily observed via the non-zero off-diagonal elements in the corresponding Pearson correlation coefficient matrix.

New Approach for a Long-Lived Quantum Memory

Xiaobo Zhu[1], Yuichiro Matsuzaki[1], Robert Amsüss[1,3],
Kosuke Kakuyanagi[1], Takaaki Shimo-Oka[4], Norikazu Mizuochi[4], Kae Nemoto[5],
Kouichi Semba[1,5], William J. Munro[2], and Shiro Saito[1]
[1]Physical Science Laboratory, [2]Optical Science Laboratory,
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A hybrid approach to couple different quantum systems is considered as a promising way to realize quantum computation, because such an approach has a potential advantage to combine the best properties of each system. One of the attractive hybrid approaches is to use a superconducting flux qubit and a spin ensemble in diamond [1-3]. The former system plays a role of a processor while the latter system is useful for a memory. In this hybrid system, an unknown long-lived state was observed [1, 2]. Although this long-lived state has a potential application for a memory, there was no theoretical explanation why the long-lived system was observed, which made it difficult to use this state for quantum computation.

We have found the mechanism how the state was so-long-lived, and have shown that this is an evidence of a dark state in the diamond [4]. A dark state has a destructive interference so that the signal from this state should be significantly suppressed. However, we theoretically show that, in this hybrid system, magnetic fields and strain variations decrease the effect of the destructive interference, which leads to a detectable signal from the dark state. We experimentally show that the lifetime of the dark state was around 150 ns [4], which is much longer than the previously observed lifetime of 20 ns in the diamond [3].

Since we understand the origin of this long-lived state, our results open a new way to realize a quantum memory for the storage of information by using this dark state. If such a quantum memory is realized, we can reduce the resource and cost for quantum computation to provide us with ultra-fast calculation. This work was supported by FIRST and NICT.

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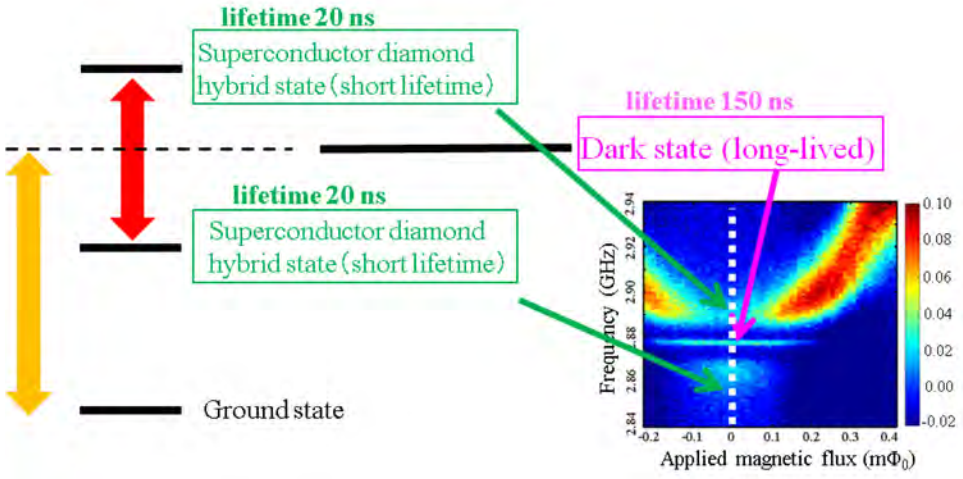

Fig. 1. Energy diagram and spectroscopy of the superconductor diamond system. A sharp peak is observed between the broader peaks. The former one denotes a long-lived dark state while the latter one corresponds to a short-lived state that was observed before.

Resonant Edge Magnetoplasmons and Their Decay in Graphene

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[4] Tokyo Institute of Technology

In quantum Hall states, which appear in two-dimensional systems under perpendicular magnetic field, current flows along sample edge. The edge channels provide unique one-dimensional systems to perform a variety of quantum transport experiments. Edge magnetoplasmons (EMPs) are collective charge excitations in the edge channels. Investigation of EMP properties, in particular, the decay mechanism is essential to obtain robust quantum effects in such systems. In this work, we show the dispersion relation and dissipation mechanisms of EMPs in graphene [1].

We prepared graphene by thermal decomposition of SiC. The samples used have disk shaped graphene. High-frequency transmission between two electrodes, which couple to graphene only capacitively, was investigated in frequency and time domains [Fig. 1(a)]. The dispersion relation of EMPs obtained by the frequency-domain measurement is nonlinear due to carrier interactions [Fig. 1(b)]. The velocity, which corresponds to the slope of the dispersion relation, is 1.7×10^6 m/s for smaller wave number, consistent with that obtained by time-of-flight measurement [2]. This value is larger than the Fermi velocity in graphene (10^6 m/s), demonstrating that charges propagate in collective modes, that is, EMPs. The EMP decay time is directly obtained by the time-domain measurement [Fig. 1(c)]. From its frequency and temperature dependence, EMP dissipations are found to be caused by capacitive and resistive couplings to localized states in the bulk graphene. We suggest that, owing to the linear band structure and the strong edge confinement, EMP dissipation in graphene can be lower than that in GaAs systems. Our results encourage using graphene for quantum transport experiments and plasmonic applications.

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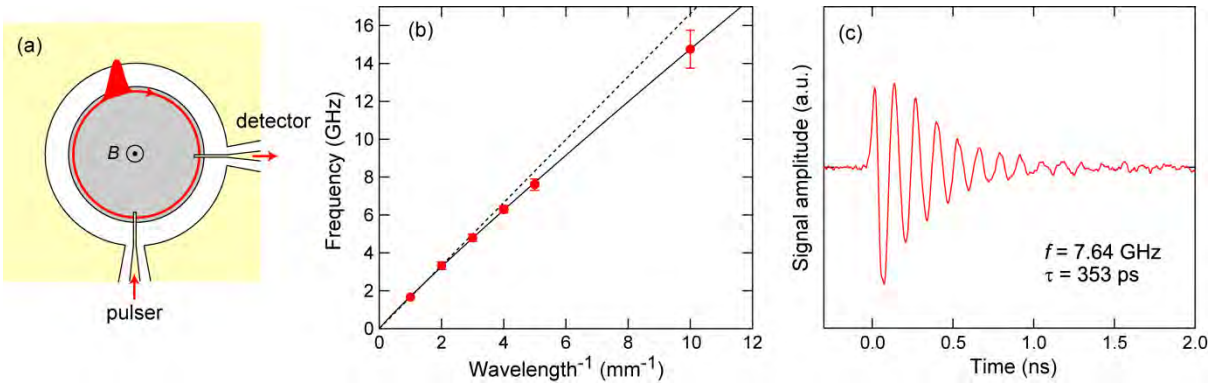

Fig.1. (a) Device structure. Graphene is circular shaped with the perimeter of 200 or 1000 μm. Two high-frequency lines to inject and detect EMPs are capacitively coupled to graphene. (b) Dispersion relation of EMPs determined by frequency domain measurement. The temperature is 4 K and the magnetic field is 10 T. (c) Example of time domain measurement. Motion along the circular path with decay of EMPs is recorded as a function of time.

Josephson Coupling in Semiconductor/Superconductor Hybrid Quantum Point Contacts

Hiroshi Irie[1], Yuichi Harada[1], Hiroki Sugiyama[2], and Tatsushi Akazaki[1]
[1]Physical Science Laboratory, [2]NTT Device Technology Laboratories

The conductance of a ballistic point contact linking two reservoirs at thermal equilibrium is quantized in multiples of the conductance quantum $2e^2/h$. The origin of this phenomenon is the quantization of the transverse momentum in the narrow constriction. Intriguingly, the conductance of the contact remains finite even though no scattering is assumed at the constriction. This raises the question as to what happens if we replace the reservoirs with superconductors. This question was answered by Beenakker and van Houten a few years after the discovery of the conductance quantization [1]. They theoretically analyzed a superconducting quantum point contact (SQPC) made of a smooth and impurity-free superconducting constriction, and showed that superconducting Josephson current flows up to $e\Delta/\hbar$ (Δ: superconducting gap) per quantized mode. Even more than 20 years after the theoretical prediction, there have been only a limited number of reports on its experimental verification [2]. In this work, we study a semiconductor/superconductor hybrid QPC that exhibits staircase variation of the Josephson critical current I_c with respect to the number of quantized mode n, which provides a compelling evidence of the quantization of I_c [3].

The hybrid QPC consists of a QPC formed in a high-In-content $In_{0.75}Ga_{0.25}As$ two-dimensional electron gas (2DEG) and two Nb electrodes in the vicinity of the QPC [Fig. 1]. Josephson coupling is attained via Andreev reflection of Bogoliubov quasiparticles confined in the 2DEG. The transport properties of the quasiparticles, and hence the Josephson junction characteristics, can be controlled by means of the external electric field from a gate electrode. Figure 2 shows the gate voltage V_g dependence of I_c measured at 20 mK. I_c shows a clear stepwise variation as n changes with V_g, demonstrating a Josephson coupling through the quantized mode. The experimental value of I_c per mode is 10.3 nA, which is one order of magnitude smaller than the theoretical value of 125 nA. This discrepancy is accounted for by the presence of a proximity layer having smaller Δ at the InGaAs/Nb interface. The suppressed stepheights for n = 1 and 2 are caused by the finite temperature effect. From those observations, we experimentally prove the quantization of Josephson current and demonstrate a single-channel SQPC for the first time.

This work was supported by KAKENHI.

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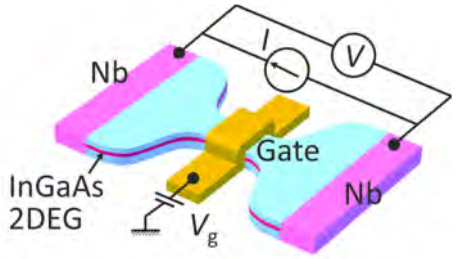

Fig. 1. Hybrid quantum point contact.

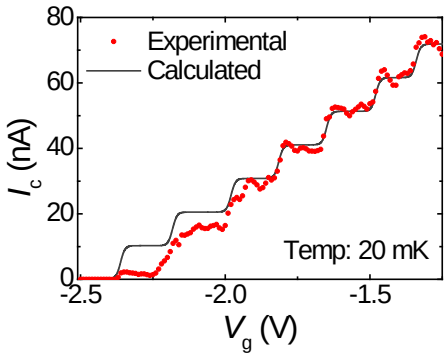

Fig. 2. Quantization of the Josephson critical current.

NMR Probing of Wigner Solids in High Magnetic Fields

Trevor David Rhone[1,2], Lars Tiemann[1,2], Naokazu Shibata[3], and Koji Muraki[1,2]
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In two-dimensional electron systems subject to strong magnetic fields, various quantum phases emerge due to electron interaction. While it is believed that electrons form Wigner solids in the low filling factor regime, where the sequence of fractional quantum Hall states terminates, experimental evidence for Wigner solids has been limited to microwave absorption measurements which show the presence of pinning-mode resonances characteristic of a solid. Here we focus on another defining feature of a solid - translational symmetry breaking. We use NMR to probe on a nanometer scale the spatial variation of probability density resulting from electron solidification, and to obtain microscopic information including the spatial extent of lattice electrons [1].

Figure 1 shows the filling factor dependence of longitudinal resistance and resistively detected NMR spectra of ^{75}As taken at various filling factors at 6.4 T. At $\nu = 1/3$, where the electron system is in a fractional quantum Hall liquid phase, the measured NMR spectrum matches a simulation assuming a uniform electron system. In contrast, at $\nu < 1/3$ and in the vicinity of $\nu = 2$, the measured spectra cannot be explained by the uniform model. Instead, a model assuming the formation of Wigner crystal domains of electrons or electrons/holes added to $\nu = 2$ reproduces the measured spectra exceedingly well. The difference in the spectral lineshapes for $\nu = 1.9$ and 2.1, which share the same effective filling of 0.1, is a manifestation of the distinct single-particle wavefunctions for the respective Landau levels. This highlights NMR's ability to resolve probability density variation on a nanometer scale.

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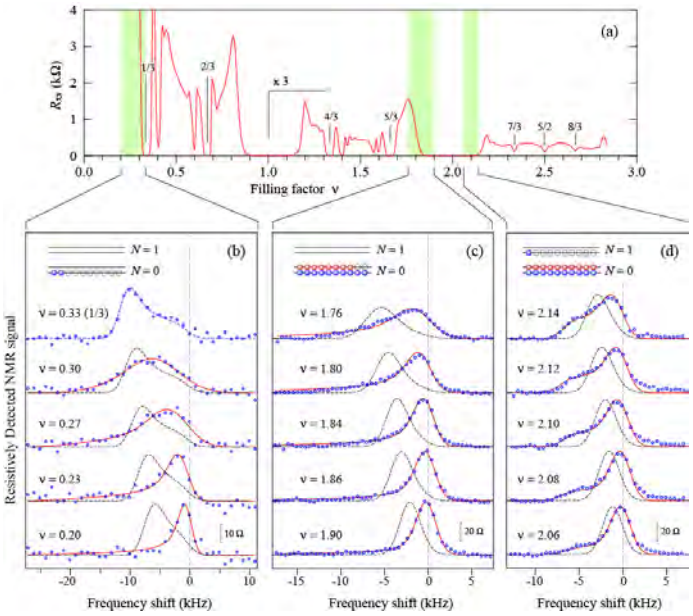

Fig. 1. (a) Filling factor dependence of longitudinal resistance. (b)-(d) Resistively detected NMR spectra of ^{75}As taken at various filling factors. The horizontal axis is the frequency shift with respect to the resonance frequency at $\nu = 2$. Dashed lines represent simulations assuming uniform electron systems. Solid lines are numerical fits using a model incorporating the presence of Wigner crystal domains. Insets: illustrations of occupied Landau levels for (b) $\nu = 0.2$, (c) 1.9, and (d) 2.1.

Flat-Band Ferromagnetism in the Multilayer Lieb Optical Lattice

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Ultracold atom gases can be trapped in an optical lattice using lasers. The high controllability of atoms provides us with an ideal tool for investigating quantum many-body systems, such as mimicking electrons in bulk materials. Thus, the system can be regarded as a quantum simulator, which stimulates theoretical and experimental efforts to observe quantum magnetism using fermionic atoms. The Kyoto university group, led by Prof. Yoshiro Takahashi, has successfully created the Lieb optical lattice [Fig. 1(a)], which attracts much attention as mentioned below. The band structure of this two-dimensional Lieb lattice shows a dispersionless band (flat band), which may induce the exotic magnetic ordering state (flat-band ferromagnetism). The emergence of this state is exactly shown (Lieb theorem [1]), which has attracted theoretical attention. The realization of the Lieb optical lattice provides an ideal opportunity for the first observation of the flat-band ferromagnetism.

In the experiment, a multilayer Lieb optical lattice [Fig. 1(b)] (L represents the number of layers) is inevitably realized. To observe the flat-band ferromagnetism, we theoretically investigate how this multilayer structure affects magnetic ordering [2]. We reveal that the property of magnetic ordering is quite different between odd layers ($L = 2l - 1$, where l is a positive integer) and even layers ($L = 2l$). Figure 2 shows average magnetization, which is an order parameter of the magnetic ordering, as a function of atom-atom interaction strength. For odd layers ($L = 2l - 1$), Fig. 2 (a) shows that finite magnetizations appear with quite weak interaction strength. This indicates the emergence of the flat-band ferromagnetism, which can be regarded as a generalized consequence of that on a single layer ($L = 1$, the two-dimensional Lieb lattice mentioned above). Further, we also find the gradual change of the magnetic ordering states from the two dimensions ($L = 1$) to the three dimensions ($L \to \infty$). This result exhibits that the flat-band magnetism, well-known for the two dimensions, appears even in the three dimensions. On the other hand, for even layers ($L = 2l$) [Fig. 2 (b)], we reveal that magnetization develops at finite interaction strength. As L increases, this critical interaction strength decreases. Thus, in the limit of $L \to \infty$ (three dimensions), the difference between odd and even layers disappears and the flat-band magnetism appears. In experiment, a multilayer Lieb optical lattice that consists of several tens of layers will show the three-dimensional flat-band magnetism, which is revealed in our study.

This work was supported by JST-CREST and KAKENHI.

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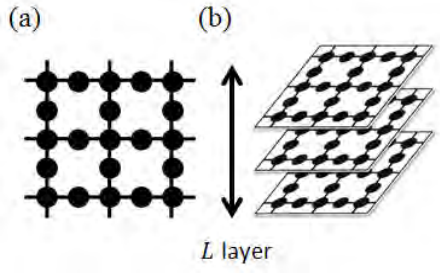

Fig. 1. (a) Lieb lattice and (b) multilayer Lieb lattice.

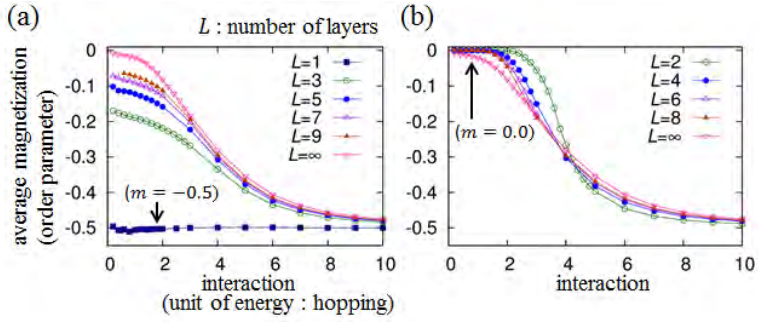

Fig. 2. Average magnetization (magnetic order parameter) vs. interaction of the multilayer Lieb lattice with L [(a) $L = 2l - 1$ and (b) $L = 2l$]. Results at zero temperature and half filling [2].

Quantum Key Distribution over a 72 dB Channel Loss Using Ultralow Dark Count Superconducting Detectors

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Quantum key distribution (QKD) offers ultimately secure communication based on the laws of quantum mechanics. For the realization of QKD network, it is necessary to increase the maximum distance of QKD. Previously, we have demonstrated the QKD over 200 km (42.1 dB loss) in fiber using superconducting nanowire single photon detectors (SSPDs) [1]. Here, we have successfully improved the S/N ratio of SSPDs by 30 dB [2], and demonstrated the QKD over 336 km (72 dB loss) in fiber [3], which is the today's world record of QKD distance.

In QKD, faint single photons are usually used as a carrier of information. When the fiber length increases, the loss of the fiber increase and the signals of single photons are masked by the noise. It is impossible to distribute the secure key when the quantum bit error rate (QBER) exceeds a certain level. Therefore, we need a single-photon detector with higher S/N ratio for the long distance QKD. We find that the origin of the dark count rate (DCR) of SSPD is the blackbody radiation at room temperature which propagate through an optical fiber, and introduce the cold optical bandpass filter to block the radiation [2]. It is possible to improve the S/N ratio of SSPDs more than 30 dB using the cold optical filter. Figure 1 shows the system detection efficiency (η) and DCR of the SSPD. At a bias current of 21.5 μA, η = 4.4% and DCR < 0.01 cps is achieved.

Using the SSPDs with ultralow DCR, we perform the QKD experiment under the differential phase shift QKD scheme using a weak coherent light. Figure 2 summarizes the results of our experiment. At the loss of 72 dB (336 km fiber), we can generate the secure keys from the sifted keys since the QBER is still below 4.1% [3].

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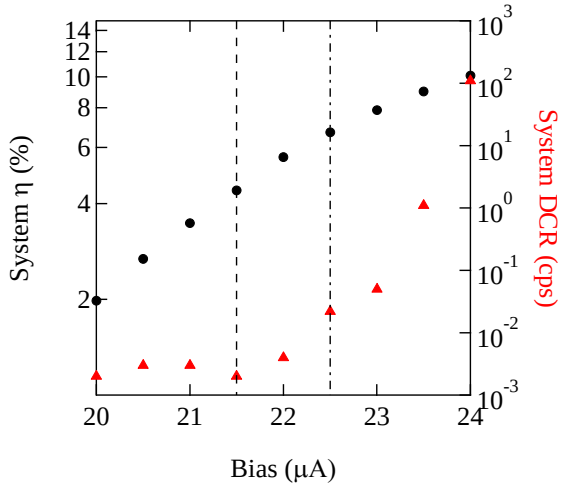

Fig. 1. Bias current dependences of detection efficiency and dark count rate of our SSPD.

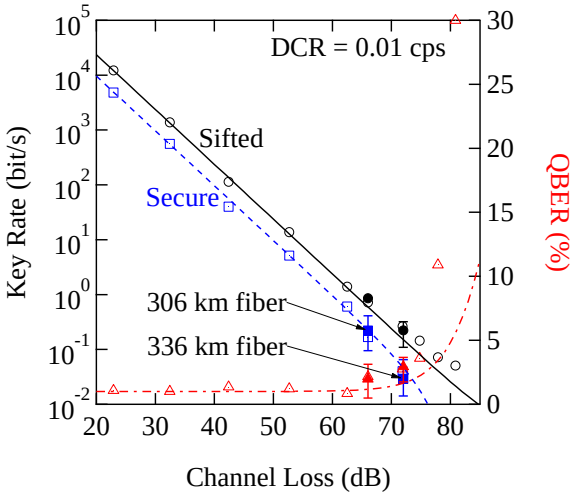

Fig. 2. Channel loss dependence of sifted key rate, secure key rate, and QBER of the experiment.

On-Chip Generation and Demultiplexing of Quantum Correlated Photons Using Si-Silica Monolithic Waveguide Platform

Nobuyuki Matsuda[1,2], Hidetaka Nishi[2,3], Tai Tsuchizawa[2,3], William J. Munro[1], Hiroki Takesue[1], and Koji Yamada[2,3]
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Integrated photonics technology has proven useful for the large-scale integration of quantum information systems on photonic chips thanks to its compactness and interferometric stability. Intense study is under way on the development of on-chip quantum components, such as quantum light sources [1], quantum circuits [2], and single photon detectors [3]. The next step is the integration and interconnection of these components on a single substrate. This time we have realized the monolithic integration of a Si waveguide photon pair source and a photon-pair demultiplexer employing a silica-based arrayed waveguide grating (AWG) [4], which can facilitate interconnecting the quantum light source and the circuit.

The circuit is schematically depicted in Fig. 1(a). In the silicon waveguide part, a correlated pair of signal and idler photons is created via spontaneous four-wave mixing process following the annihilation of two photons inside the pump pulse. Thanks to the high material nonlinearity of Si as well as the strong light confinement of the waveguide, non-degenerate photon pairs are efficiently created in the telecommunication wavelength. The photon pairs are subsequently spectrally separated [Fig. 1(b)] by AWG into different output channels. We employed silica-based material (SiO_x), which is a low nonlinear material, as the core of the AWG in order to mitigate noise photon generation outside of the photon pair source. The integration of the two quantum photonic components has been realized with the monolithic photonic integration technology [5]. Using the device, we have successfully demonstrated the on-chip generation and demultiplexing of quantum correlated photons on a chip [Fig. 1(c)]. Furthermore, we have confirmed that the silica part of the device does not contribute to noise photon generation.

The device can be used as a compact correlated photon pair source, and will be useful for many quantum information applications including wavelength-division multiplexing quantum communication technologies and heralded single photon sources. Moreover, the silica-based AWG can provide an interface between a Si-based photon pair source and silica-based lightwave circuits, which are useful as linear-optics-based quantum circuits.

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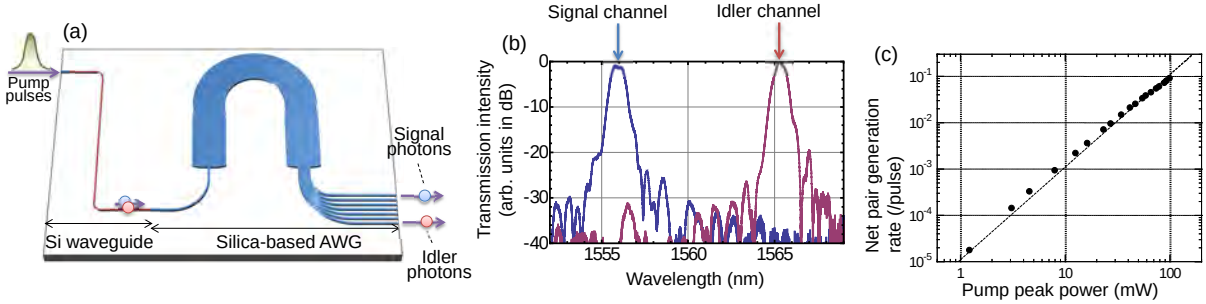

Fig. 1. (a) Monolithic chip housing a Si wire photon pair source and a silica-based arrayed waveguide grating. (b) Transmission spectra of AWG output ports. (c) Photon pair generation rate.

Loss-Tolerant Quantum Cryptography with Imperfect Sources

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Quantum key distribution (QKD) is a way to distribute a random bit sequence, which is called a key, between a sender (Alice) and a receiver (Bob). Its striking advantage is that the leakage of the information on the key to an eavesdropper (Eve) can be arbitrary set according to Alice and Bob's demand. In order to achieve such high security, the QKD devices must operate as the security theory requires. For instance, in the case of the most well-known protocol, BB84 [1], the phase modulator is required to apply an exact phase modulation, which is randomly chosen from 0, $\pi/2$, π, $3\pi/2$, for each pulse. However, such exact values can never be achieved due to the imperfections in the modulator.

This kind of modulation error would not seem to be so problematic to affect the security, unfortunately however, this is not the case. In a typical QKD communication, due to the inevitable photon losses in the quantum channel, a single photon is detected only once out of 1000 emission pulse. Eve may exploit these losses in such a way that only when she succeeds in exploiting the modulation error, she sends out a pulse to Bob to cause the detection event. In other words, she may enlarge the effective modulation errors. This is exactly what happened in the existing theory [2]. Figure 1(a) is a plot of the key generation rate against the distance between Alice and Bob, and the solid, dashed and dotted lines respectively represent the case with perfect modulation, the modulation error case with about 3.6 degree, and the modulation error case with about 7.2 degree. One can see in the figure that the small errors have a severe impact on the achievable communication distance.

In our work [3], we have proposed a technique to drastically decrease the effect that the imperfect state preparation has on the communication distances. This is made possible by utilizing the data, which was used to be discarded in the BB84 protocol. Figure 1 (b) is the plot of the key rate against the distance based on the same experimental data as used in Fig. 1(a). The three lines are almost superposed, implying that the state preparation flaw is not problematic. Moreover, it can be concluded from our observation that sending three states is enough in the BB84 where sending four states was considered to be needed.

Our research is in part supported by FIRST and NICT.

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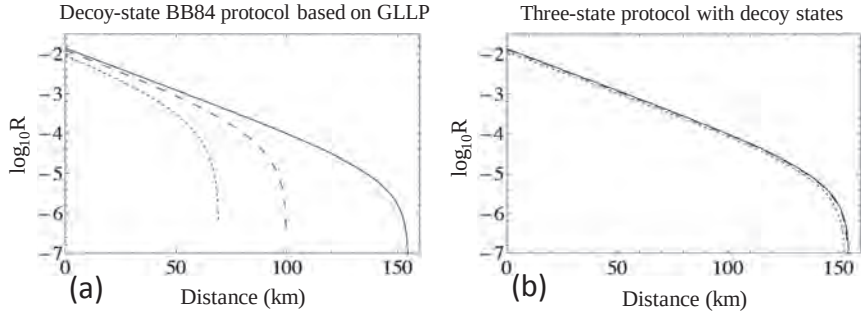

Fig. 1. The key rate vs. the communication distance. (a) based on [1]. (b) based on our technique [2].

The Design of a Scalable and Distributed Quantum Information Processor in Diamond

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[1]Optical Science Laboratory, [2]TU Wien, [3]NII

Physics and information are intimately connected together. It is now widely accepted that the ultimate "information" processing devices will be those that harness and utilize the principles of quantum mechanics. There have been many physical systems identified that can be used for such processing [1]. Many proof of principle experiments have been performed, but none of these are immune from errors. One needs to find a path from today's experiments to tomorrow's scalable quantum computers and communication networks. Here, we develop an architecture based on a simple quantum module comprising an optical cavity containing a single negatively charged nitrogen vacancy center (NV^-) in diamond. The modules can be connected together by photons propagating in an optical fiber network and thus collectively used to generate a topological cluster state, a robust substrate for quantum information processing. We show that this architecture enables us to start with a few modules and scale up to large capacity quantum information processing with existing technology [2].

The module at the center of this approach is depicted in Fig. 1(a) where the cavities mediate interactions between the photons and the electron spins. The electron spins are coupled to nuclear spins: the later constitute long-lived quantum memories where quantum information is stored and processed. The electron spin is acting as an interface between the nuclear spin and optical photons. Entanglement can be generated between two modules using a single photon propagating in the fiber-optical network [Fig. 1(a)]. The scheme works by dividing a photon on a 50/50 beam splitter and sending each half to a module where it interacts (gaining a phase shift if the electron spin is in its |1> state). The reflected photon parts from each module are then recombined on the beam splitter and the dark port measured. If the detector clicks, entanglement has been generated between the electron spins in each module [2]. This entanglement is then transferred to the nuclear spins creating a long-lived link between the modules. Once this has been done entanglement generation can be attempted with further modules allowing a large-scale cluster state to be generated [Fig. 1(b)]. Such a resource is useful for universal quantum computation and long-range quantum communication.

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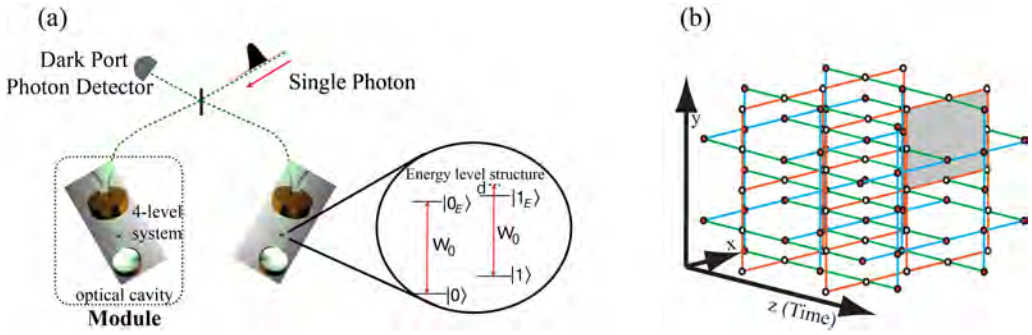

Fig. 1. NV center based quantum architecture. (a) Entanglement of two quantum modules using a single photon interferometer (inset shows the energy level structure of the NV center). (b) Entanglement between many modules creating a 3D lattice for general quantum computation and communication.

Characterizing Inner-Shell Electron Motion with Isolated Attosecond Pulse

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Optical Science Laboratory

We aim to observe and manipulate ultrafast electron motion using attosecond (10^{-18} s) laser pulses, which is shortest optical pulse in the world. In an atom, electrons are classified into outer shell (valance-shell) and inner shell (core-shell) types. In common devices, the outer shell with a low energy band gap (a few electronvolts) is used. However, since the inner shell has a larger band gap (a few orders magnitude higher than the outer shell), the electron motion is much faster. For instance, the decay time of an excited inner-shell electron is on a scale from a few attoseconds to several hundred femtoseconds (that of an outer-shell electron is on the scale of nanosecond).

We successfully observed electron motion with the dipole response in the inner shell using the combination of an IAP (isolated attosecond pulse) and SPIDER (spectral phase interferometry for direct electric field reconstruction) method [1]. We generated the IAP with 192-as duration –one of the shortest laser pulses in the world– and this IAP can approach the time scale of the electron motion. Figure 1 shows the dipole response in neon atom (2*s*-3*p* states) induced by the IAP. The dipole response produces the coherent photoemission, which is interfered with the IAP and detected by a spectrometer. The SPIDER method can fully characterize the dipole response (the decay time, dipole phase, and periodicity of dipole oscillation). The decay time indicates 35 fs (10^{-15} s), which is million times shorter than general outer-shell decay time. In addition, the periodicity of dipole oscillation corresponds to 90 as. Principally, the periodicity produces 10 PHz (10^{15} Hz) responses for the optical device. The achievement for inner shell with ultrafast motion may pave the way for the development of new types of ultrafast devices.

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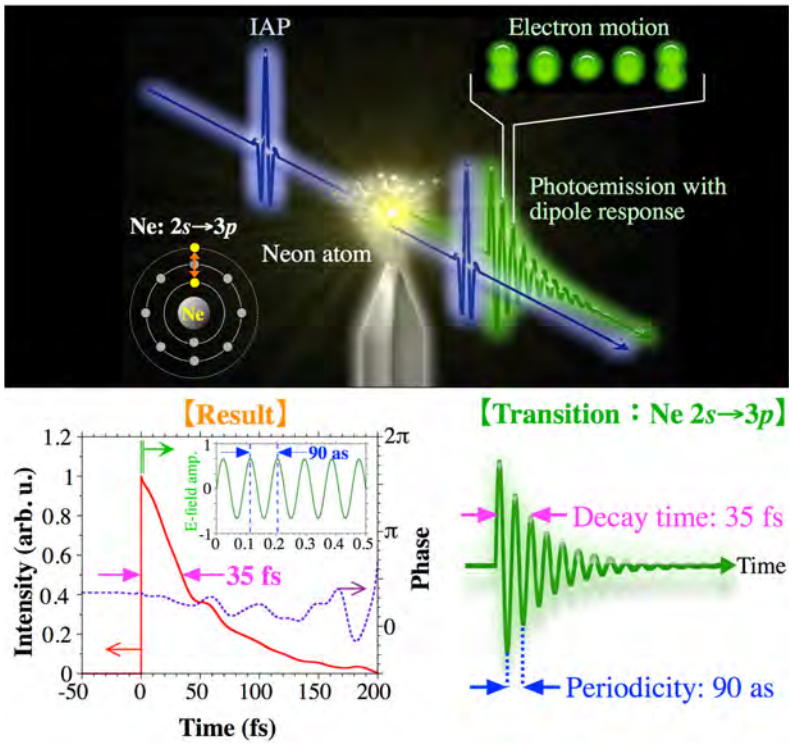

Fig. 1. Characterizing dipole response with inner shell in neon atom using the IAP.

Multi-Stacked InAs/InP Heterostructure Nanowires Grown by Self-Assisted Vapor-Liquid-Solid Mode

Guoqiang Zhang, Kouta Tateno, and Hideki Gotoh
Optical Science Laboratory

Semiconductor nanowires (NWs) have provided a new platform for fundamental physics research and have become next-generation building blocks in photonics, electronics, and energy conversion. One crucial challenge for NWs has been the development of a CMOS-compatible synthesis approach which produces semiconductor heterostructure NWs with excellent optical properties. This remains challenging because gold (Au), which is widely used as a catalyst particle when NWs are synthesized with the bottom-up vapor-liquid-solid (VLS) approach, is not permitted in the mainstream CMOS process.

Here, we report gold-free multi-stacked InAs/InP heterostructure NWs with controlled luminescence wavelength in 1.1-1.6 μm. We realized the NW by using an indium-particle-assisted VLS synthesis approach [1-3]. The growth temperature as low as 320°C enables in the formation of an atomically abrupt InP/InAs interface by supressing the diffusion and weakening the reservoir effect in the indium droplet (Fig. 1). The low growth temperature also enables us to grown multi-stacked InAs/InP NWs in the axial direction without any growth on the NW side face in the vapor phase epitaxy mode.

The high controllability of the growth technology ensures that the luminescence can be tailored by the thickness of InAs segment and cover the 1.3-1.5 μm telecommunication window range. By using the nanoscale-spatial-resolution technology combing CL with SEM, we directly correlated the site of different-thickness InAs segments with its luminescence property in a single NW and demonstrate the InAs-thickness controlled energy of optical emission in 1.1-1.6 μm (Fig. 2).

This work was supported by KAKENHI.

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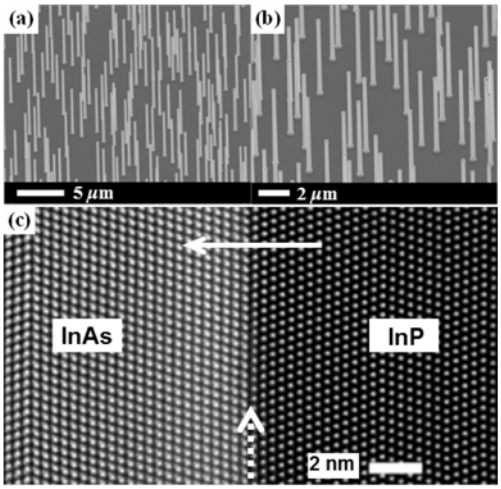

Fig. 1. Multi-stacked InAs/InP hetero-NW. (a) and (b) SEM images (tilt: 38º) of the InP/InAs NW grown on an InP (111)B substrate. (c) HAADF-STEM image of the InP/InAs heterointerface. The dashed arrow indicates the atomically-abrupt interface.

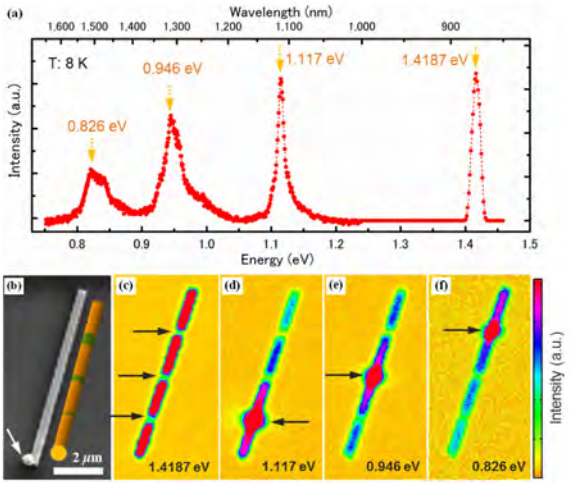

Fig. 2. SEM-CL analysis. (a) CL spectra of a single InP/InAs NW. (b) SEM image of an InP/InAs NW and the schematic diagram of the NW structure. (c)-(f) Monochromatic mapping images of the four peak-energy values shown in (a). The arrows indicate the positions of the InAs layers with varied thickness.

Energy Transfer in Er_2O_3 Epitaxial Thin Layers

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The intra-4*f* orbitals in rare-earth ions are attractive as a robust material platform for the manipulation of quantum information in a solid because they form deterministic and discrete quantum levels that do not depend on either host material or temperature. We concentrate on erbium oxide (Er_2O_3) epitaxial thin films, which can match the lattice constant of Si(111) and interact with telecom-band photons. In this study, we investigate the dynamics of excited populations in the intra-4*f* orbital of Er ions that are indispensable if we are to realize quantum information manipulation.

Figure 1 shows a cross-sectional TEM image of a grown Er_2O_3 sample and a schematic of a unit cell. The TEM image proves that the Er_2O_3 is epitaxially grown on the Si(111) surface without crystalline defects [1]. A unit cell of Er_2O_3 contains 32 erbium ions, 24 at sites with C_2 (non-inversion) symmetry and 8 at sites with C_{3i} (inversion) symmetry. Since these energy levels differ at different sites and exhibit narrow inhomogeneous broadening, we can select the excitation site and the level precisely by tuning the laser frequency. Figure 2 shows energy diagrams of the ground [$Z^{(')}_1$] and 1st excited [$Y^{(')}_{1\text{-}5}$] states and a color plot of photoluminescence excitation (PLE) spectra. When the energy level of the C_2 site is excited resonantly (e.g. Y_3 level), the PL is not from the same C_2 site, and it is observed only from the spatially separate C_{3i} site (e.g. Y'_1-Z'_1 transition). This means that energy migrates between distant C_2 and C_{3i} sites as a result of a resonant energy transfer arising from a dipole-dipole interaction or wave function overlap. We determined that the time constant of the energy transfer from C_2 to C_{3i} is 8 μs by performing a simple rate-equation analysis. This is much shorter than the emission decay from the Y_1 to Z_1 state (100 μs), but is sufficiently long compared with the time required to complete quantum information manipulation in Er_2O_3 crystals [2]. These results show that the Er_2O_3 epitaxial thin layers constitute a promising material platform for the manipulation of quantum information in a solid.

This work was undertaken in collaboration with Hokkaido University and was supported by KAKENHI.

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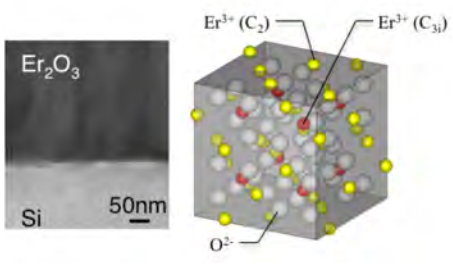

Fig. 1. Cross-sectional TEM image and schematic of unit cell.

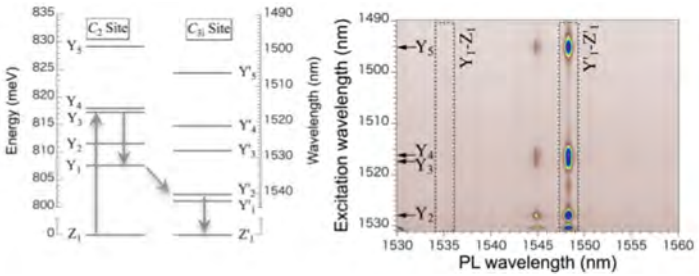

Fig. 2. Energy diagrams and PLE color plot.

Over-100-bit Integrated Optical RAM Chip

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[3]NTT Device Technology Laboratories

Optical memory is a key device for all-optical routing/signal-processing. The former is applicable for both broadband networks in telecommunication and data centers and on/off-chip optical interconnects for large-scale CMOS electronic chips. The transportation of photonics over electronics is considered to be a way of dealing with the huge data-transfer cost (power, heat, space, overhead), which becomes serious as the integration density increases. We have previously demonstrated an ultra-small optical random access memory (o-RAM) with an ultra-small operating power (30 nW) by using a high-*Q* photonic crystal nanocavity [1]. However, the highly dense integration of many o-RAMs is difficult to achieve with the previous nanocavity design.

In this study, we employed a novel three-missing-hole nanocavity (L3) with the systematic tuning of multiple holes [Fig. 1(a)], which enhanced the *Q* factor 10-fold compared with the conventional L3 [2]. Thanks to the narrow cavity mode linewidth, enhanced carrier-plasma bistability, and wide free spectrum range, we could employ wavelength-division-multiplexing technology to realize write/read-out access to every o-RAM via one common side-coupling waveguide, and eventually 128-bit o-RAMs were integrated as a simple tandem array of 128 L3s [Fig. 1(b)] [3]. The lattice constant *a* at every L3 was changed from 408 to 424 nm in 0.125 nm steps to set a wavelength spacing of ~30 GHz and the cavity spacing was 20*a*. The total length of the 128-bit integrated o-RAM was only 1.1 mm. We fabricated this precise 128 L3 array in a Si photonic crystal using electron beam lithography. In the experiment, we realized o-RAM operation by injecting bias light at the wavelength of the target o-RAM, and we switched the "1" state and "0" state with set/reset pulses. As shown in Fig. 1(c), we successfully demonstrated the o-RAM operation of 105 L3s. In addition to the groundbreaking jump in bit number from the several bits of conventional o-RAMs, the total operating power of 30 mW was surprisingly low. We applied the same technology to a more sophisticated InP-based nanocavity with an embedded buried heterostructure and realized multi-bit o-RAM operation on lower power consumption and a second time scale [3].

The success of state-of-the-art nanophotonics has opened the way to the monolithic integration of 1000 nanophotonics devices (or 1000 bits) and even one million devices on a chip by employing parallel integration.

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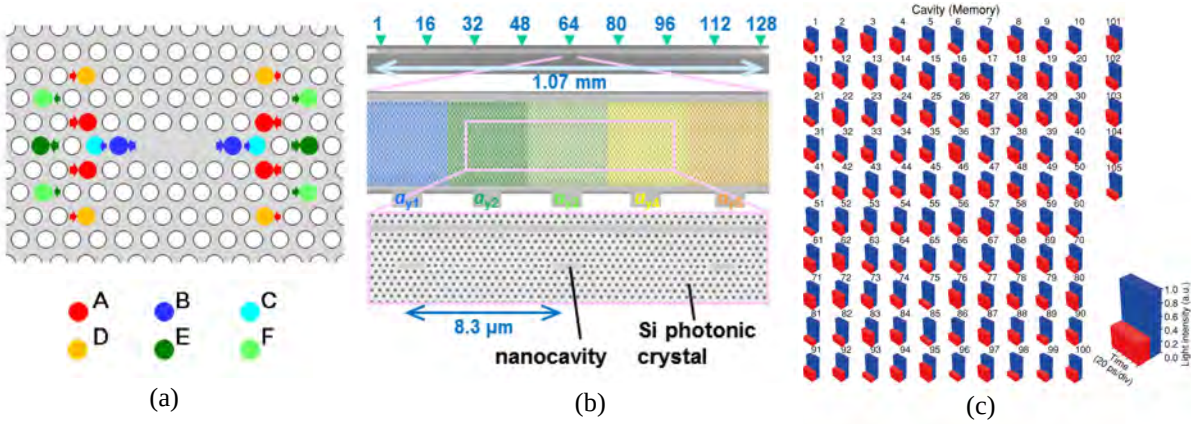


(a) (b) (c)

Fig. 1. Over-100-bit integrated o-RAM chip. (a) L3 with novel hole-tuning. (b) Microscope images. (c) Temporal output of 105 bits.

Nanocavity-Enhanced Raman Scattering of Single-Walled Carbon Nanotubes

Hisashi Sumikura[1,2], Eiichi Kuramochi[1,2], Hideaki Taniyama[1,2], and Masaya Notomi[1,2]
[1]Optical Science Laboratory, [2]NTT Nanophotonics Center

Carbon nanotubes emit intense spontaneous Raman scattering thanks to a strong electron-phonon interaction under low-dimensional quantum confinement, and they are expected to exhibit a large Raman gain. To observe the stimulated Raman scattering and Raman laser action of carbon nanotubes, we study the nanocavity-enhanced Raman scattering of semiconducting single-walled carbon nanotubes (SWCNTs) placed in high-Q silicon photonic crystal (Si PhC) nanocavities. Figure 1(a) shows a fabricated point-defect Si PhC nanocavity covered with randomly oriented SWCNTs. The experimental cavity Q value was 1100. Figure 1(b) shows the Raman spectrum of a PhC sample when it was excited with a 940-nm-wavelength laser. An intense Stokes Raman peak is seen at around 1600 cm^{-1}, which is assigned to the G^+ mode of the SWCNTs. Figures 1(c) and (d) show the Raman spectra and peak intensities of the G^+ mode, respectively, as the wavelength of the excitation laser changes. Figure 1(c) also shows the PhC cavity mode at 1117 nm. When the Raman scattering wavelength of the G^+ mode is adjusted to the cavity resonance, the peak Raman intensity is resonantly increased. This result shows that the resonant PhC nanocavity enhances the spontaneous Raman scattering of SWCNTs [1]. When we took the excitation and emission extraction efficiencies of our samples into consideration, we found that the Raman intensity was two orders of magnitude larger than the intensity of SWCNTs on a flat Si film. This enhanced Raman intensity results from a 20-fold increase in the emission extraction efficiency and a 5-fold increase in the density of the optical state, both of which are provided by the resonant PhC nanocavity. Further enhancement of the Raman scattering intensity will need novel PhC nanocavities with an air slot holding many SWCNTs.

The nanocavity-enhanced spontaneous Raman scattering demonstrated here is the first step towards realizing low-threshold and nanometer-scale Raman lasers based on a high-Q Si PhC cavity and carbon nanotubes.

[1] H. Sumikura et al., Appl. Phys. Lett. **102**, 231110 (2013).

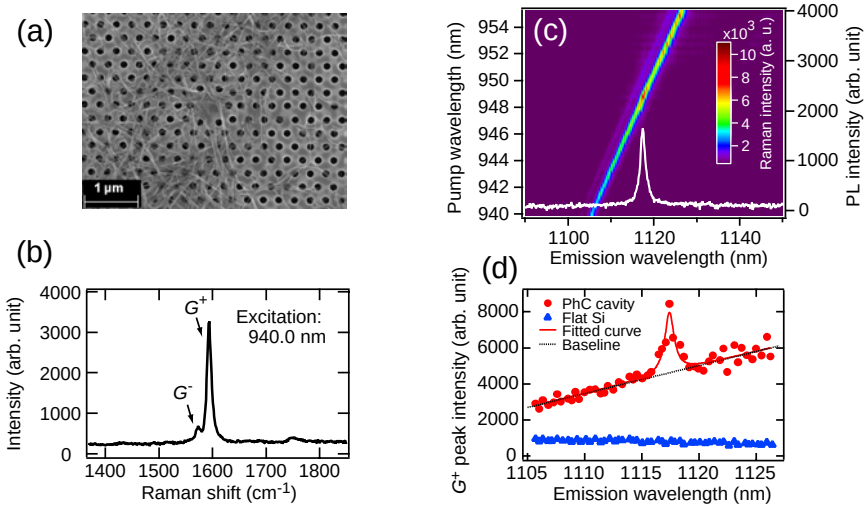


Fig. 1. (a) Scanning electron microscope image of a silicon PhC nanocavity covered with SWCNTs. (b) Stokes Raman spectrum of a fabricated PhC sample. (c) Raman spectra of a PhC sample as a function of the excitation laser wavelength. The photoluminescence of the PhC nanocavity is also shown. (d) G^+ Raman peak intensity as a function of the Raman scattering wavelength.

Emission Enhancement in a Nanowire Coupled to a Nanoantenna

Masaaki Ono[1,3], Eiichi Kuramochi[1,3], Guoqiang Zhang[1], Hisashi Sumikura[1,3], Yuichi Harada[2], David Cox[4], and Masaya Notomi[1,3]
[1]Optical Science Laboratory, [2]Physical Science Laboratory, [3]NTT Nanophotonics Center, [4]National Physical Laboratory, U.K.

Nanoemitters such as quantum dots and nanowires have small active regions, and are good candidates for realizing optical devices with low power consumption, a small footprint, and high-speed responsivity. On the other hand, it is difficult to couple them efficiently to light because they are much smaller than the wavelength of light. Therefore, we have focused on plasmonics, which overcomes the diffraction limit of light, and studied a bowtie nanoantenna to enhance the light-matter interaction. The modes of bowtie nanoantennas are localized in a region of the order of 10 nm in size, which is close to the size of the nanoemitters. However, it is very difficult to place nanoemitters in the subwavelength region precisely, and a dispersion technique has been mainly used for nanoemitter placement [1]. In this study, we fabricated a nanowire-nanoantenna coupled system, where we placed a single InP nanowire within the gap of a gold bowtie nanoantenna by using a nanomanipulator installed in a focused ion beam system [Fig. 1(a)]. Moreover, we observed significant emission enhancement in the fabricated coupled system [2].

We positioned the InP nanowire in the gap during in-situ scanning electron microscope observation [Fig. 1(b)]. We investigated the emission characteristics at a temperature of 80 K by photoluminescence (PL). The excitation and emission wavelengths were 636 and 875 nm, respectively. Figure 2 shows a map of the PL intensity. Here, $E_{\perp}$ ($E_{//}$) is the light polarized perpendicular (parallel) to the nanoantenna. The black dashed line (red solid line) was obtained under $E_{\perp}$ ($E_{//}$) excitation and $E_{\perp}$ ($E_{//}$) detection. The PL intensity (I) was normalized by the intensity at a point R (I_R), which is far from the nanoantenna. Although I/I_R was close to unity at the antenna position for $E_{\perp}$ polarization, that for $E_{//}$ polarization was 6.1, which indicates that the emission was strongly enhanced by the nanoantenna. When we consider that the diameter of excitation laser was much larger than the antenna mode, the intrinsic enhancement factor was as large as 110. The obtained enhancement is due to the double enhancement of the excitation and emission, and our numerical analysis agrees very well with the experimental results. Moreover, a numerical analysis indicated that nanowire-nanoantenna interplay leads to additional enhancement in our coupled system. Here, we established a nanomanipulation technique for subwavelength nanowires, and achieved emission enhancement by efficiently utilizing the plasmonic structure.

[1] A. Kinkhabwala et al., Nature Photon. **3**, 654 (2009).
[2] M. Ono et al., 2014 IEEE Photonics Conference, WH2.1 (2014).

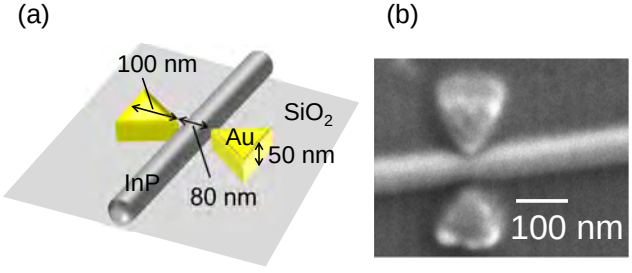


Fig. 1. (a) Schematic structure of the coupled system. (b) SEM image of the fabricated sample. We inserted a nanowire with a diameter of 60 nm and a length of 7 μm.

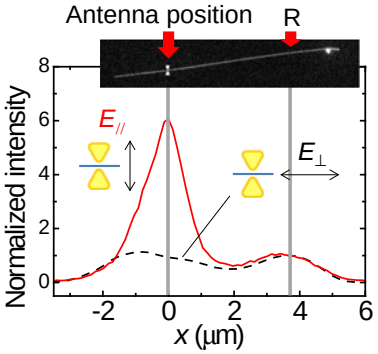


Fig. 2. Normalized PL intensity map on the nanowire. Inset: SEM image that shows the antenna and reference positions.

Continuous-Wave Operation of Lambda-Scale Embedded Active-Region Photonic-Crystal Lasers on Silicon

Koji Takeda[2,3], Tomonari Sato[2], Takuro Fujii[2,3], Eiichi Kuramochi[1,2], Masaya Notomi[1,2], Koichi Hasebe[2,3], Takaaki Kakitsuka[2,3], and Shinji Matsuo[2,3]
[1]Optical Science Laboratory, [2]NTT Nanophotonics Center,
[3]NTT Device Technology Laboratories

Recent CMOS processors employ multi-core architectures, and the network of interconnections between cores is very important. However, there is a bandwidth bottleneck in current electrical interconnects. To overcome it, many researchers are attempting to form optical interconnects on CMOS chips because they provide a larger bandwidth with lower energy consumption. We have studied lambda-scale embedded active-region photonic-crystal (LEAP) lasers on InP substrates as light sources for on-CMOS-chip optical interconnects [2]. Here we report the continuous-wave (CW) operation of LEAP lasers on Si substrates as the first step to realizing on-CMOS-chip light sources.

Device fabrication procedures were similar to those we have reported elsewhere [3]. We carried out crystal (re)growths and lateral p-i-n junction formation on InP substrates to form an ultrasmall buried heterostructure (BH). After SiO_2 had been deposited on the InP substrates, the surfaces were planarized by chemical mechanical polishing (CMP) and the 2-inch InP substrates were bonded to 2-inch Si substrates. After the bonding, the host InP substrates were removed by mechanical polishing and wet etching so that a 250-nm-thick III-V membrane was transferred onto the Si. Two-dimensional photonic-crystal (PhC) holes were then formed by electron-beam lithography and dry etching, followed by metallization processes. Figure 1 shows a schematic of the fabricated device.

We injected current and measured light output from the direction normal to the wafer at room temperature. The measured output power and applied voltage versus injected current (L-I-V characteristics) are shown in Fig. 2. We achieved a CW operation of the LEAP lasers on Si substrates with a threshold current of 31 μA, which is the record low value among semiconductor lasers on Si. The device showed single-mode operation with a lasing wavelength of 1501 nm. This achievement reveals that the LEAP lasers can operate not only on InP but also on Si substrates, and we believe this is an important step to realizing LEAP lasers as on-CMOS-chip light sources.

[1] D. A. B. Miller, Proc. IEEE **97**, 1166 (2009).
[2] K. Takeda et al., Nature Photon. **7**, 569 (2013).
[3] K. Takeda et al., Opt. Express, **22**, 702 (2014).

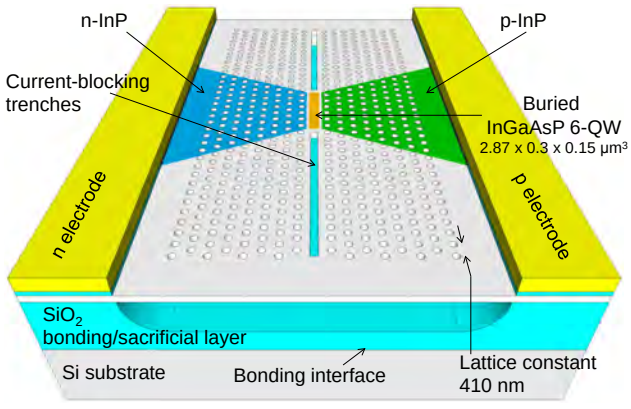


Fig. 1. Schematic of the LEAP lasers on Si.

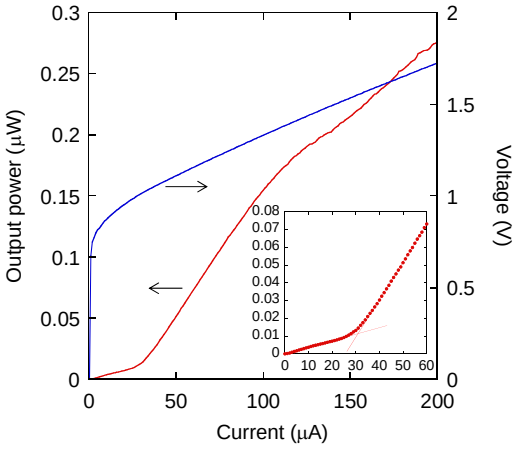


Fig. 2. L-I-V characteristics.

Mode MUX/DEMUX on Three-Dimensional SiOx-Waveguide Platform

Tatsurou Hiraki[1, 2], Tai Tsuchizawa[1, 2], Hidetaka Nishi[1, 2], Tsuyoshi Yamamoto[2], and Koji Yamada[1, 2]
[1]NTT Nanophotonics Center, [2]NTT Device Technology Laboratories

Space division multiplexing (SDM) can increase the spectral efficiency per fiber by multiplexing the signals in orthogonal LP modes in a few-mode fiber. In SDM systems, mode multiplexer/demultiplexer (MUX/DEMUX) selectively launches each LP mode. The Mode MUX/DEMUX should be integrated on a cost-effective platform, because the spatial parallelism lets network cost grow linearly with the number of multiplicities. However, it is difficult to build an integrated and low-cost system with reported fiber- and free-space optics devices. In this work, using a three-dimensional SiOx waveguide platform, we demonstrated an integrated mode MUX/DEMUX on a Si chip.

Fig. 1(a) shows a schematic of an integrated mode MUX/DEMUX for three modes. We used two layers of SiOx film with different refractive indices: 1.5 for the lower layer and 1.49 for the upper one. The interlayer clad thickness is 2.0 μm. The calculated electrical field patterns are shown in Fig. 1(a). At the fiber-chip interface (0 mm), the mode field patterns of the waveguides match the fiber-mode patterns with low losses. On the other hand, with changing the core width, the power of each mode converges in a different core (3 mm). The cores are separated (3.2 mm), and cores 3 and 4 are coupled into one single-mode port with a multi-mode interference coupler. Consequently, LP01, LP11a, and LP11b travel through single-mode ports 1, 3, and 2, respectively. The device has an area of 0.6 mm^2, and the calculated loss and intermodal crosstalk are less than 2.3 dB and −11 dB, respectively. The fabrication process features the low-temperature formation of controlled-refractive-index SiOx films, which prevents thermal damage in the vertical stacking process, and is compatible with the silicon photonics platform [1, 2].

Figure 1(b) shows the measured near-field patterns (NFPs) of a fabricated device with different fiber-mode inputs. As designed, the LP01, LP11a, and LP11b modes were mainly demultiplexed to output ports 1, 3, and 2, respectively. The estimated intermodal crosstalk is less than −6.4 dB. The results show the feasibility of the integrated mode MUX/DEMUX. In future work, we plan to monolithically integrate it with Si/Ge active devices.

[1] T. Hiraki et al., Elec. Lett. **51**, 74 (2014).
[2] T. Hiraki et al., Proc. in OFC2015 W1A.2 (2015).

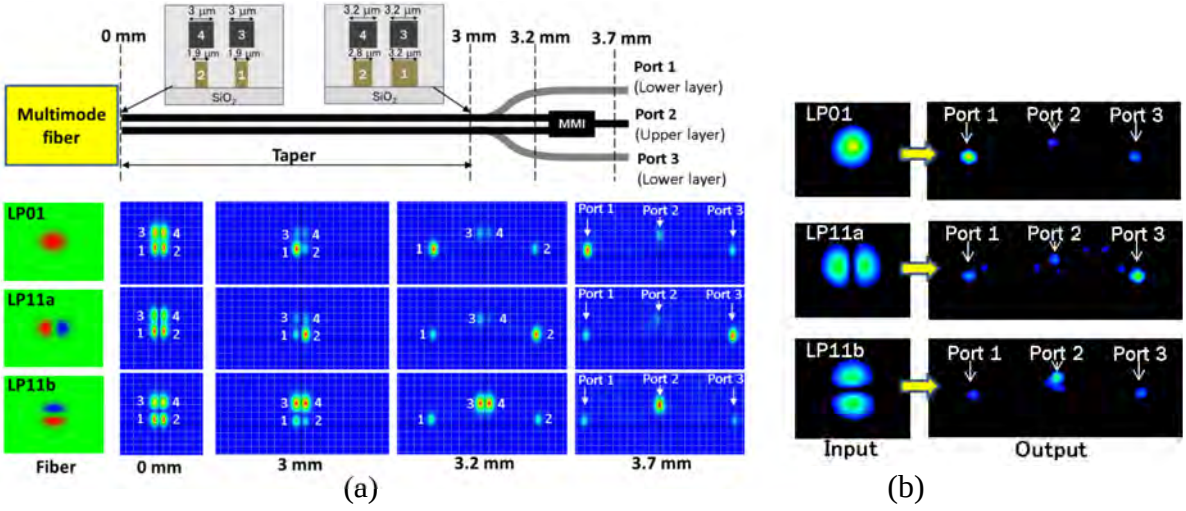


Fig. 1. (a) Schematic of the three-mode MUX/DEMUX and calculated electrical field patterns. (b) Measured NFPs of outputs of fabricated device with different fiber-mode inputs.

Ⅱ. Data

Fiscal 2014: April 1, 2014 ～ March 31, 2015

The 8th Advisory Board

The NTT BRL Advisory Board, first convened in 2001, held its 8th meeting during January 26 - 28 (2015). The focus of this Advisory Board was to provide an objective evaluation of our research activities, plans, and directions, so as to enable us to utilize strategic management to systematically coordinate and align our resources and actions in a timely manner. On this occasion, the board was composed of nine distinguished scientists.

Over the course of the three days, the board evaluated our work and made valuable suggestions and comments in relation to our research and its management. They indicated that our research level was globally leading, and but suggested that it was important for us to disseminate and publicize our research achievements more. They also raised several issues related to human resources, research budgets, and collaborations (both internal and external). We are actively addressing all these issues currently.

At this meeting, our BRL researchers had lunch with the board members and also met them during a lively poster session, where they had chances to present their research. The poster session also included a dinner party, so the board members and the BRL researchers were able to interact in a casual atmosphere. For the BRL and NTT executives, a Japanese style dinner was arranged. This provided an excellent good opportunity to discuss the future management strategy of NTT BRL with an international perspective in mind.

The next board meeting will be held in two years.

Board members	Affiliation	Research field
Prof. Abstreiter	Walter Shottky Inst.	Low-dimentional physics
Prof. Clarke	Univ. California, Berkeley	Superconductor physics
Prof. Hu	Harvard Univ.	Nanodevice
Prof. Jonson	Univ. Gothenburg	Condensed matter physics
Prof. Knight	Imperial College London	Quantum optics
Prof. Leggett	Univ. Illinois at Urbana-Champaign	Quantum physics
Prof. MacDonald	The Univ. Texas at Austin	Condensed matter physics
Prof. Offenhäusser	Forschungszentrum Jülich	Nano-bio electronics
Prof. Rubinsztein-Dunlop	The Univ. Queensland	Quantum electronics
Prof. von Klitzing	Max Planck Inst.	Semiconductor physics

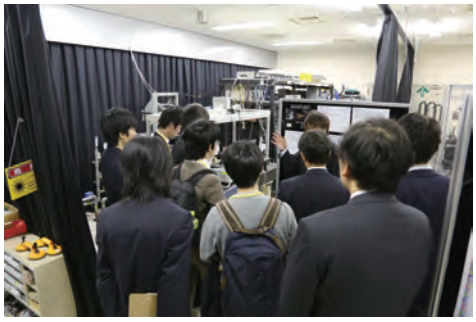
Science Plaza 2014

"Science Plaza 2014", an open-house event of NTT Basic Research Laboratories (BRL), was held at NTT Atsugi R&D Center on Friday, November 21st, 2014. Under the banner "Frontier Science: Open Door to the Future", Science Plaza aimed to disseminate our latest research accomplishments through various sections of people inside and outside of NTT and to gather diverse opinions.

Following an opening address from Dr. Tetsuomi Sogawa, the director of BRL, the project manager of NTT Nanophotonics Center, Dr. Masaya Notomi gave a lecture on "Extreme investigation of optical devices using photonic crystals". In the afternoon session, Professor / Chief Scientist Hidetoshi Katori of The University of Tokyo and Quantum Metrology Laboratory in RIKEN, gave a special lecture entitled "The relativistic space-time embossed by optical lattice clocks". Each lecture was well-attended and followed by heated question and answer sessions.

As regards the poster exhibits, 38 posters, including 16 from Nanophotonics Center, Device Innovation Center, Device Technology Laboratories and Communication Science Laboratories presented our latest research accomplishments. Universities and the research institutes also presented 29 posters of their joint research with NTT in the poster exhibits. While explaining the originality and impact—as well as the future prospects—, these posters were intensively discussed, and many meaningful opinions were heard. This year's "Lab Tour"—a guided tour of research facilities at NTT BRL that has been receiving high reputation from visitors over the years—took place at four different labs, so that as many people as possible could join the tour. After all lectures, presentations, and exhibitions, a banquet was held in Center's dining room, where lively conversation among participants deepened their amity.

About 220 people from research institutes, universities, and general industries, as well as from NTT Group, attended Science Plaza 2014. Thanks to the efforts of all participants, the conference ended on a high note. We would thus like sincerely to express our gratitude to all of the participants.



List of Visitors' Talks

Date	Speakers	Affiliation Title
Apr. 10	Prof. Katsushi Fujii Dr. Shinichiro Nakamura	The University of Tokyo / RIKEN, Japan Artificial photosynthesis for hydrocarbon generation system
Apr. 11	Dr. Yutaka Wakayama	International Center for Materials Nanoarchitectonics, National Institute for Materials Science, Japan Control of tunneling current by molecules
Apr. 17	Dr. Robert Johansson	iTHES in RIKEN, Japan Entangled-state generation in nanomechanical resonators and optomechanical-like coupling in microwave circuits
Apr. 22	Dr. Yuimaru Kubo	CEA Saclay, France Hybrid Quantum Circuit with a Superconducting Qubit and an Electron Spin Ensemble
May 8	Mr. Naotomo Takemura	École Polytechnique Fédérale de Lausanne (EPFL), Switzerland Photon correlation measurement of VCSEL, and nonlinear optical spectroscopy of semiconductor minute resonator polariton
May 14	Prof. Alberto Morpurgo	University of Geneva, Switzerland Transport through suspended graphene
June 27	Prof. Christos Flytzanis	École Normale Supérieure, France Ultrafast high THz-field photo-driven carrier dynamics and transport
July 2	Prof. Christos Flytzanis	École Normale Supérieure, France Nanophononics: a nonlinear battleground par excellence
July 16	Prof. Junko Ishi-Hayase	Keio University, Japan Quantum interfaces and sensors using two-level system ensembles in semiconductors
July 17	Dr. Justin Waugh	University of Colorado at Boulder, U.S.A. Spin-Orbital Texture of Topological Insulators Bi_2X_3 (X = Se,Te)
July 28	Prof. Jiro Temmyo	Shizuoka University, Japan Compound ZnO Growth with Oxygen Radical Assisted MOCVD and Optical Device (LED/PD/PV) Application
Aug. 4	Prof. Akira Suda	Tokyo University of Science, Japan High-order harmonic generation by non-collinear wave mixing

Date	Speakers	Affiliation Title
Sep. 1	Dr. Kanta Tsumoto	Mie University, Japan Preparation of giant recombinant proteoliposomes by baculovirus membrane fusion
Sep. 4	Prof. Takahiro Sagawa Mr. Sosuke Ito	The University of Tokyo, Japan Information and thermodynamics
Sep. 5	Ms. Kana Iwakuni	Keio University, Japan Dual-comb spectroscopy with narrow linewidth optical frequency combs
Oct. 8	Dr. Hiroyuki Inoue	Weizmann Institute of Science, Israel Observation of neutral modes in fractional quantum Hall regime
Oct. 23	Dr. Paulo V. Santos	Paul Drude Institute for Solid State Electronics, Germany Acoustic control and manipulation of quantum wells excitons
Oct. 31	Dr. Takeshi Fukuhara	RIKEN, Japan Quantum dynamics of magnons in optical lattices
Oct. 31	Dr. Stefan Heun	The National Enterprise for nanoScience and nanoTechnology, Italy Exploring the physics of one-dimensional systems by scanning gate microscopy
Oct. 31	Dr. Yuya Murata	The National Enterprise for nanoScience and nanoTechnology, Italy Correlation between morphology and transport properties of quasi-free-standing monolayer graphene
Nov. 10	Dr. Stefan Fölsch	Paul Drude Institute for Solid State Electronics, Germany Generating and probing semiconductor quantum structures with single-atom precision
Nov. 19	Prof. Klaus Ensslin	Eidgenössische Technische Hochschule Zürich, Switzerland Non-local transport in InAs-GaSb quantum wells
Nov. 26	Dr. Koji Usami Dr. Rekishu Yamazaki	RCAST, Research Center for Advanced Science and Technology at the University of Tokyo, Japan Quantum transducers with collective excitations in solid
Nov. 27	Prof. Barbaros Özyilmaz	National University of Singapore, Singapore From Graphene to Phosphorene
Jan. 8	Dr. Peter S. Turner	University of Bristol, U.K. Experimental Demonstration of Quantum Data Compression

Date	Speakers	Affiliation Title
Jan. 9	Prof. Yuji Mochizuki Prof. Kaori Fukuzawa	Rikkyo University / Nihon University, Japan Fragment molecular orbital method and its application examples
Jan. 14	Dr. Akihisa Goban	California Institute of Technology, U.S.A. Strong atom-light interactions in 1D photonic crystals
Jan. 14	Prof. Ken Morita	Chiba University, Japan Terahertz pulse generation for electron spin control in semiconductors
Jan. 22	Prof. Silvija Gradečak	Massachusetts Institute of Technology, U.S.A. Semiconductor nanowires for energy applications
Jan. 22	Dr. Rao Tatavarti	MicroLink Devices, U.S.A. Large Area Inverted Metamorphic (IMM) ELO Solar Cells
Mar. 2	Mr. Samuele Grandi	Imperial College London, U.K. Waveguide coupling of single photons from a solid state emitter: from room temperature to cryogenic condition
Mar. 10	Prof. Qiang Zhang	University of Science and Technology of China, China Quantum Key Distribution with Realistic Devices
Mar. 11	Dr. Ryuji Itakura	Japan Atomic Energy Agency Researches on ultrafast dynamics in VUV region: Time-resolved reflection spectroscopy of highly excited solid surface and coherence of atomic ions created in ultrafast ionization
Mar. 17	Dr. Nicolò Lo Piparo	University of Leeds, U.K. Long-distance quantum key distribution with imperfect devices

List of Award Winners

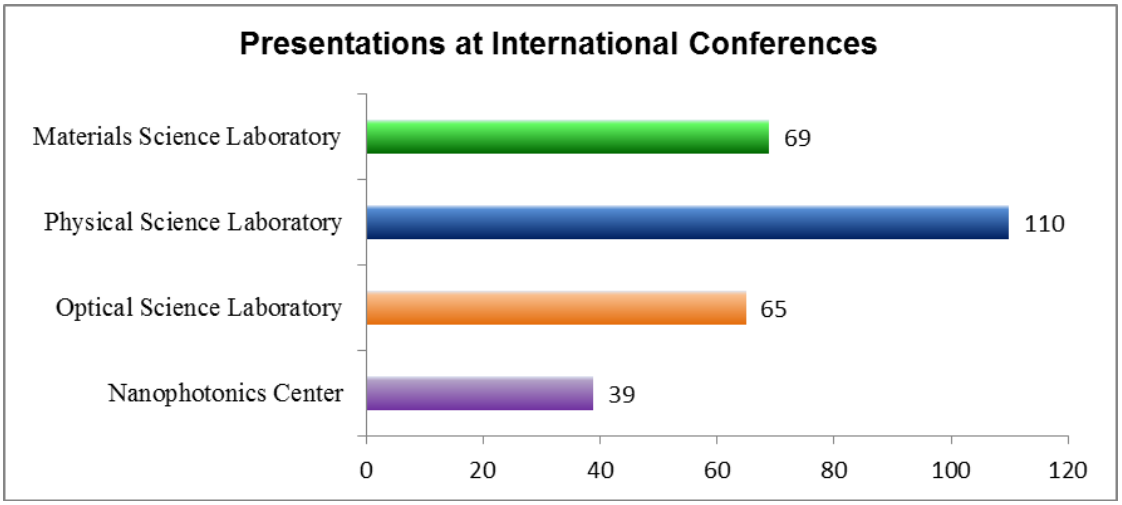
Award	Award Winners	Title	Date
The Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology, The Young Scientists' Prize	H. Okamoto	A study of the quantum nanomechanical sensing technology	Apr. 15, 2014
Conference on LED and Its Industrial Application (LEDIA '14) Young Researcher's Paper Award	R. G. Banal	Nonpolar M-Plane AlGaN Deep-UV LEDs	Apr. 24, 2014
Multidisciplinary Digital Publishing Institute Entropy Best Paper Award 2014	K. L. Brown W. J. Munro V. M. Kendon	Using Quantum Computers for Quantum Simulation	Apr. 30, 2014
Spectroscopy & Innovation Award	Y. Ueno	Demonstration of industrial applicability of spectroscopy through R&D at NTT Laboratories	May 29, 2014
Fellowship of the Optical Society of America (OSA)	W. J. Munro	Research in Quantum Optics and Quantum Information Processing.	Oct. 27, 2014
Award for Encouragement of Research in International Union of Materials Research Societies, International Conference in Asia (IUMRS-ICA)	K. Hirama	Nitride/diamond heterostructure systems - from growth to devices -	Oct. 31, 2014
Research Institute of Electrical Communication RIEC Award	H. Sanada	Electron spin resonance using spin-orbit interaction	Nov. 28, 2014
IEICE Electronics Society LQE Young Researchers Award	K. Nozaki	InGaAs photodetectors based on photonic crystal waveguide including ultrasmall buried heterostructure	Dec. 19, 2014
JSAP Young Scientist Oral Presentation Award	T. Inagaki	Low-voltage optical phase modulation by electric-field-induced phase transition of KTN crystal	Mar. 11, 2015

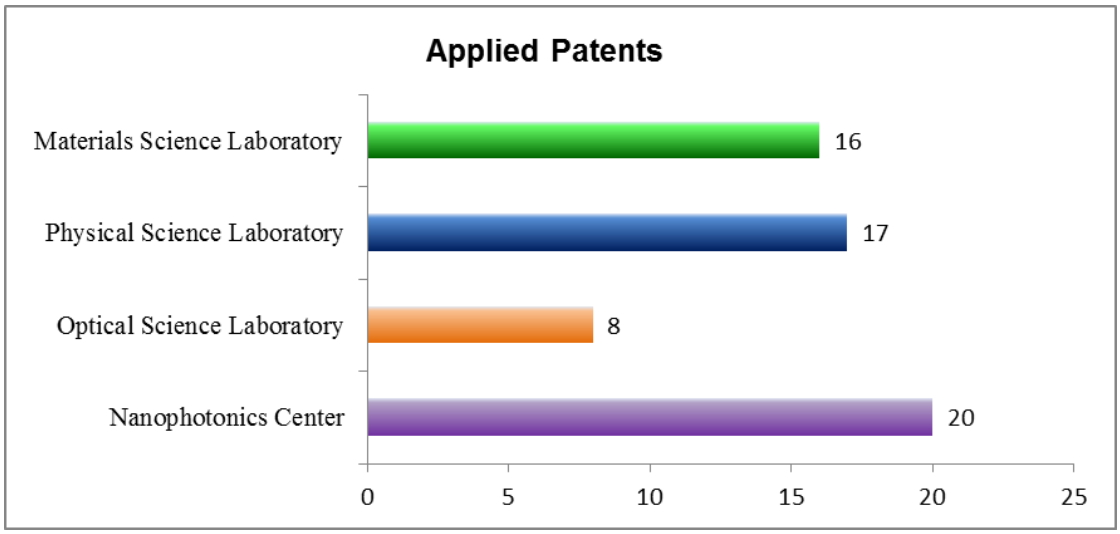
List of In-House Award Winners

Award	Award Winners	Title	Date
NTT Science and Core Technology Laboratory Group Director Award	G. Yamahata K. Nishiguchi A. Fujiwara	Research on high-accuracy and high-sensitivity electronics using single-electron manipulation and detection	Dec. 5, 2014
NTT Science and Core Technology Laboratory Group Director Award	K. Fujii K. Ono T. Ogasawara M. Seyama H. Koizumi S. Tsukada H. Nakashima N. Kasai K. Sumitomo S. Kuno	Development and commercialization of functional materials, "hitoe", that enables continuous measurement of biological information just by wearing	Dec. 5, 2014
BRL Director Award Award for Achievements	D. Hatanaka I. Mahboob K. Onomitsu H. Yamaguchi	Proposal for dynamic phononic crystal using compound semiconductors and its demonstration	Mar. 27, 2015
BRL Director Award Award for Achievements	T. D. Rhone L. Tiemann G. Gamez K. Muraki	For the realization of high-mobility two-dimensional electron systems exhibiting highly correlated electronic phases and for the elucidation of their properties	Mar. 27, 2015
BRL Director Award Award for Excellent Papers	J. Noborisaka K. Nishiguchi A. Fujiwara	“Electric tuning of direct-indirect optical transitions in silicon” Scientific Reports **4**, 6950 (2014)	Mar. 27, 2015
BRL Director Award Award for Best Paper for Environmental Contribution	Y. Taniyasu	“An aluminium nitride light-emitting diode with a wavelength of 210 nanometres” Nature **441**, 325 (2006)	Mar. 27, 2015
BRL Director Award Award for Performance	T. Ota M. Yamaguchi T. Hayashi S. Sasaki	Contribution for renewal of helium gas purification system and continuous supply of liquid helium	Mar. 27, 2015
BRL Director Award Award for Encouragement	H. Sumikura	Large cavity QED effect on copper impurities in silicon	Mar. 27, 2015

Numbers of Papers, Presentations and Patents (Fiscal 2013*)

The numbers of papers published in international journals, presentations at international conferences and applied patents in fiscal 2013 are 118, 283, and 61, respectively. The numbers for each research area are as follows;

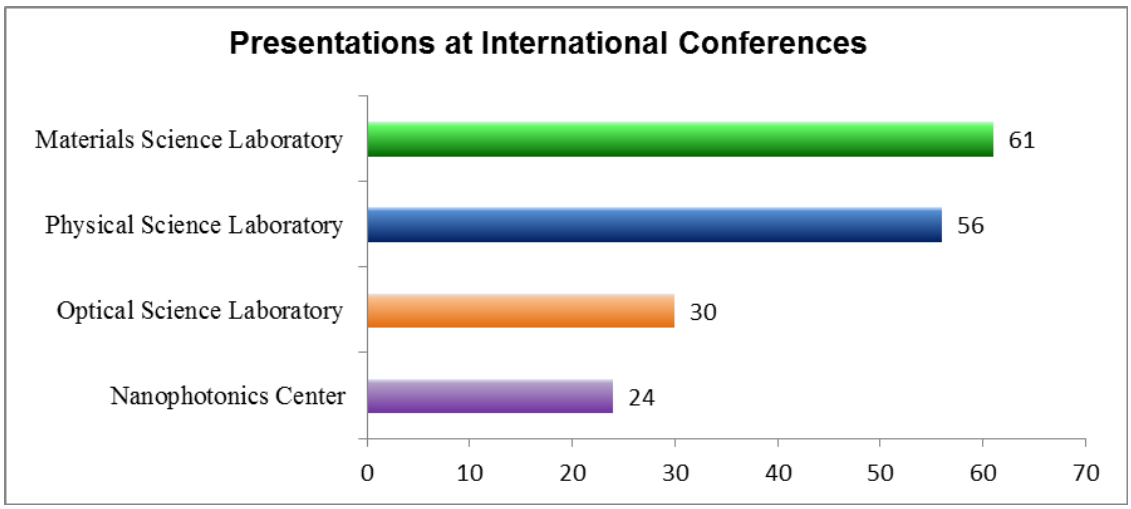


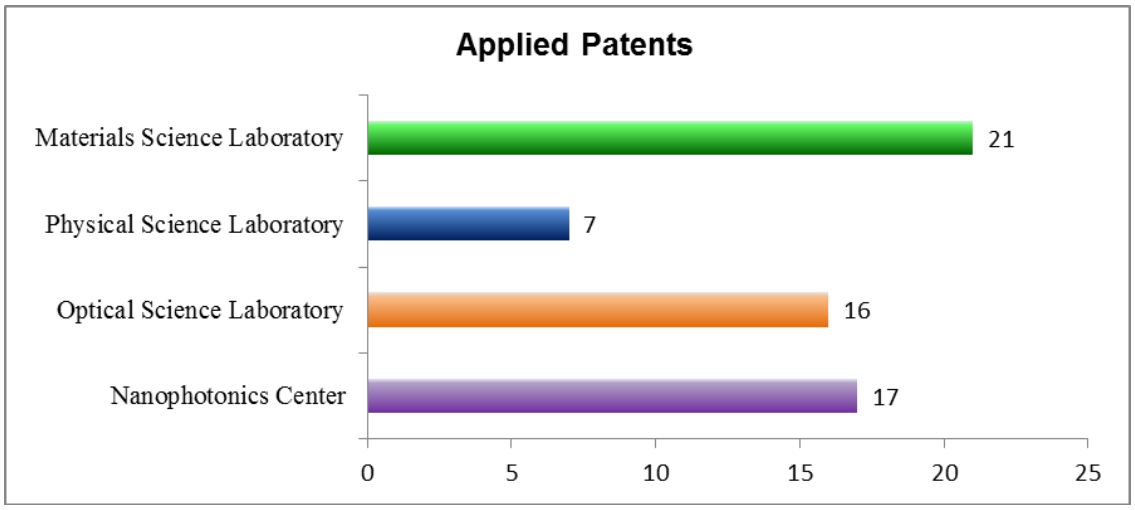


*April 1, 2013-March 31, 2014

Numbers of Papers, Presentations and Patents (Fiscal 2014)

The numbers of papers published in international journals, presentations at international conferences and applied patents in fiscal 2014 are 103, 171, and 61, respectively. The numbers for each research area are as follows;





The numbers of research papers published in the major journals are shown below.

Journals	IF2013*	Numbers
Physical Review B	3.664	10
Japanese Journal of Applied Physics	1.057	9
Optics Express	3.525	7
Applied Physics Letters	3.515	7
Physical Review A	2.991	7
Applied Physics Express	2.567	6
Nature Communications	10.742	4
Journal of Crystal Growth	1.693	4
Physical Review Letters	7.728	3
Scientific Reports	5.078	3
Optics Letters	3.179	3
Nature Nanotechnology	33.265	2
Nature Photonics	29.958	2
Nanotechnology	3.672	2
New Journal of Physics	3.671	2
Journal of Lightwave Technology	2.862	2
Journal of Applied Physics	2.185	2
Journal of the Physical Society of Japan	1.475	2
Nature Physics	20.603	1
Nano Letters	12.940	1
ACS Nano	12.033	1
Chemistry of Materials	8.535	1
Physical Review X	8.463	1
Nanoscale	6.739	1
Analytica Chimica Acta	4.517	1

***IF2013: Impact Factor 2013**
The average IF2013 for all research papers from NTT Basic Research Laboratories is 4.927.

The numbers of presentations in the major conferences are shown below.

Conferences	Numbers
The Conference on Lasers and Electro-Optics (CLEO 2014)	13
The 7th International Symposium on Surface Science (ISSS-7)	12
2014 International Conference on Solid State Devices and Materials (SSDM 2014)	9
APS March Meeting 2015	9
27th International Microprocesses and Nanotechnology Conference (MNC 2014)	7
The International Symposium on Compound Semiconductors (ISCS 2014)	5
32nd International Conference on the Physics of Semiconductors (ICPS)	4
International Union of Materials Research Societies (IUMRS-ICA 2014)	4

Publication List

(1) T. Akasaka and H. Yamamoto, "Nucleus and Spiral Growth Mechanisms of Nitride Semiconductors in Metalorganic Vapor Phase Epitaxy", Jpn. J. Appl. Phys. **53**, 100201 (2014).

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List of Invited Talks at International Conferences (Jan. 2014 – Mar. 2015)

I. Materials Science Laboratory

(1) H. Omi and T. Tawara, "MBE Growth and Optical Properties of Rare Earth Oxides on Si(111)", Symposium on Surface and Nano Science 2014 (SSNS'14), Furano, Japan (Jan. 2014).

(2) Y. Kobayashi, K. Kumakura, T. Akasaka, H. Yamamoto, and T. Makimoto, "Application of BN for GaN Devices", Photonics West 2014, San Francisco, U.S.A. (Feb. 2014).

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