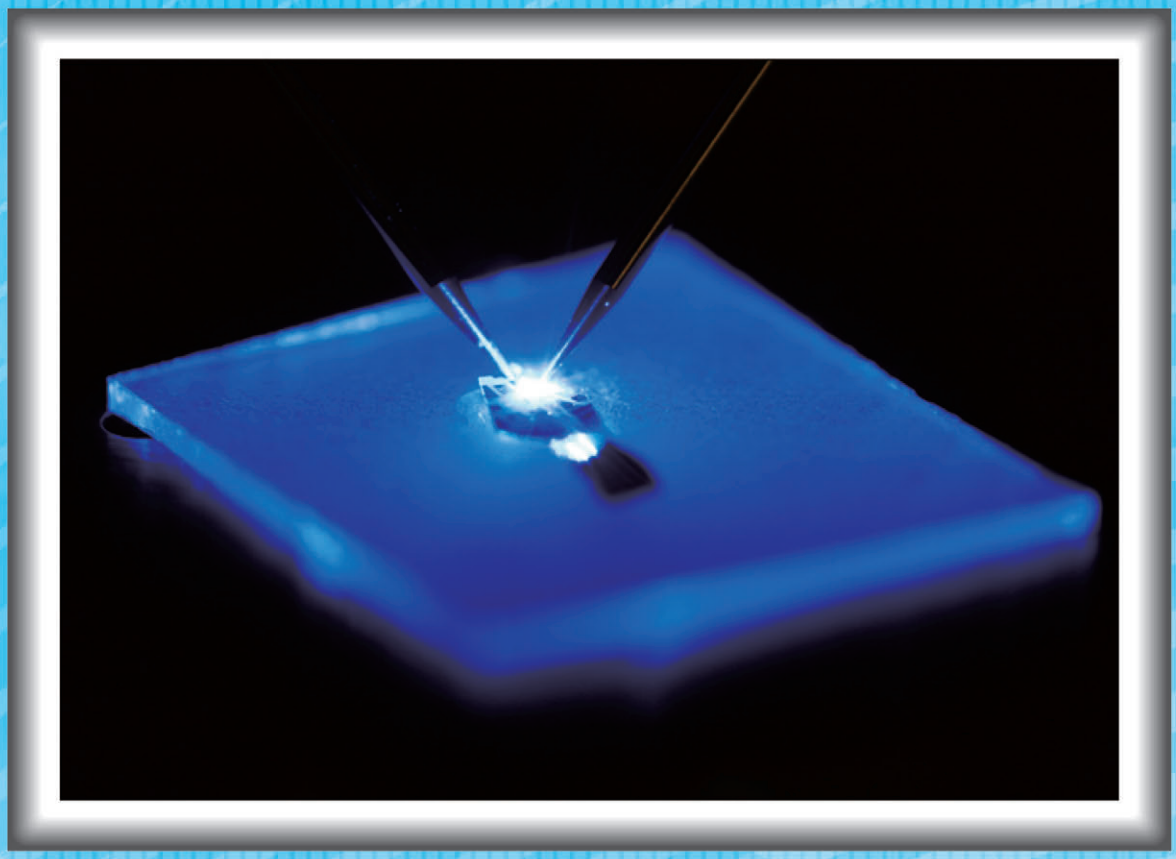
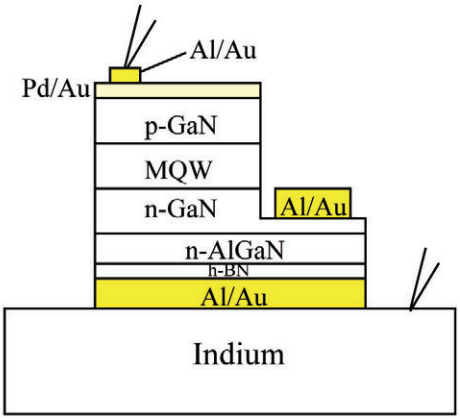


Research Activities in NTT Basic Research Laboratories

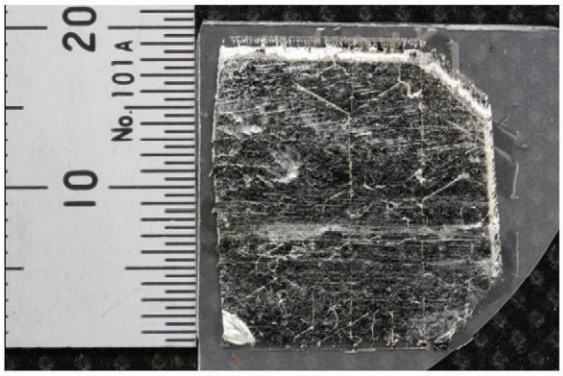
Volume 22
Fiscal 2011

July 2012

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



Schematic illustration of the vertical-type transferred LED.



Photograph of the transferred AlGaN/GaN structure on the foreign sapphire substrate.

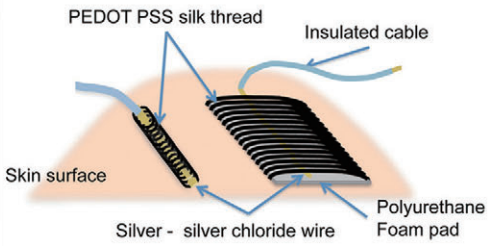
Cover photograph:

Optical Image of the Blue-Light Electroluminescence from the Transferred Vertical-Type Light-Emitting Diode

We demonstrate that hexagonal boron nitride can form a release layer that enables the mechanical transfer of gallium nitride-based devices structures onto foreign substrates. For the vertical-type transferred light-emitting diode (LED), after the LED structure had been released, the electrodes were deposited on the back side of the LED. Then, we mounted it onto the indium sheet. An AlGaN/GaN heterostructure, an InGaN/GaN multiple-quantum-well (MQW) structure, and the MQW LED, in area from five millimeters square to two centimeters square, are then mechanically released from the sapphire substrates and successfully transferred onto other substrates. (Page 14)

PEDOT-PSS silk (left) and naive silk (right) thread

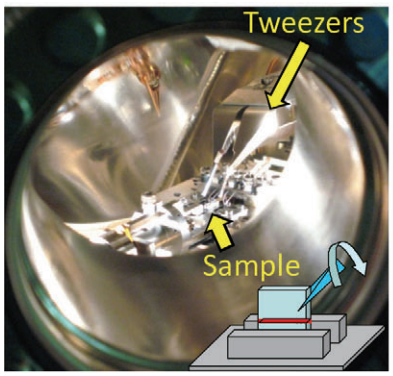
Macroscopic image



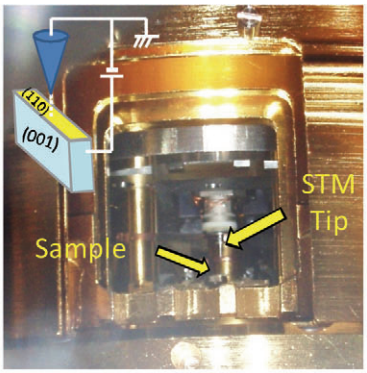
Skin surface electrodes

Conductive Polymer Combined with Silk Fibers for Biomedical Electrodes

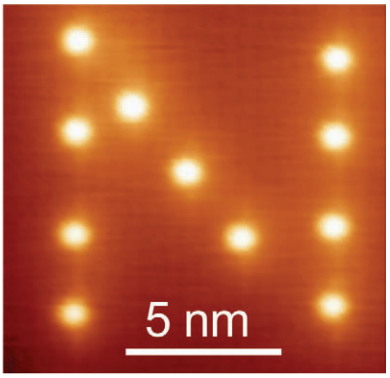
We developed and characterized bio-interface material with a conductive polymer combined silk fibers for biomedical signal recordings, such as electroencephalography. Biocompatible, soft and hydrophilic electrode offers long-term stable communication to living tissues for biomedical and information and communication technology without stress to the subjects. (Page 23)



Cleavage in ultra- high vacuum



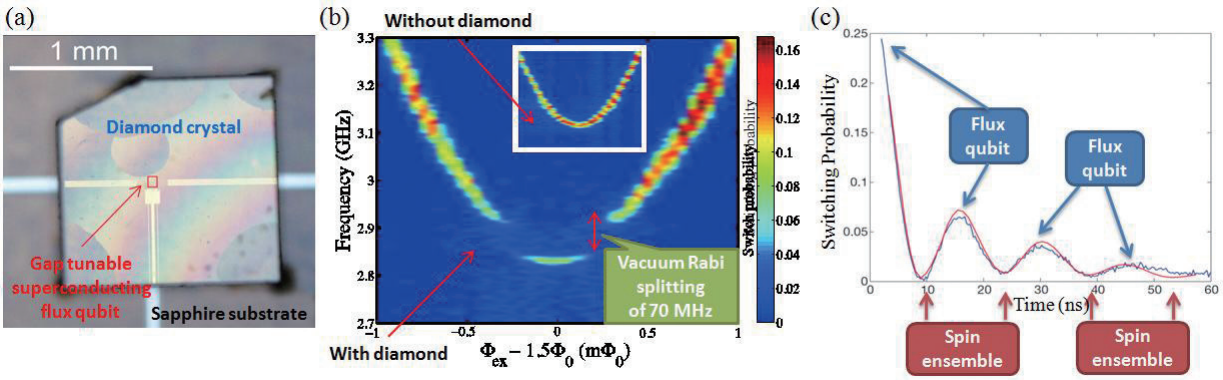
Manipulation with scanning tunneling microscope



"N" made by 11 In atoms

In Atom Manipulation on Cleaved InAs(110) Surface

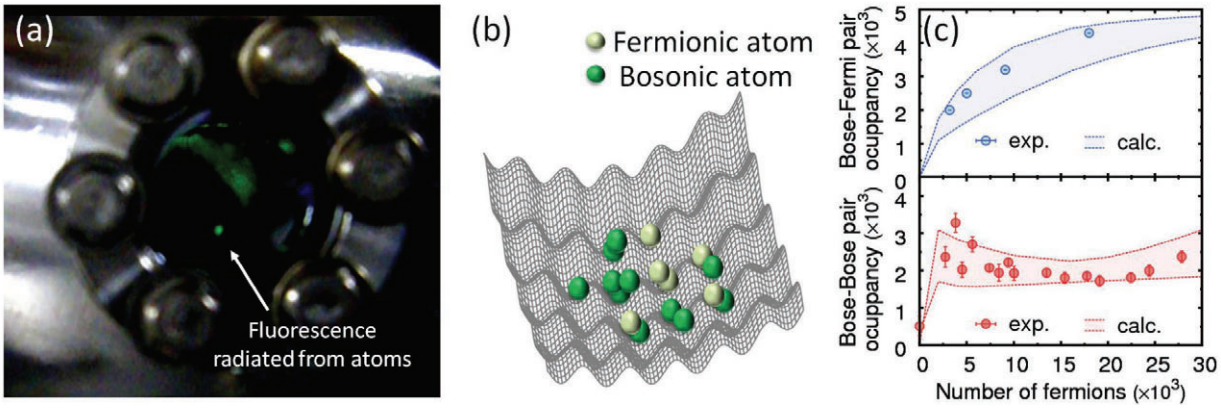
We have succeeded in manipulating In atoms vertically and horizontally on an InAs(110) surface obtained by cleaving in ultra-high vacuum using scanning tunneling microscope (STM). Atomic-scale devices made by this atom manipulation technique are expected in future. (Page 30)



(a) Superconductor-diamond hybrid system. (b) Microwave spectrum of a superconducting flux quibt. (c) Vacuum Rabi oscillation between a flux qubit and a spin ensemble.

Coherent Coupling of a Gap-Tunable flux Qubit to an Electron Spin Ensemble in Diamond

A superconductor-diamond hybrid system has attracted considerable interest as the electron spin trapped at a nitrogen-vacancy (NV) center in diamond has the potential to be a quantum memory for a superconducting qubit. In this research we have achieved strong coupling between a gap-tunable flux qubit and an NV spin ensemble. Furthermore we also observed the coherent exchange of a single quantum of energy between them. This is the first step towards the realization of a long-lived quantum memory and hybrid devices coupling microwave and optical systems. (Page 33)



(a) Ultracold atoms in a vacuum chamber. (b) Schematic diagram of Bose-Fermi mixtures in an optical lattice that is a periodic potential created by the laser interference. (c) Pair occupancies obtained by both experiments and numerical calculations considering ambiguity of experimental parameters.

Exploring Novel Quantum Phases of Bose-Fermi Mixtures Trapped in an Optical Lattice

Collaborating with the group at Kyoto University, we investigated the Bose-Fermi mixtures trapped in an optical lattice, and observed novel quantum phases induced by the interaction between bosons and fermions. We developed a numerical method for efficiently analyzing this system, and quantitatively reproduced the experimental observations done by the Kyoto University group. We further analyzed quantities that are difficult to be measured by the current experimental techniques. Based on these results, we determined what kind of quantum phases appear in this system, and finally clarified the appearance of the novel quantum phases. (Page 35)

Message from the Director

We at NTT Basic Research Laboratories (BRL) are extremely grateful for your interest and support with respect to our research activities.

BRL's missions are to promote progress in science and innovations in leading-edge technology to advance NTT's business. To achieve these missions, researchers in fields including physics, chemistry, biology, mathematics, electronics, informatics, and medicine, conduct basic research on materials science, physical science and optical science.

Our management principle is based on an "open door" policy. For example, we are collaborating with many universities and research institutes in Japan, US, Europe, and Asia as well as other NTT laboratories. We co-organize international conferences relating to quantum information and atom manipulation with other research institutions to disseminate our research output and to give NTT researchers including the younger ones the opportunity to share ideas with the foremost authorities and to learn from them.

These activities enable us to realize our "open door" policy and 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, 2012

Toshiki Makimoto

Toshiki Makimoto
Director
NTT Basic Research Laboratories

Contents

NTT Basic Research Laboratories Organogram

As of March 31, 2012

Director

Toshiki Makimoto, Dr.

Nano Bio Research

Executive Manager

Keiichi Torimitsu, Dr.

Research Planning Section

Executive Manager

Tetsuomi Sogawa, Dr.

Materials Science Laboratory

Executive Manager

Toshiki Makimoto, Dr.

Physical Science Laboratory

Executive Manager

Hiroshi Yamaguchi, Dr.

Optical Science Laboratory

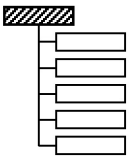
Executive Manager

Yasuhiro Tokura, Dr.

Member List

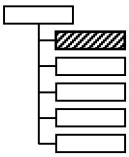
As of March 31, 2012
(*/ left NTT BRL during the year)

NTT Basic Research Laboratories



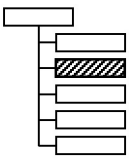
Director, **Dr. Toshiki Makimoto**

Nano Bio Research



Executive Manager, **Dr. Keiichi Torimitsu**

Research Planning Section

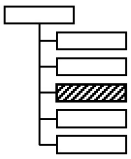


Executive Research Scientist, **Dr. Tetsuomi Sogawa**

Senior Research Scientist, Dr. Hiroki Takesue

Senior Research Scientist, Dr. Akihiko Shinya

Materials Science Laboratory



Executive Manager, **Dr. Toshiki Makimoto**

Dr. Nahoko Kasai

Thin-Film Materials Research Group:

Dr. Hideki Yamamoto (Group Leader)

Dr. Makoto Kasu*	Dr. Yasuyuki Kobayashi	Dr. Hisashi Sato
Dr. Tetsuya Akasaka	Dr. Kazuhide Kumakura	Dr. Yoshitaka Taniyasu
Dr. Yoshiharu Krockenberger	Dr. Kazuyuki Hirama	

Low-Dimensional Nanomaterials Research Group:

Dr. Hiroki Hibino (Group Leader)

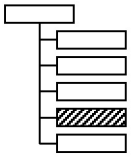
Dr. Fumihiko Maeda	Dr. Kazuaki Furukawa	Dr. Hiroo Omi
Dr. Satoru Suzuki	Dr. Ken-ichi Kanzaki	Shin-ichi Tanabe
Dr. Makoto Takamura	Dr. Yuya Murata	

Molecular and Bio Science Research Group:

Dr. Koji Sumitomo (Group Leader)

Dr. Akiyoshi Shimada	Dr. Hiroshi Nakashima	Dr. Yoshiaki Kashimura
Dr. Touichiro Goto	Dr. Aya Tanaka	Dr. Shingo Tsukada

Physical Science Laboratory



Executive Manager, **Dr. Hiroshi Yamaguchi**

Toru Yamaguchi

Takeshi Karasawa

Nanodevices Research Group:

Dr. Akira Fujiwara (Group Leader)

Dr. Yukinori Ono	Dr. Hiroyuki Kageshima	Dr. Katsuhiko Nishiguchi
Dr. Jin-ichiro Noborisaka	Dr. Gento Yamahata	Dr. Gabriel Lansbergen

Nanostructure Technology Research Group:

Dr. Hiroshi Yamaguchi (Group Leader)

Dr. Kenji Yamazaki	Dr. Koji Onomitsu	Dr. Hajime Okamoto
Daiki Hatanaka	Dr. Imran Mahboob	Junzo Hayashi

Quantum Solid State Physics Research Group:

Dr. Koji Muraki (Group Leader)

Dr. Kiyoshi Kanisawa	Dr. Satoshi Sasaki	Dr. Kyoichi Suzuki
Dr. Toshiaki Hayashi	Dr. Takeshi Ohta	Dr. Norio Kumada
Dr. Ken-ichi Hitachi	Dr. Keiko Takase	Dr. Takashi Kobayashi
Tadashi Saku*		

Superconducting Quantum Physics Research Group:

Dr. Kouichi Semba (Group Leader)

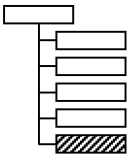
Dr. Hayato Nakano	Dr. Shiro Saito	Dr. Shin-ichi Karimoto
Hirotaka Tanaka	Dr. Kousuke Kakuyanagi	Dr. Yuichiro Matsuzaki
Dr. Xiaobo Zhu		

Spintronics Research Group:

Dr. Tatsushi Akazaki (Group Leader)

Dr. Yuichi Harada	Dr. Hiroyuki Tamura	Dr. Masumi Yamaguchi
Dr. Yoshiaki Sekine	Dr. Hiroshi Irie	

Optical Science Laboratory



Executive Manager, **Dr. Yasuhiro Tokura**

Dr. Takehiko Tawara

Quantum Optical State Control Research Group:

Dr. Yasuhiro Tokura (Group Leader)

Dr. Kaoru Shimizu	Kazuhiro Igeta	Dr. Masami Kumagai
Dr. Makoto Yamashita	Dr. Hiroyuki Shibata	Dr. Tetsuya Mukai
Dr. Fumiaki Morikoshi	Dr. Kiyoshi Tamaki	Daisuke Hashimoto
Dr. Kensuke Inaba	Dr. Koji Azuma	Dr. Nobuyuki Matsuda
Dr. Hiromitsu Imai	Dr. William John Munro	Dr. Toshihiro Kubo
Dr. Haruka Tanji		

Quantum Optical Physics Research Group:

Dr. Tetsuomi Sogawa (Group Leader)

Dr. Tadashi Nishikawa	Dr. Hideki Gotoh	Dr. Kouta Tateno
Dr. Katsuya Oguri	Dr. Atsushi Ishizawa	Dr. Haruki Sanada
Dr. Guoquiang Zhang	Dr. Keiko Kato	Dr. Ken-ichi Hitachi
Dr. Ken-ichi Sasaki		

Photonic Nano-Structure Research Group:

Dr. Masaya Notomi (Group Leader)

Dr. Atsushi Yokoo	Dr. Eiichi Kuramochi	Dr. Hideaki Taniyama
Dr. Hisashi Sumikura	Dr. Kengo Nozaki	Dr. Masato Takiguchi
Dr. Masaaki Ono	Dr. Jimyung Kim	Dr. Danang Birowosuto
Dr. Xu, Hao		

Senior Distinguished Researcher

Masaya Notomi was born in Kumamoto, Japan, on 16 February 1964. He received his B.E., M.E. and Ph. D. degrees in applied physics from University of Tokyo, Japan in 1986, 1988, and 1997, respectively. In 1988, he joined NTT Optoelectronics Laboratories. 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. He has been in NTT Basic Research Laboratories since 1999, and a group leader of Photonic Nanostructure Research Group since 2004. He is also entitled as Senior Distinguished Scientist of NTT. From 1996-1997, he was with Linköping University in Sweden as a visiting researcher. He was a guest associate professor of Department of Applied Electronics in Tokyo Institute of Technology (2003-2009), and is currently a guest professor of Department of Physics in Tokyo Institute of Technology. He received IEEE/LEOS Distinguished Lecturer Award in 2006, JSPS (Japan Society for the Promotion of Science) prize in 2009, Japan Academy Medal in 2009, and 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. 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 was born in Osaka on October 30, 1961. He received the B.E., M.S. in physics and Ph.D. degrees in engineering from the Osaka University in 1984, 1986 and 1993, respectively. He joined NTT Basic Research Laboratories in 1986 and has 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 in 2008 and 2009. He served as more than 40 committee members of academic societies and international conferences. He received Inoue Prize for Science (2012), Institute of Physics Fellowship (2011), SSDM2009 Paper Award (2010), MNC2008 Outstanding Paper Award (2009), and the Paper Awards of Japan Society of Applied Physics (1989, 2004, 2010). He is currently an executive manager of Physical Science Laboratory and a group leader of Nanostructure Technology Research Group. He is a member of the Japan Society of Applied Physics, the Physical Society of Japan, Institute of Physics (UK), and IEEE.

Distinguished Researchers

Akira Fujiwara was born in Tokyo, Japan on March 9, 1967. He 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. In 1994, he joined NTT LSI Laboratories 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 received the SSDM Young Researcher Award in 1998, SSDM Paper Award in 1999, and Japanese Journal of Applied Physics (JJAP) Paper Awards in 2003 and 2006. He was awarded the Young Scientist Award from the Minister of MEXT (Ministry of Education, Culture, Sports, Science, and Technology) in 2006. He was a director of the Japanese Society of Applied Physics in 2010 and 2011. He is a member of the Japan Society of Applied Physics and the IEEE.

Koji Muraki was born in Tokyo, Japan in 1965. He 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. In 1994, he joined NTT Basic Research Laboratories, Kanagawa, Japan. 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 is a member of the Physical Society of Japan and Japan Society of Applied Physics.

Yoshitaka Taniyasu was born in Toyama, Japan on June 10, 1973. He received his B.E., M.E., and Dr. Eng. degrees in electrical engineering from Chiba University, Japan in 1996, 1998, and 2001, respectively. He joined NTT Basic Research Laboratories in 2001. He has been engaged in wide bandgap semiconductor research. His current interests are epitaxial growth and device application of nitride semiconductors, especially aluminum nitride (AlN). He is a visiting researcher at Ecole Polytechnique Fédérale de Lausanne (EPFL) during 2011-2012. He received the Young Scientist Award for the Presentation of the Excellent Paper at the Japan Society of Applied Physics (JSAP) in 2001, the Young Scientist Award at the 14th Semiconducting and Insulating Materials Conference (SIMC-XIV) in 2007, and the Young Scientists' Prize from the Minister of Education, Culture, Sports, Science and Technology in 2011, the Young Scientist Award at the 38th International Symposium on Compound Semiconductors (ISCS2011) in 2011. He is a member of the JSAP.

Norio Kumada was born in Gifu, Japan in 1975. He received his B.S., M.S., and Ph.D. degrees in physics from Tohoku University, Japan, in 1998, 2000, and 2003, respectively. In 2003, he joined NTT Basic Research Laboratories, Kanagawa, Japan. Since then, he has been engaged in the study of highly correlated electronic states realized in semiconductor heterostructures. He received Young Scientist Award of the Physical Society of Japan in 2008. He is a member of the Physical Society of Japan.

Katsuhiko Nishiguchi was born in Hiroshima, Japan in 1975. He received the B.E., M.E., and Ph. D in electrical engineering in 1998, 2000, and 2002, respectively, from Tokyo Institute of Technology, Tokyo, Japan. Since joining NTT Basic Research Laboratories in 2002, 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. 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, and Young Scientist Award at the Japan Society of Applied Physics Spring Meeting in 2000. He is a member of the Japan Society of Applied Physics.

Advisory Board (2011 Fiscal Year)

Name	Affiliation
Prof. Gerhard Abstreiter	Walter Schottky Institute, Germany
Prof. Boris L. Altshuler	Department of Physics, Columbia University, U.S.A.
Prof. Serge Haroche	Département de Physique, De l'Ecole Normale Supérieure, France
Prof. Theodor W. Hänsch	Max-Planck-Institut für Quantenoptik, Germany
Prof. Mats Jonson	Department of Physics, Göteborg University, Sweden
Prof. Anthony J. Leggett	Department of Physics, University of Illinois at Urbana-Champaign, U.S.A.
Prof. Johan E. Mooij	Kavli Institute of Nanoscience, Delft University of Technology, The Netherlands
Prof. John F. Ryan	Clarendon Laboratory, University of Oxford, U.K.
Prof. Klaus von Klitzing	Max-Planck-Institut für Festkörperforschung, Germany

Invited / Guest Scientists (2011 Fiscal Year)

Name	Affiliation	Period
Dr. Lars Tiemann	Japan Science and Technology Agency (JST), Japan	Apr. 2009 – Feb. 2012
Dr. Takasumi Tanabe	Keio University, Japan	Jul. 2010 – Mar. 2012
Dr. Kenichiro Kusudo	National Institute of Informatics (NII), Japan	Apr. 2011 – Mar. 2012
Dr. Mao-Chuang Yeh	University of Illinois at Urbana-Champaign, U.S.A.	May 2010 – Jun. 2011
Dr. Stefan Fölsch	Paul-Drud-Institute, Germany	Oct. 2011 – Nov. 2011
Dr. Trevor David Rhone	Japan Science and Technology Agency (JST), Japan	Feb. 2012 – Jan. 2013

Overseas Trainees (2011 Fiscal Year)

Name	Affiliation	Period
Roberto Lo Nardo	Palermo University, Italy	Jan. 2011 – Aug. 2011
Diego Sabbagh	University of Studies "Roma Tre", Italy	Jan. 2011 – Aug. 2011
Yibo Fu	University of Toulouse, France	Feb. 2011 – Sep. 2011
Yasir Makhdoom	University of British Columbia, Canada	May 2011 – Aug. 2011
Mohamed Oudah	University of Ottawa, Canada	May 2011 – Aug. 2011
Rahul S. Deshpande	Indian Institute of Technology Guwahati, India	Jun. 2011 – Jul. 2011
Gregory Webber	University of Victoria, Canada	Jul. 2011 – Dec. 2011
Hanna Le Jeannic	ESPCI ParisTech (École supérieure de physique et de chimie industrielles de la ville de Paris), France	Jul. 2011 – Dec. 2011
Melanie Marcel	ESPCI ParisTech (École supérieure de physique et de chimie industrielles de la ville de Paris), France	Jul. 2011 – Dec. 2011
Amaury Badon	ESPCI ParisTech (École supérieure de physique et de chimie industrielles de la ville de Paris), France	Jul. 2011 – Dec. 2011
Henri J. Suominen	The University of Edinburgh, Switzerland	Aug.2011 –
Vincent Nier	ESPCI ParisTech (École supérieure de physique et de chimie industrielles de la ville de Paris), France	Aug.2011 – Dec. 2011
Adrien Gourgout	ESPCI ParisTech (École supérieure de physique et de chimie industrielles de la ville de Paris), France	Sep. 2011 – Dec. 2011
Benjamin Pingault	ESPCI ParisTech (École supérieure de physique et de chimie industrielles de la ville de Paris), France	Sep. 2011 – Jan. 2012
Andy Berry	University of Victoria, Canada	Sep. 2011 –
Michael Firka	University of Victoria, Canada	Sep. 2011 –
Jingjing Huang	California Institute of Technology, U.S.A.	Sep. 2011 – Dec. 2011
Elan Grossman	Georgia Institute of Technology, U.S.A.	Jan. 2012 –
Bennett Eleazer	Georgia Institute of Technology, U.S.A.	Jan. 2012 –
Yong Fan Jiang	The University of British Columbia, Canada	Jan. 2012 –
Gediminas Dauderis	Vilnius University, Lithuania	Jan. 2012 –
Maria Anagosti	University of Gent, Belgium	Jan. 2012 –
Roger Molto Pallares	Chemical Institute of Sarria (IQS), Spain	Jan. 2012 –
Sanna Maria Rauhamäki	University of Jyväskylä, Finland	Jan. 2012 –
Alex Yang	The University of British Columbia, Canada	Jan. 2012 –
Shibin Thomas	Mahatma Gandhi University, India	Mar. 2012

Domestic Trainees (2011 Fiscal Year)

Name	Affiliation	Period
Takayuki Watanabe	Tohoku University	Apr. 2011 – Mar. 2012
Shogo Aihara	Keio University	Apr. 2011 – Mar. 2012
Hiroshi Kamata	Tokyo Institute of Technology	Apr. 2011 – Mar. 2012
Shun Dai	University of Tokyo	Apr. 2011 – Mar. 2012
Naoyuki Masumoto	University of Tokyo	Apr. 2011 – Mar. 2012
Yuma Okazaki	Tohoku University	Apr. 2011 – Mar. 2012
Yoji Kunihashi	Tohoku University	Apr. 2011 – Mar. 2012
Rento Osugi	Tohoku University	Apr. 2011 – Mar. 2012
Tatsuya Baba	Tokyo University of Science	Apr. 2011 – Mar. 2012
Shunichi Matsumoto	Tokyo University of Science	May 2011 – Mar. 2012
Hajime Suzuki	Tokyo University of Science	May 2011 – Mar. 2012
Mohammed Fauzi	Tohoku University	Jun. 2011
Takanobu Tsunoi	Yokohama National University	Jun. 2011 – Mar. 2012
Atsushi Iwamoto	The University of Tokushima	Aug. 2011– Sep. 2011
Rui Asaoka	Tohoku University	Sep. 2011 – Oct. 2011
Masato Inoue	Kyushu University	Sep. 2011 – Dec. 2011
Atsushi Hagiwara	The University of Electro- Communications	Sep. 2011
Takayuki Tanaka	Hokkaido University	Sep. 2011
Yuta Noguchi	Nagaoka University of Technology	Oct. 2011 – Feb. 2012
Yamato Munataka	Nagaoka University of Technology	Oct. 2011 – Feb. 2012
Keita Sakuma	Nagoya University	Oct. 2011 – Dec. 2011
Hiroto Oomae	Nagaoka University of Technology	Oct. 2011 – Dec. 2011
Yoshiyuki Abe	Toyohashi University of Technology	Oct. 2011 – Feb. 2012

Ⅰ. Research Topics

Overview of Research in Laboratories

Materials Science Laboratory Toshiki Makimoto

The Materials Science Laboratory (MSL) aims at producing new functional materials and designing of advanced device based on novel materials and biological function. Controlling the configuration and coupling of atoms and molecules is our approach to accomplish these goals. We have three research groups covering from thin film materials, such as nitride semiconductors, diamond, graphene, and superconductors, to biological molecules, such as receptor proteins and lipid bilayers. The distinctive characteristic of MSL is its effective sharing of the unique nanofabrication and measurement techniques of each group. This enables fusion of research fields and techniques, which leads to innovative material research for the future information technology.

This year, we successfully obtained research results on the mechanical transfer of large-size GaN devices using layered BN (Mechanical Transfer using a Release-layer : "METRE" method), the unique transport characteristics of the monolayer epitaxial graphene, and the biomedical electrodes using conductive polymer and silk.

Physical Science Laboratory Hiroshi Yamaguchi

We are studying semiconductor and superconductor-based solid-state devices, which will have a revolutionary impact on communication and information technologies in the 21st century. In particular, we promote research of nanoscale devices fabricated using high-quality crystal growth and fine lithographic techniques.

The five groups in our laboratory are working in the following areas: precise and dynamical control of single electrons, nanodevices operating with ultra low power consumption, novel nanomechanical systems utilizing mechanical degrees of freedom in solid-state architectures, coherent quantum control of semiconductor and superconductor systems, carrier interactions in semiconductor hetero- and nanostructures, spintronics manipulating both electron and nuclear spins. We also promote the studies of cutting-edge nanolithography techniques, high-quality crystal growth, and theoretical studies including first-principle calculations.

Optical Science Laboratory Yasuhiro Tokura

This laboratory aims for the development of core-technologies that will innovate on optical communications and optical signal processing, and seeks fundamental scientific progresses.

The groups in our laboratory are working for the quantum state control by very weak light, the search for intriguing phenomena using very intensive and short pulse light, and very small optical integrated circuits using two-dimensional photonic crystals, based on the optical properties of semiconductor nanostructures like a quantum dot.

In this year, we demonstrated a highly efficient optical non-linearity with a coupled resonator optical waveguide and established a comprehensive theoretical description for quantum mechanical properties of cooled atoms trapped in an optical lattice made with lightwaves. We also demonstrated spin transport and manipulation in semiconductors by surface acoustic waves, and developed an ultralow-power all-optical RAM based on photonic crystal nanocavities.

Layered Boron Nitride as a Release Layer for Mechanical Transfer of GaN-Based Devices

Yasuyuki Kobayashi, Kazuhide Kumakura, Tetsuya Akasaka, and Toshiki Makimoto
Materials Science Laboratory

Nitride semiconductors are the materials of choice for a variety of device applications. One important practical goal is to realize such devices on large, flexible and affordable substrates, on which direct growth of nitride semiconductors of sufficient quality is problematic. Several techniques have been investigated to enable the transfer of nitride devices from one substrate to another, but existing methods still have some important disadvantage. Here we demonstrate that hexagonal boron nitride (h-BN) can form a release layer that enables the mechanical transfer of GaN-based device structures onto foreign substrates [1].

Photograph in Figure 1 shows the transferred AlGaN/GaN heterostructure, approximately 2 cm square, on an adhesive sheet (an indium sheet in this case) attached to a foreign sapphire substrate. We can see the surface of the indium sheet because the AlGaN is transparent. The size of the transferred area can be controlled by the adhesive sheet size. Some protrusions from the indium sheet are clearly visible, indicating the AlGaN/GaN heterostructure is mechanically released from the native sapphire substrate. No cracks were observed in the transparent AlGaN/GaN heterostructure up to maximum size of about 1 cm square, suggesting that mechanical release process using the h-BN layer ensures minimal crack formation. Next, we describe the electroluminescence emitted from the transferred multiple quantum well (MQW) light-emitting diode (LED) at room temperature. For comparison, the same MQW LED structure was grown on a typical low-temperature AlN buffer layer on a sapphire substrate and the conventional MQW LED was fabricated without lift-off. Current-voltage characteristics of the transferred LED show clear rectification. The electroluminescence intensities from the transferred LED were comparable to or higher than the intensities from the conventional LED on the low-temperature AlN buffer layer at the same current. The comparable intensities of the electroluminescence of the conventional and transferred LED indicate that the MQW preserves its original quality after the transfer. We further succeeded in transferring a vertical-type LED. This vertical-type LED emits blue light at room temperature (Figure 2).

The process we report here opens the way to releasing and transferring a wide range of nitride semiconductor devices to large-area, flexible and affordable substrates.

[1] Y. Kobayashi, K. Kumakura, T. Akasaka, and T. Makimoto, Nature **484** (2012) 223.

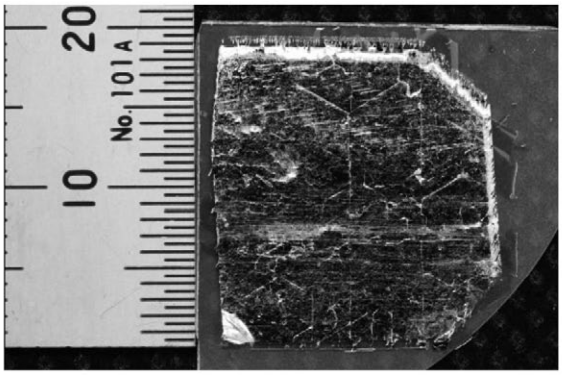


Fig. 1. Photograph of the transferred AlGaN/GaN structure on the foreign sapphire substrate.

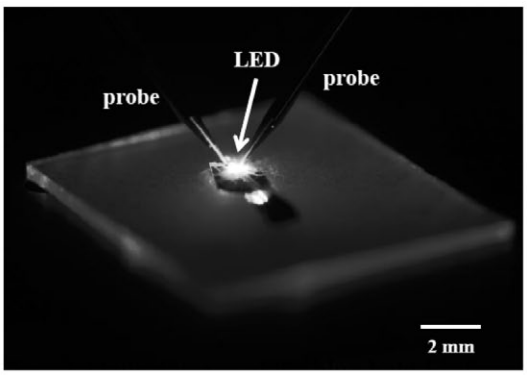


Fig. 2. Optical image of the blue-light EL from the transferred vertical-type LED.

Deep-UV Light Emission from AlN/GaN Short-Period Superlattices

Yoshitaka Taniyasu and Makoto Kasu
Materials Science Laboratory

AlGaN alloys are promising materials for ultraviolet (UV) light-emitting diodes (LEDs) with emission wavelengths ranging from 210 nm (AlN) in deep-UV to 365 nm (GaN) in near-UV regions. At present, the emission efficiency of deep-UV LEDs is much lower than that of near-UV LEDs. One intrinsic reason for the lower emission efficiency is attributed to the valence band structure [1]. For GaN the topmost valence band is the heavy hole (HH) band. The transition between the conduction band (CB) and HH band is allowed for electric field perpendicular to the c-axis (E⊥c), and the emission intensity is therefore strong along the c-axis (from C-plane). On the contrary, for AlN the topmost valence band is the crystal-field split-off (CH) band. The transition between the CB and CH band is allowed for electric field parallel to the c-axis (E||c), and the emission intensity is therefore weak along the c-axis (from C-plane). Because the LEDs are fabricated with the C-plane orientation, which is suitable for high-quality growth, the emission intensity is intrinsically low for deep-UV LEDs using high-Al-content AlGaN. Recently, we demonstrated that AlN/GaN short-period superlattices (SLs) show stronger deep-UV light emission from the C-plane than the AlGaN alloys [2].

Transmission electron microscopy (TEM) images of AlN/GaN short-period SLs are shown in Fig. 1. The GaN well thickness was 0.48 nm (1.8 monolayesr) and the AlN barrier thickness was 1.82 nm (7.3 monolayers). The growth of the SL structure with abrupt interfaces between AlN and GaN was confirmed. The emission properties of the AlN/GaN short-period SLs were characterized by photoluminescence (PL). As the GaN well thickness decreased from 2.5 to 0.9 monolayers, the emission wavelength decreased from 275.8 to 236.9 nm due to the quantum size effect. To investigate the polarization property, angle-dependent PL was carried out (Fig. 2). For an AlGaN alloy, the emission along the c-axis (θ = 0°) was weak because of the E||c polarization. On the contrary, for the AlN/GaN short-period SLs, the emission along the c-axis was strong. This is because the quantized energy level for holes originates from the HH band of GaN and therefore the transition between the electron and hole quantized energy levels is allowed for E⊥c. Due to the different polarization properties, the AlN/GaN short-period SL shows four times higher emission intensity than the AlGaN alloy. We also fabricated a deep-UV LED with AlN/GaN short-period SLs as an emission layer and confirmed strong deep-UV light emission from C-plane.

[1] Y. Taniyasu and M. Kasu, Appl. Phys. Lett. **90** (2007) 261911.
[2] Y. Taniyasu and M. Kasu, Appl. Phys. Lett. **99** (2011) 251112.

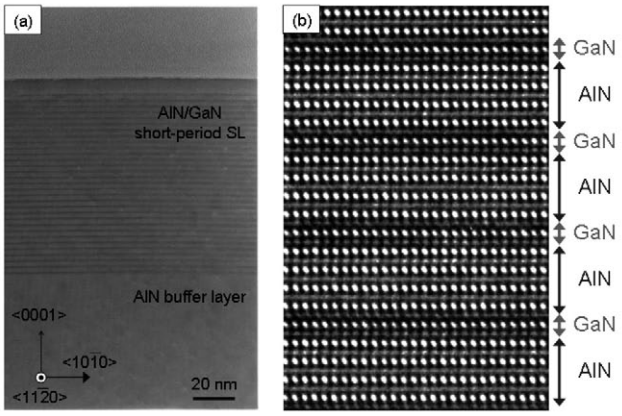


Fig. 1. (a) Cross-sectional TEM image of the AlN/GaN short-period SLs and (b) its higher magnification.

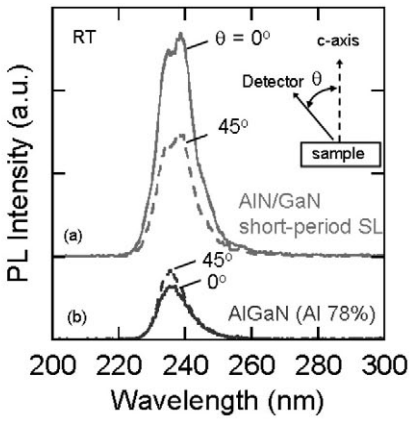


Fig. 2. PL of (a) the AlN/GaN short-period SLs and (b) the AlGaN alloy.

Molecular Beam Epitaxy of High Quality Thin Films of Infinite Layer Cuprate Superconductor (Sr, La)CuO_2

Yoshiharu Krockenberger, Keita Sakuma, and Hideki Yamamoto
Materials Science Laboratory

Infinite layer cuprate superconductors are built up only by CuO_2 planes spaced by Sr or La. Consequently, their crystal structure is the simplest among all of the cuprate superconductors. However, the synthesis of the infinite layer phase remains arduously as the tetragonal crystal structure (P4/*mmm*, S.G. 221) is stabilized only under high pressure synthesis conditions [1]. Nonetheless, early studies have shown that $Sr_{1-x}La_xCuO_2$ thin films can be grown by molecular beam epitaxy (MBE) [2]. In contrast to bulk samples synthesized under high pressure, single phase thin films readily allow electronic transport measurements. We have synthesized high quality infinite layer cuprate superconductors by MBE [3]. Crucial growth parameters are a stringent stoichiometry control which was done by electron impact emission spectroscopy. Beside the stoichiometry of the cations, the oxidizing conditions during the growth play a significant role for the appearance of superconductivity. Infinite layer cuprate films grown by MBE have been analyzed by high resolution transmission electron microscopy. Over large areas (>1000 nm^2) crystalline imperfections are not observed, in contrast to films synthesized by other methods. Those films are grown coherently on $DyScO_3$(110) as shown in Fig. 1. Notably Laue oscillations are also observed the reciprocal space map (Fig. 1). In Fig. 2, we show the temperature dependence of the resistivity. Metallic conduction as well as an RRR value of >4 are observed. Also shown in Fig. 2 are the magneto resistivity curves, where the magnetic field is applied perpendicular to the CuO_2 planes. In addition to the resistive transition into the superconducting phase, we also observed a clear Meissner shielding by a SQUID magnetometer. The residual resistivity of those films is estimated to be approximately 10 μΩcm, thus small enough for further investigations on the Fermi surface of infinite layer cuprate superconductors from Shubnikov - de Haas oscillations.

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[2] S. Karimoto et al., Appl. Phys. Lett. **79** (2001) 2767.
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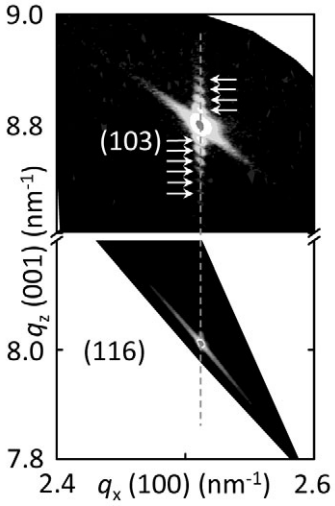

Fig. 1. Reciprocal space map of a $Sr_{0.90}La_{0.10}CuO_2$ film grown on a $DyScO_3$(110) substrate.

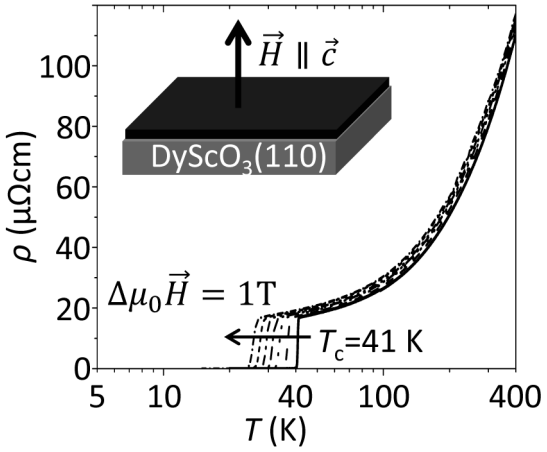

Fig. 2. Temperature dependence of the electrical resistivity of a $Sr_{0.90}La_{0.10}CuO_2$ film grown on a $DyScO_3$(110) substrate for magnetic fields applied perpendicular to the CuO_2 planes.

Thermally Stable Operation of Hydrogen-Terminated Diamond FETs by Al_2O_3 Passivation

Kazuyuki Hirama[1], Hisashi Sato[1], Yuichi Harada[2], and Makoto Kasu[1, 3]
[1]Materials Science Laboratory, [2]Physical Science Laboratory, [3]Saga University

High-frequency (>100 GHz) operations have been demonstrated for hydrogen-terminated (H-terminated) diamond field effect transistors (FETs) with a hole accumulation layer channel [1]. Recently, we revealed that the hole carriers are mainly generated by nitrogen-dioxide (NO_2) adsorpted on the H-terminated surface. However, there still remains a thermal stability problem: With increasing temperature in a vacuum, the hole carrier density decreases, most likely due to desorption of the adsorbates. In this work, to solve the problem, we passivated the H-terminated diamond surface with Al_2O_3.

After highly concentrated NO_2 adsorption (2% in N_2) to the H-terminated diamond surface, a 10-nm-thick Al_2O_3 passivation layer was deposited by the atomic layer deposition (ALD) method. Figure 1 shows the temperature dependence of sheet hole concentration (p_s) and hole mobility (μ) of the hole accumulation layer on the passivated diamond surface. Both p_s and μ were the same values in the repeated measurements. This confirms that the hole accumulation layer on the passivated diamond surface is thermally stable. In a temperature range > 30°C, the ionization energy was estimated to be as low as 6.2 meV. On the other hand, μ changes in proportion to 1/T (the T^{-1} rule) for T > 100°C. The T^{-1} rule indicates the degeneration of the hole carriers at higher temperatures [2].

Next, we applied the Al_2O_3 passivation technique to diamond FETs. Figure 2 shows the drain current-voltage (I_{DS}-V_{DS}) characteristics of the passivated diamond FET at 200°C and RT before and after the 200°C heating in a vacuum. Before the 200°C heating, the maximum I_{DS} (I_{DSmax}) at RT was −200 mA/mm. At 200°C, the I_{DSmax} decreased to −180 mA/mm. After the 200°C heating, the I_{DSmax} increased to the initial value of −200 mA/mm at RT. Before and after the heating, I_{DS} at every V_{GS} clearly agree well with each other. The threshold voltage (V_{th}) remained constant (+1 V), which implies that the hole density under the gate electrode stayed exactly the same value after the heating cycle below 200°C. Therefore, the I_{DS} decrease at 200°C is attributed to the temperature dependence of hole mobility, as observed in Fig. 1(b). These results reveal that the Al_2O_3 passivated diamond FETs can be operated without thermal degradation at least up to 200°C.

[1] M. Kasu et al., Electronics Lett. **41** (2005) 1249.
[2] M. Kasu, H. Sato, and K. Hirama, Appl. Phys. Express **5** (2012) 025701.

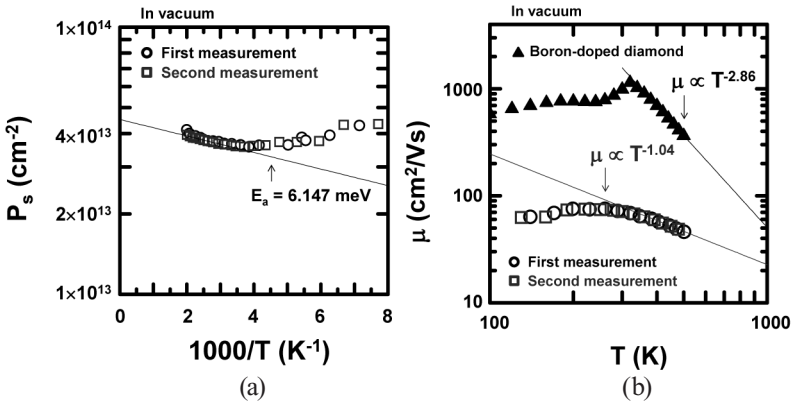

Fig. 1. Temperature dependence of (a) sheet hole density and (b) mobility.

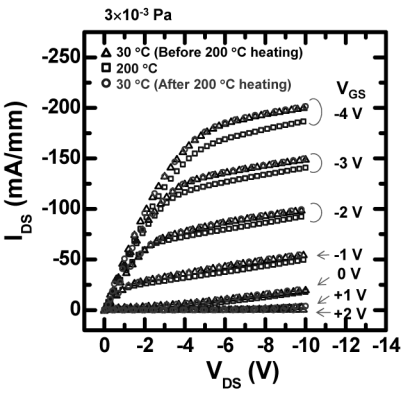

Fig. 2. I_{DS}-V_{DS} characteristics of a passivated diamond FET.

Molecular Beam Epitaxal Growth of Graphene and Nanofin Networks

Fumihiko Maeda and Hiroki Hibino
Materials Science Laboratory

For graphene, which is a material of great interest for the future electronics, establishing a method for its wafer-scale fabrication remains a challenge for its application to large-scale integration. We have proposed a new approach to fabricate graphene based on gas-source molecular beam epitaxy (MBE) and have shown its feasibility [1]. Then, we observed an interesting nanostructure, which forms a network. Here, we report an investigation of its structural details [2].

As a substrate, we used graphene, from one to two layers, formed on n-type SiC(0001) by annealing at 1800°C in Ar ambient at about 100 Torr. For the MBE growth, the substrate was heated under the flow of ethanol cracked by a W filament set at 2000°C. By atomic force microscopy (AFM), the topographic image of a sample grown at 915°C was obtained [Fig. 1(a)]. In this image, the network structure can be seen on the substrate surface. Cross-sectional transmission electron microscopy (TEM) images of this sample in Fig. 2 reveal that these networks consist of one or two layers of graphene, which stick out from the surface like a fin whose height is about 5 nm. (Here, we call this ridge-structure a "graphene nanofin".) We speculate that the nanofins would be formed by collisions between incommensurate domains of the laterally growing graphene at their boundary, which means that a single domain of graphene islands is surrounded by the nanofins. Thus, the domain size of the laterally grown graphene is estimated to be less than 100 nm using the average distance between the nanofins from the section analysis of Fig. 1(b). This fin structure of atomic layer thickness with an open end has not been reported previously and is observed here for the first time. We expect that the graphene nanofin could be applied for interconnection and devices as the thinnest material of one atomic layer.

This work was supported by KAKENHI.

[1] F. Maeda and H. Hibino, Phys. Status Solidi B **247** (2010) 916.
[2] F. Maeda and H. Hibino, J. Phys. D: Appl. Phys. **44** (2011) 435305.

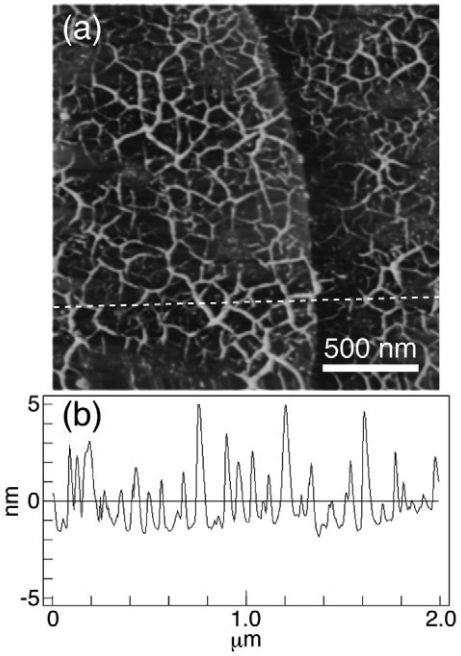

Fig. 1. (a) Topographic AFM image and (b) AFM section analysis along the dotted line in the image.

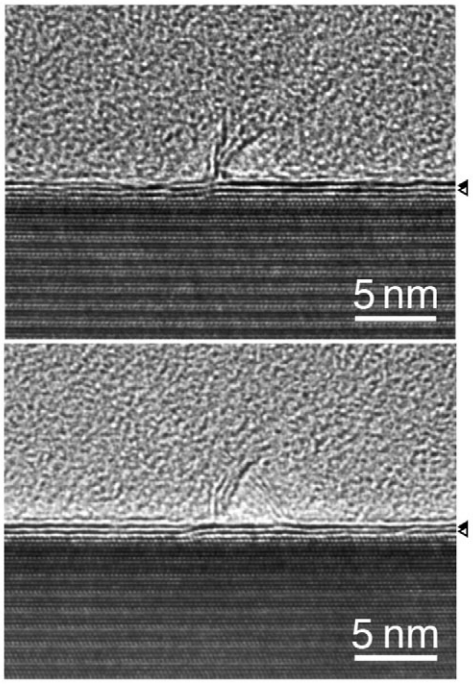

Fig. 2. Cross-sectional TEM images after MBE growth.

Erbium Silicates as Advanced Optical Materials for Light Emission at Telecommunicatios Wavelength in Silicon Photonics

Hiroo Omi and Takehiko Tawara*
Materials Science Laboratory, *Optical Science Laboratory

Erbium silicates and erbium oxide, such as Er_2SiO_5 and $Er_2Si_2O_7$, are promising materials as light emitters at the telecommunications wavelength and as optical amplifiers in the field of silicon photonics. In the erbium compounds, the density of erbium ions is 10^{22} atoms/cm^3, which is orders of magnitude greater than that typically obtained by Er ion implantation in silicon substrate, allowing access to a large number of emitting centers. In this work, we combined real-time synchrotron radiation grazing incidence X-ray diffraction (GIXD) and PL experiments to optimize the structures and optical properties of erbium silicates on silicon substrate. We firstly studied the formation of the erbium silicates during annealing in Ar gas and O_2/Ar mixture gases in real time. We determined the crystallographic structures and the temperature of crystallization, and assessed the possible reactions for the silicate formation. We secondly measured the photoluminescence (PL) from a sample annealed at 1060℃ [1].

The 100-nm-thick erbium oxides were deposited on 100-nm-thick silicon oxide film grown on Si(001) substrates by reactive sputtering at room temperature. The samples are then annealed at up to 1300℃ in Ar and O_2/Ar mixture gases. In micro-PL experiments, the samples were pumped by CW laser at the wavelength of 532 nm.

The GIXD measurements show that erbium silicates and erbium oxide are formed by interface reactions between silicon oxide and erbium oxides deposited on silicon oxide by reactive sputtering in Ar gas and O_2/Ar mixture gas ambiences. The erbium silicates are formed above 1060℃ in Ar gas ambience and above 1010℃ in O_2/Ar gas ambience, and erbium silicides are dominantly formed above 1250℃. The $I_{15/2}$-$I_{13/2}$ Er^{3+} PL from the erbium silicate exhibits abnormal temperature dependence (see Fig. 1). The PL intensity from the Er_2SiO_5 silicate exhibits abnormal temperature dependence of 1.529-μm Er^{3+} PL; the PL intensity decreases from 4 to 70 K and increases from 70 to 300 K. The increase of the PL intensity with increasing temperature observed at off-resonant excitation conditions can be explained by the phonon-assisted resonant absorption of the 532-nm excitation photons at the $^2H_{11/2}$ levels of Er^{3+} ions in the erbium silicate films.

[1] H. Omi, T. Tawara, and M. Tateishi, AIP Advances **2** (2012) 012141.

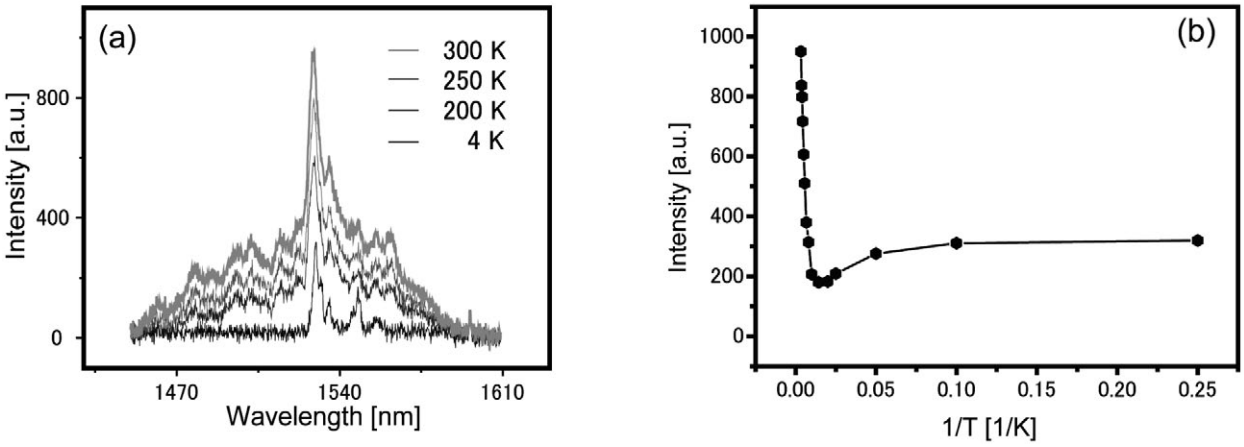

Fig. 1. Photoluminescence from erbium silicates grown on Si substrate (a), Temperature dependence of the PL intensity (b).

Peculiar Temperature Dependence of Resistance in Epitaxial Monolayer Graphene

Shinichi Tanabe[1], Yoshiaki Sekine[2], Hiroyuki Kageshima[2],
Masao Nagase[3], and Hiroki Hibino[1]
[1]Materials Science Laboratory, [2]Physical Science Laboratory, [3]The University of Tokushima

Monolayer graphene is expected to have high mobility due to its unique electronic structure, and it is an attractive material for electronics applications. Although its properties are being investigated in monolayer graphene flakes obtained by mechanical exfoliation of graphite, mechanical exfoliation is not suitable for obtaining large-area monolayer graphene. Thus, establishing a method for its mass production is needed. Monolayer graphene on SiC can be grown on a large scale by thermal decomposition of SiC(0001) in an Ar environment [1]. In top-gated Hall bar devices using monolayer graphene on SiC as the channel, promising results, such as ambipolar characteristics and the quantum Hall effect, were obtained at 2 K [2]. As a further step towards utilizing monolayer graphene on SiC for devices at room temperature, we investigated its electronic transport characteristics up to 200 K.

Figure 1 shows the gate-voltage (V_G) dependence of four-terminal resistance from 2 to 200 K. When V_G is at the charge neutrality point (V_{CNP}), the resistance decreases as temperature (T) increases. However, when V_G is away from the V_{CNP}, for example $V_G - V_{CNP}$ = 30 V, the resistance increases as T increases. The T dependence of resistance at the V_{CNP} is due to the increase of thermally activated carriers. The T dependence of resistance at V_G away from the V_{CNP} originates from decrease in mobility as shown in Fig. 2. The T dependence of mobility is determined by temperature-independent scatterings (A), acoustic phonon scattering in graphene (B), and phonon scattering from extrinsic sources (C). From the analysis in Fig. 2, the phonon scattering from extrinsic sources, which is thought to be from the substrate, strongly affects the T dependence of mobility [3]. The mobility decrease with increasing T is expected to be suppressed by controlling the phonon scattering from the substrate.

This work was supported by KAKENHI.

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[2] S. Tanabe et al., Appl. Phys. Express **3** (2010) 075102.
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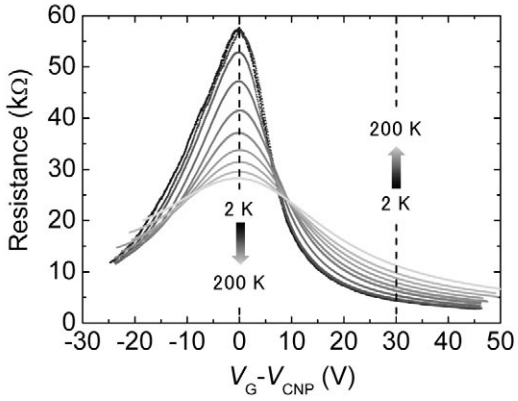

Fig. 1. Gate-voltage dependence of resistance from 2 to 200 K.

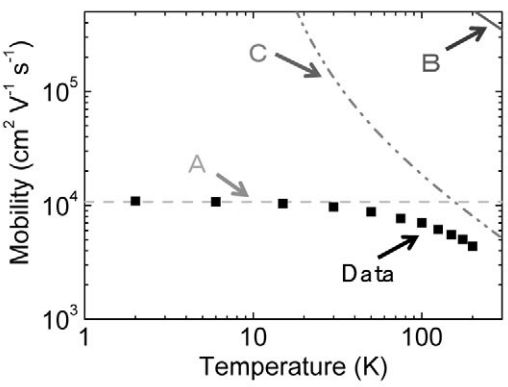

Fig. 2. Temperature dependence of mobility at electron density of 6×10^{11} cm^{-2}.

Functional Analysis of Membrane Proteins Using Microwell Array

Koji Sumitomo, Yukihiro Tamba*, Yoshiaki Kashimura, and Aya Tanaka
Materials Science Laboratory, *Suzuka Nat. Coll. Tech.

For the functional analysis of ion channel activity, an artificial lipid bilayer suspended over microwells was formed that ruptured giant unilamellar vesicles on a Si substrate. Ca^{2+} ion indicators (fluo-4) were confined in the microwells by sealing the microwells with a lipid bilayer as shown in Fig. 1. An overhang formed at the microwells prevented the lipid membrane from falling into them and allowed the stable confinement of the fluorescent probes. The transport of Ca^{2+} ions through channels formed by α-hemolysin inserted in a lipid membrane was analyzed by employing the fluorescence intensity change of fluo-4 in the microwells [1]. The insertion of α-hemolysin into a suspended lipid membrane and the formation of nanopores induce the transport of Ca^{2+} ions, and the fluorescence intensity of fluo-4 increased as a result. When the α-hemolysin concentration is higher, the fluorescence intensity should reach its maximum value earlier as shown in Fig. 2.

The microwell volume was very small (1~100 femtoliters), so a highly sensitive monitor could be realized. The detection limit is several tens of ions/sec/μm^2, and this is much smaller than the ion current in a standard electrophysiological measurement. Smaller microwells will make it possible to mimic a local ion concentration change in the cells, although the signal to noise ratio must be further improved for the functional analysis of a single channel. We demonstrated that a microwell array with confined fluorescent probes sealed by a lipid bilayer could constitute a basic component of a highly sensitive biosensor array that works with functional membrane proteins. This array will allow us to realize parallel testing devices with a high throughput.

[1] K. Sumitomo et al., Biosensors and Bioelectronics **31** (2012) 445.

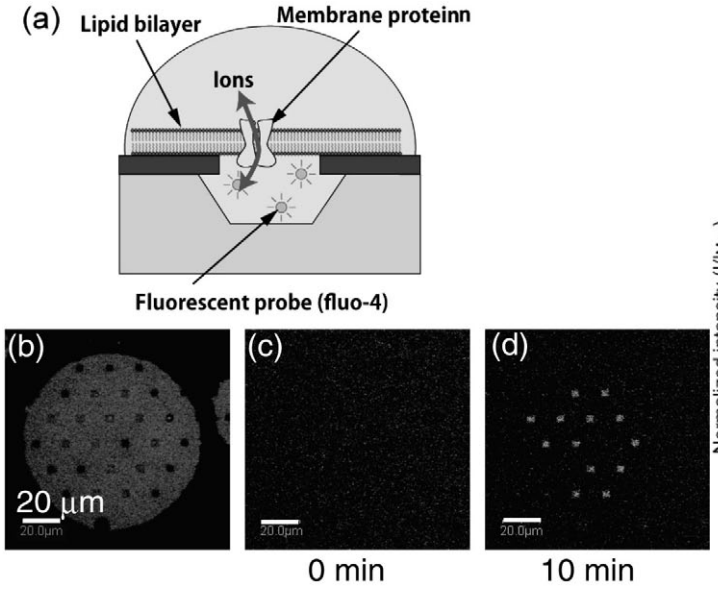

Fig. 1. Microwell sealed with lipid bilayer. (a) Schematic illustration of the model. Fluorescent images of lipid patch (b) and microwells before (c) and after (d) Ca^{2+} ion transport.

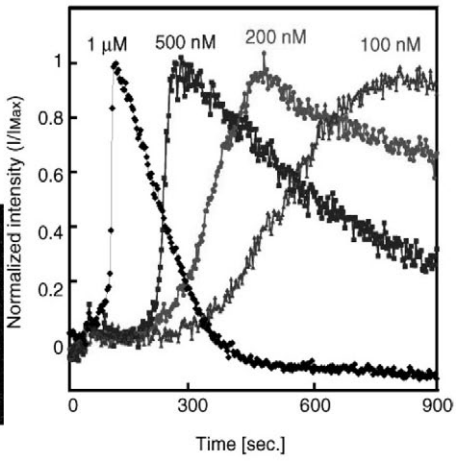

Fig. 2. Change in fluorescence intensity induced by the addition of various concentrations of α-hemolysin.

Multifunctional Stimulation Electrode for Optical, Electrical and Chemical Stimulation

Akiyoshi Shimada[1], Shuichiro Asakawa[2], and Kazuhide Nakajima[3]
[1]Materials Science Laboratory, [2]Photonics Laboratories, and [3]Access Network Service System Laboratories

We have developed a new method for delivering water-soluble chemicals, broadband light and electrical stimulation using one optical fiber. This constitutes a new tool in photorelease technology for controlling cellular chemistry and physiology [1].

First we injected caged glutamate (4-Methoxy-7-nitroindolinyl-caged-L-glutamate) into a culture consisting of dissociated cortical neurons of an embryonic day 18 rat using a hole-assisted optical fiber (HAF)[2]. The HAF has a Ge-doped silica core and six equally spaced holes with a diameter of 14 μm in the cladding surrounding the core (Fig. 1). The end of the HAF was located just above the neurons. 250 μM of caged glutamate was injected into these holes with a syringe pump via a microfluidic device (Fig. 2). To photorelease caged glutamate, 365 nm ultraviolet (UV) light from an LED was coupled into the HAF through the microfluidic device. The cortical neurons were preloaded with the Ca^{2+} sensitive fluorescent dye, fluo-4. When the UV light released the glutamate, we observed an increase in the intracellular Ca^{2+} concentration using fluorescent microscopy [Fig. 3(a)]. We then applied electrical stimulation from this HAF by utilizing these holes filled with electrolyte solution and observed an increase in the intracellular Ca^{2+} concentration [Fig. 3(b)].

The HAF has an outer diameter of 125 μm and an extremely low bending loss characteristic compared with conventional optical fiber. This HAF provides the possibility of achieving a less invasive approach to surgery.

[1] A. Shimada et al., Neuroscience2011, 204.27, Washington DC, 2011.
[2] K. Nakajima et al., Photonics Technology Letters, IEEE **15** (2003) 1737.

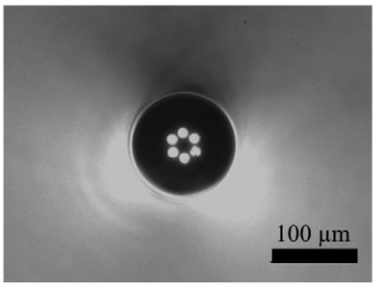

Fig. 1. Hole-assisted optical fiber.

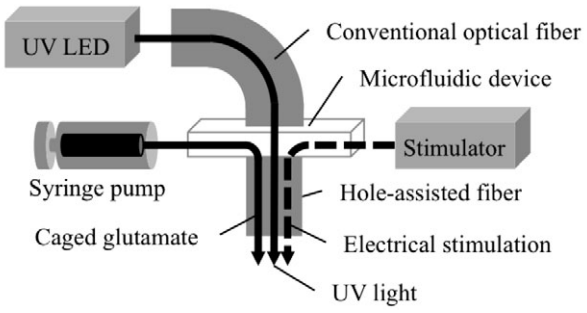

Fig. 2. Multifunctional stimulation fiber.

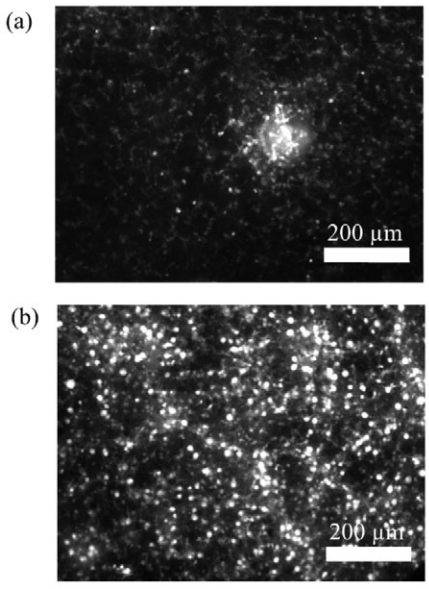

Fig. 3. Dissociated rat cortical neurons labeled with calcium florescent dye. Neural activity evoked by opt-chemical stimulation (a) and electrical stmulation (b).

Conductive Polymer Combined with Silk Fibers for Biomedical Electrodes

Shingo Tsukada, Hiroshi Nakashima, and Keiichi Torimitsu
Materials Science Laboratory

A bio-electrode is an essential tool for nano-bio research as an interface between living organs and electrical devices (circuits). Electrode materials for biomedical signal recordings, such as electrocardiograms (ECG) and electroencephalography (EEG) are expected to be soft, hydrophilic and electro-conductive to minimize the stress imposed on living tissue, especially for long-term monitoring. We have developed and characterized string shaped electrodes consisting of a conductive polymer combined with silk fibers, which provide a new biocompatible interface with living tissue under both dry and wet conditions [1].

An electro-conductive polyelectrolyte, Poly (3,4-ethylenedioxythiophene) poly (styrenesulfonate) (PEDOT-PSS) was electrochemically combined with silk fibers from Bombyx mori (Fig. 1). The polymer composite 280 μm fiber bundle exhibited a conductivity of 0.0018 S/cm (260 Kohm/mm) and a tensile strength of 1,000 CN in dry and wet states. The chemical addition of glycerol to the PEDOT-PSS silk fiber improved the conductivity to 0.23 S/cm (2 Kohm/mm). Glycerol also controls the wettability of PEDOT-PSS thus improving its durability in water and washing cycles. Without using any electrolytes, pastes or solutions, the electroconductive string directly collects electrical signals from living tissue and transmits them to metal cables (Fig. 2). This PEDOT-PSS silk glycerol fiber composite offers a new class of biocompatible electrodes for biomedical, information and communication technology without imposing any stress on the subjects.

[1] S. Tsukada et al., PLoS ONE **7(4)** (2012) e33689.

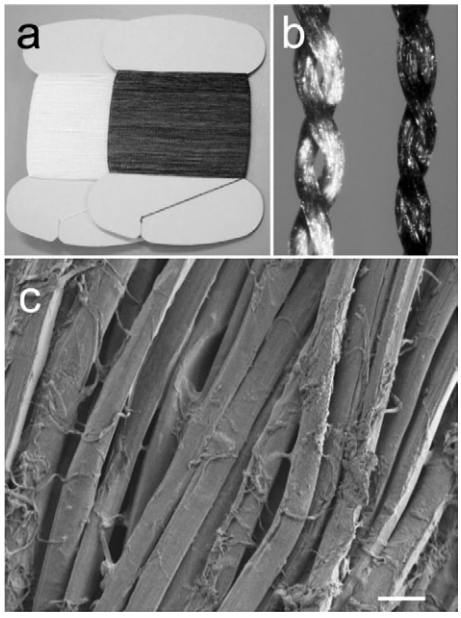

Fig. 1. a. PEDOT-PSS silk thread (right), bare silk thread (left). b. Macroscopic image of PEDOT-PSS silk thread (right) and bare silk (left). c. SEM image of PEDOT-PSS silk thread (Scale bar 20 μm).

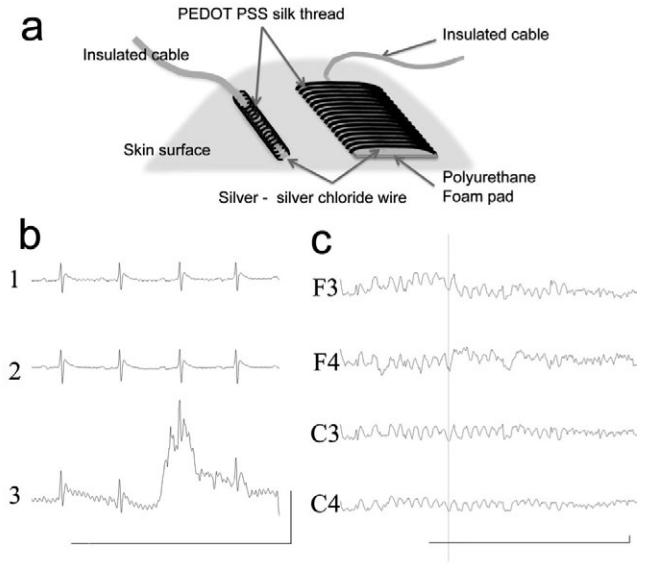

Fig. 2. a. Structure of skin surface electrode made of PEDOT-PSS silk thread. b. Electrocardiogram simultaneously recorded by PEDOT-PSS silk electrode (1), conventional medical electrodes (2) and textile electrode (Scale bar 1 sec 50 mV). c. EEG recordings from rat brain (Scale bar 1 sec 50 μV, F3, F4: Frontal head left & right, C3, C4: Central left & right).

Single-Electron Stochastic Resonance Using Nanowire Transistors

Katsuhiko Nishiguchi and Akira Fujiwara
Physical Science Laboratory

Stochastic resonance (SR) is a unique phenomenon that takes advantage of noise to enhance the response of a system to a weak signal [1]. SR is known to be beneficial in geographic and biological systems and has motivated studies seeking to implement an SR function into electronic devices. However, since noise is artificially superimposed on the devices, total system becomes complicated and operation speed for SR is limited by the bandwidth of the artificial noise spectrum. In this work, we demonstrate fast SR operation utilizing shot noise originating from single-electron (SE) transfer in nanowire transistors [2].

The device is composed of two transistors fabricated on a silicon-on-insulator wafer (Fig. 1). The first transistor (T-FET) transfers single electrons. An upper gate (UG) and lower gate (LG2) are used to induce an electron source (ES) and electron-storage node. LG1 controls SE transfer from the ES to the node in the same manner as that in the subthreshold regime of a transistor, i.e., non-linear characteristics. The SEs transferred to the MN are detected by the other transistor (D-FET) as shown in Fig. 2 [3]. An analysis of individual SE transports, in which the histogram of interval δt between each SE transport shows exponential decay (inset of Fig. 2), reveals that SEs are transferred randomly to the node, which means shot noise in the transistor. Since such non-linear characteristics and random transport are fundamental in a transistor, they are available when δt is on the order of nanoseconds or shorter, which allows fast SR.

When square waveforms as input signal S_{in} are applied to the ES and the differential of current flowing through the D-FET is monitored as output signal S_{out}, the similarity (or correlation coefficient) between S_{in} and S_{out} becomes the maximum at the particular voltage applied to LG1. This means that shot noise originating from SE transport activates SR. On the other hand, when the number of electrons transferred to the node within the particular interval is also used as S_{out}, SR characteristics are confirmed even at the interval of 10 ns because shot noise guarantees complete randomness of SE transport. SR utilizing these features allows fast pattern perception: an input image with low contrast is converted to an image with higher contrast (Fig. 3). Here, S_{in} is extremely small so that S_{out} is represented by a few hundred electrons and the interval of each signal input is 10 ns. Therefore, SR using SE-based shot noise is useful for single-shot sensing of quickly moving targets.

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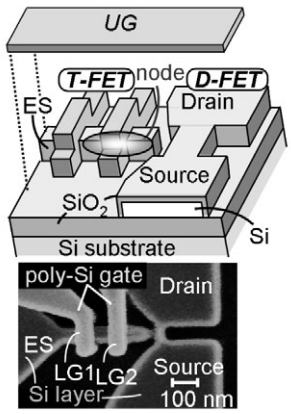

Fig. 1. Device structure.

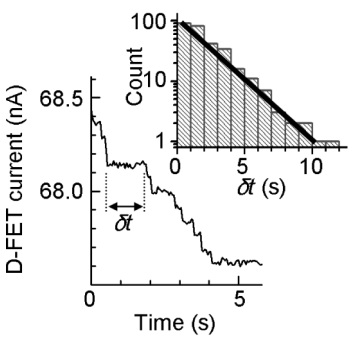

Fig. 2. SE detection. The inset is a histogram of δt.

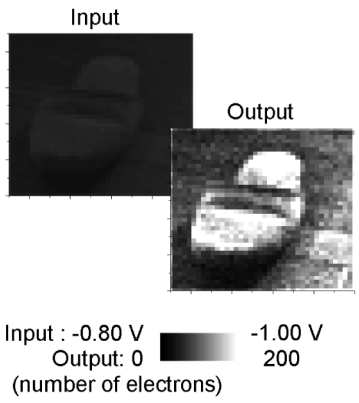

Fig. 3. Pattern perception using SR.

Absolute Accuracy Evaluation of Si Single-Electron Transfer Devices

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

Single-electron (SE) transfer is expected to be used in ultralow power consumption circuits and current standards in metrology. Accuracy of the SE transfer is crucial for determining bit errors or uncertainty in the current standards. A sufficiently low error rate, typically an error per transferred electron of about 1 part in 10^8, is necessary for the current standards. Here we demonstrate an absolute accuracy evaluation of the SE transfer [1] in high-speed transfer devices constructed by using Si nanowire metal-oxide-semiconductor field-effect transistors (MOSFETs) [2].

Figures 1 and 2 show a schematic diagram and a scanning electron microscope image of the device, respectively. The SE transfer device comprises three Si nanowire MOSFETs (FET1, 2, and 3) on a silicon-on-insulator wafer. A high-sensitivity charge sensor is composed of another Si nanowire MOSFET (S-FET). For the absolute evaluation of accuracy of the SE transfer, a node is first formed by turning FET3 off. Then, pulse voltages are applied to FET1, FET2, and the source (S) to shuttle an SE between the source and the node. Finally, we evaluate the transfer error by detecting the number of electrons in the node during the SE shuttle transfer. The merit of this scheme is that the error of the high-speed transfer is evaluated by detecting the average number of electrons in the node with a low-speed sensor. As a first step, we carried out single-shot measurement and thereby separated SE captures into the node and SE ejections from the node to investigate the transfer mechanism.

Figure 3 shows a typical result of the detection during the SE shuttle transfer at a temperature of 17 K. The abrupt changes of the detection current ($I_{S\text{-}D}$) indicate the capture and ejection of an SE. Here, two capture errors are observed. From longer measurements, the best error rates of the capture and ejection are estimated to be about 2.1 % and 0.25 %, respectively. The former can be explained by thermal fluctuations, indicating the possibility of achieving high-accuracy transfer by reducing temperature or scaling down the device size. The latter can not be explained by thermal fluctuations. From the dependence of the pulse voltage amplitude, we attribute it to transfer mediated by a trap level. Since the trap-mediated transfer shows low error, it could be possible to achieve high-accuracy SE transfer.

[1] G. Yamahata et al., Appl. Phys. Lett. **98** (2011) 222104.
[2] A. Fujiwara et al., Appl. Phys. Lett. **92** (2008) 042102.

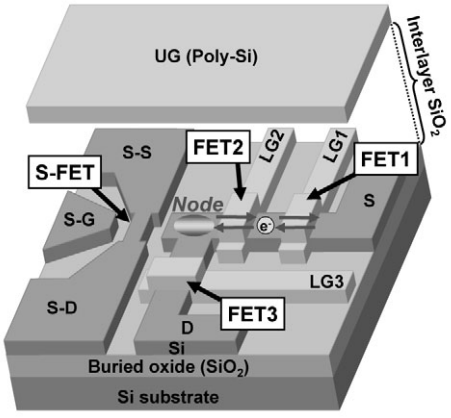

Fig. 1. Schematic of the SE transfer device for accuracy evaluation.

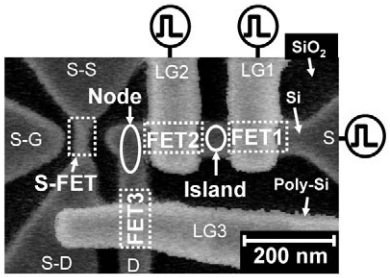

Fig. 2. Scanning electron microscope image of the device.

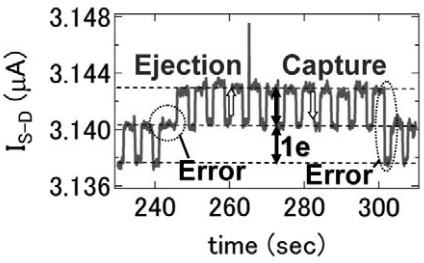

Fig. 3. Charge detection during SE shuttle transfer.

A New Charge Sensing Scheme Using the Anti-Symmetric Vibration of Coupled Mechanical Resonators

Hajime Okamoto, Koji Onomitsu, and Hiroshi Yamaguchi
Physical Science Laboratory

High-sensitive charge detection using a micromechanical resonator has recently attracted great attention [1]. There is however a drawback in such mechanical sensing in that the vibration of the resonator itself causes backaction on the object to be measured. In this study, we propose a new mechanical sensing protocol that suppresses the vibrational backaction based on the unexcited anti-symmetric vibration mode in two GaAs based coupled micromechanical resonators [Figs. 1(a) and 1(b)]. When the two resonators are perfectly coupled and simultaneously driven, the anti-symmetric vibration mode is not excited because the out-of-phase vibration is cancelled by the in-phase actuation [Fig. 1(c)]. However, once the frequency of one of the resonators is detuned by added charges via the piezoelectric effect in GaAs, the perfect coupling is broken and the anti-symmetric mode is excited [Fig. 1(c)]. Therefore, by monitoring the change in the amplitude of the anti-symmetric mode one can detect charges that are added to the resonator.

The two elastically coupled doubly-clamped beams consist of *i*-GaAs, *n*-GaAs, and GaAs/AlGaAs superlattice layers and Au gates [Figs. 1(a) and 1(b)]. The frequency of beam B is matched to that of beam A by using the photothermal frequency shift induced by HeNe laser irradiation [2]. The two beams are simultaneously actuated by a piezo-actuator set beneath the resonators in a vacuum at room temperature, while the mechanical motion of beam B is detected with the reflected laser via optical interferometry. Highly-sensitive charge detection is demonstrated by applying a low-frequency (313 Hz) gate voltage to beam A. This gate modulation induces an electric field between the top gate and the *n*-GaAs layer, resulting in piezoelectric stress in the longitudinal ([110]) direction. This causes the frequency detuning and therefore breaking the symmetry of the anti-symmetric vibration mode. The change in the vibrational amplitude is detected with a spectrum analyzer via lock-in detection of the output signal from the interferometer. The charge sensitivity is derived from the corresponding noise spectrum and the highest sensitivity of 147 e/Hz$^{0.5}$ is obtained at room temperature [Fig. 1(d)] [3]. Because this sensing scheme is based on the unexcited initial state, the vibration backaction can be minimized. This sensing scheme can also be extended for mass sensing.

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[2] H. Okamoto et al., Appl. Phys. Express **2** (2009) 062202.
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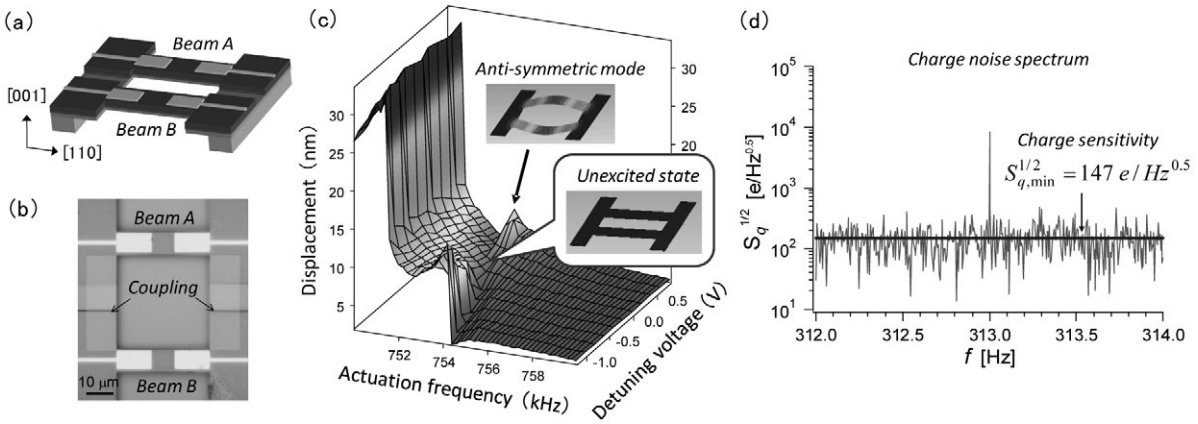

Fig. 1. (a) A schematic drawing of the coupled resonators. (b) Optical micrograph of the sample. (c) Change in the anti-symmetric mode by DC detuning. (d) Charge noise spectrum for the actuation frequency of 753.5 kHz.

Remote Actuation of an Electromechanical Resonator

Daiki Hatanaka, Imran Mahboob, and Hiroshi Yamaguchi
Physical Science Laboratory

Electromechanical resonators with small mass and high quality-factor have attracted intensive attention due to their potential applications as sensors [1], signal processors [2] and to study macroscopic quantum phenomena [3]. Actuation of the electromechanical resonator is essential in order to access the various mechanical functions. In the actuation methods reported so far, mechanical oscillations were induced by directly applying a voltage to an electrode on the mechanical resonator. The presence of the electrode for these direct electrical actuations not only loads the resonator but can also yield Joule heating which increases the mechanical energy dissipation and thus degrades the resonator performance. In order to overcome these obstacles, a contact free driving technique that does not need the direct electrical actuation was developed [4].

A GaAs/AlGaAs-based mechanical resonator containing a two dimensional electron gas (2DEG) and gold top-gates (TGs) was fabricated, which was placed inside a coil operating in the radio-frequency (RF) range as shown in Fig. 1. The mechanical resonator reveals the fundamental mode f_{res} = 172990.5 Hz at less than 200 mK as shown in the inset of Fig. 1. The coil shows a number of LC resonances (the upper panel in Fig. 2) and it emits RF waves to the mechanical resonator when the coil transmission is maximized. To demonstrate remote actuation using the RF waves, the mechanical response as function of the coil frequency f_{coil} ranging from 10 to 130 MHz was measured (the lower panel in Fig. 2). The RF wave's amplitude was modulated at frequency f_{AM} and when $f_{AM} = f_{res}$, the mechanical oscillator resonated at frequencies that corresponded to the LC resonances in the coil. The RF waves generated from the coil could drive the mechanical oscillator to resonance. This driving scheme enables the mechanical oscillations to be remotely induced and paves the way towards new applications for electromechanical resonators.

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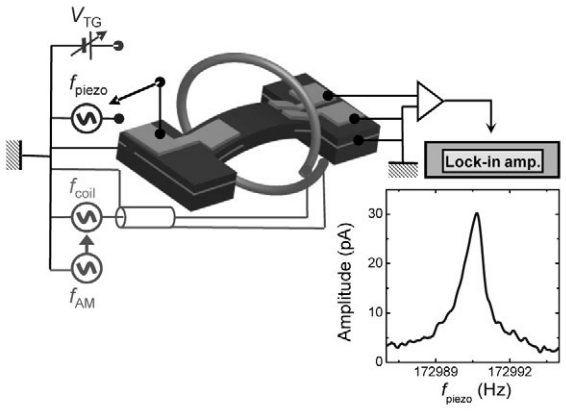

Fig. 1. A schematic of the micron-sized mechanical resonator inside a coil and the experimental set-up. The inset shows piezoelectrically driven and detected mechanical response at an actuation voltage of 12 mV_{rms}.

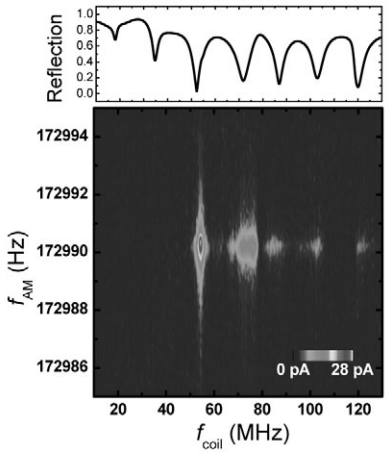

Fig. 2. The coil and the mechanical resonator response when excited by AM RF waves whilst sweeping the coil frequency with a power of −25 dBm.

Unraveling the Spin Polarization of the ν = 5/2 Fractional Quantum Hall State

Lars Tiemann[1, 2], Gerardo Gamez[1], Norio Kumada[1], and Koji Muraki[1, 2]
[1]Physical Science Laboratory, [2]Japan Science and Technology Agency

Fundamental particles in nature are classified as either fermions or bosons according to how the wave function changes sign with interchange of two particles. Remarkably, behavior of particles in a correlated state is often described in terms of quasiparticles possessing properties different from those of the original particles. In two dimensions, a quasiparticle behaving differently from fermions or bosons is theoretically possible. In particular, theory predicts the existence of quasiparticles with exceedingly unusual properties. These quasiparticles, known as non-Abelian quasiparticles, whose interchange takes the system from one of its many ground states to another, have attracted strong interest from both theory and experiment as it would establish the foundation for topological quantum computing—an entirely novel architecture for error free quantum computation [1].

Fractional quantum Hall states that emerge in a two-dimensional electron system confined to a heterointerface of pristine semiconductor crystals, such as GaAs/AlGaAs, are expected to host such exotic quasiparticles that are neither fermions or bosons. Of particular interest is the one at Landau level filling factor ν = 5/2 [2], which is predicted to support non-Abelian quasiparticles. However, unlike other states, the exact origin of the ν = 5/2 state remains unknown. The likely candidates for its wave function that emerged through experiment [3] include one that does not support non-Abelian quasiparticles. Exploiting the fact that these wave functions have different spin states, we have demonstrated for the first time that all the electrons in the ν = 5/2 state have their spins fully polarized along the applied field using resistively detected nuclear magnetic resonance (NMR) (Fig. 1) [4]. With our results, possible theoretical models are narrowed down to only those supporting non-Abelian quasiparticles.

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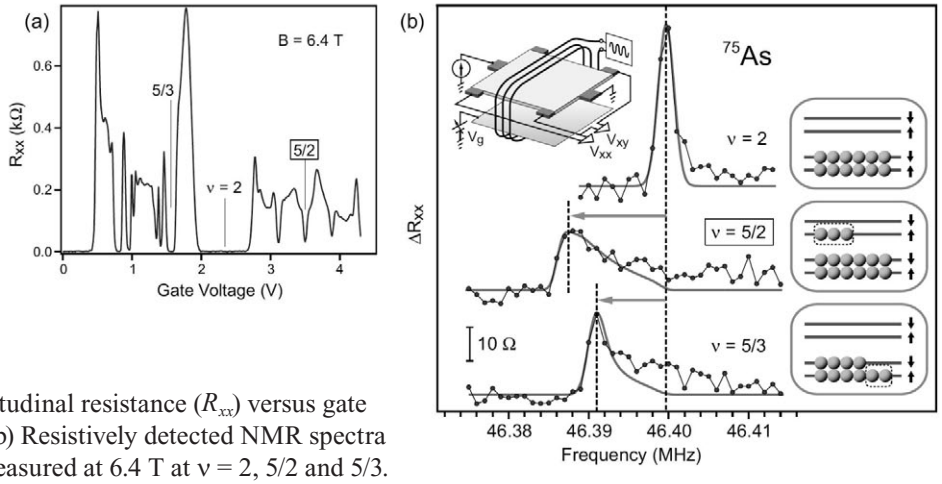

Fig. 1. (a) Longitudinal resistance (R_{xx}) versus gate voltage. (b) Resistively detected NMR spectra of ^{75}As measured at 6.4 T at ν = 2, 5/2 and 5/3. Insets show the measurement set up (left) and the spin configuration at each ν (right).

Gate Operation of InAs/AlGaSb Heterostructures with an Atomic-Layer-Deposited Insulating Layer

Kyoichi Suzuki, Yuichi Harada, Fumihiko Maeda*,
Koji Onomitsu, Toru Yamaguchi, and Koji Muraki
Physical Science Laboratory, *Materials Science Laboratory

InAs/AlGaSb heterostructures are promising for applications to high-speed electronic devices, such as high-frequency field-effect transistors, because of their large electron concentration and high room-temperature electron mobility. There remains a serious impediment to achieving the expected device characteristics, however, posed by the large gate leakage through the AlGaSb barrier and GaSb cap layers. To circumvent this difficulty, various methods of fabricating a gate insulator have been examined. In particular, atomic layer deposition (ALD), which makes it possible to deposit a thin and uniform insulating layer with high dielectric constant, is considered to be an up-and-coming technique [1,2].

It is well known in the InAs/AlGaSb system that, without any surface treatment, native oxides of the GaSb cap layer and/or defects at the cap/insulator interface induce electron trap states. Accumulation and release of electrons in and out of these trap states partially compensate the gate electric field and thus impede the gate operation. We have investigated the effects of the surface treatments before forming an Al_2O_3 insulating layer by ALD (Fig. 1) [3]. We find that dilute HCl treatment for only 10 s effectively removes the electron trap states and greatly improves the gate operation (Fig. 2).

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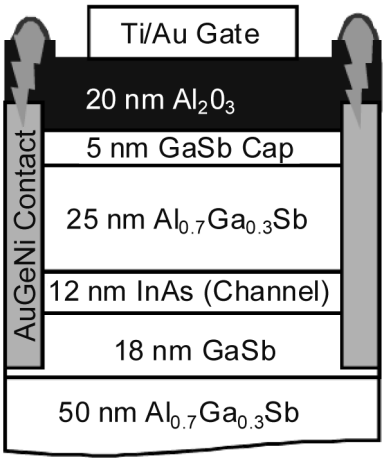

Fig. 1. InAs/AlGaSb heterostructure with an Al_2O_3 insulating layer by ALD.

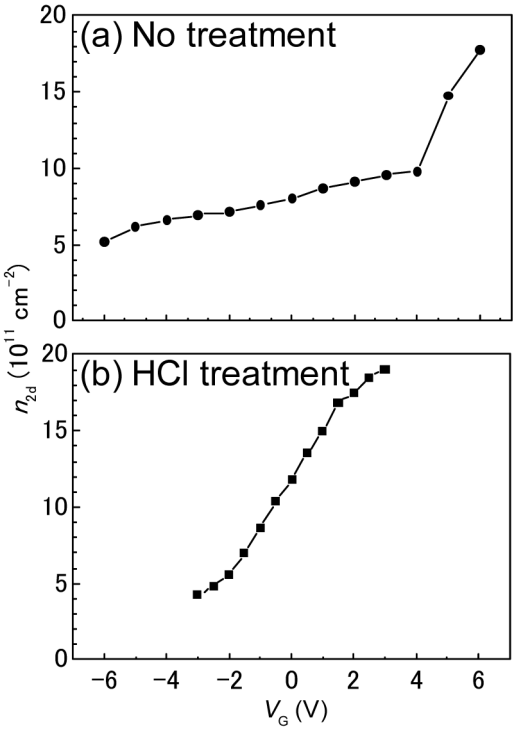

Fig. 2. Electron concentration (n_{2d}) as a function of gate voltage (V_G). (a)No-treatment. (b)HCl-treatment

Indium Atom Manipulation on a Cleaved InAs Surface

Kyoichi Suzuki, Stefan Fölsch*, and Kiyoshi Kanisawa
Physical Science Laboratory, *Paul-Drude-Institut

As semiconductor devices become more advanced and more highly integrated, further miniaturization and further reduction of power consumption are desired. Atomic-scale devices are the ultimate ones for meeting these demands. A promising way to construct these devices is to use a scanning probe microscope system. Up to now, we have achieved vertical manipulation of In atoms on an InAs(111)A surface by means of reversible tip-surface transfer [1]. Here we have succeeded manipulation of In atoms in not only vertical but also horizontal directions on an InAs(110) surface obtained by cleaving in ultra-high vacuum [2].

On the InAs(111)A surface, the manipulated In atom is bound to the potential pocket originating from the surface reconstruction resulting in difficulty for the lateral manipulation. In contrast, on the InAs(110) surface, the surface reconstruction effect is small and the potential pockets are not very deep. Taking advantage of inelastic tunneling excitation and inversion asymmetry of the surface, the In atoms can be manipulated in the specific horizontal direction ([001]) (Fig. 1).

Many compound semiconductors have same zinc-blend crystal structure as InAs. Wide and flat (110) surface can be obtained easily by cleaving. On the basis of our achievement, progress of the atom manipulation on other semiconductor (110) surfaces and on cross-sectional surfaces of heterostructures is expected.

This work was partly supported by a subsidy from the Strategic Japanese-German International Cooperative Program on Nanoelectronics supported by the Japan Science and Technology Agency (JST) and the German Research Foundation (DFG).

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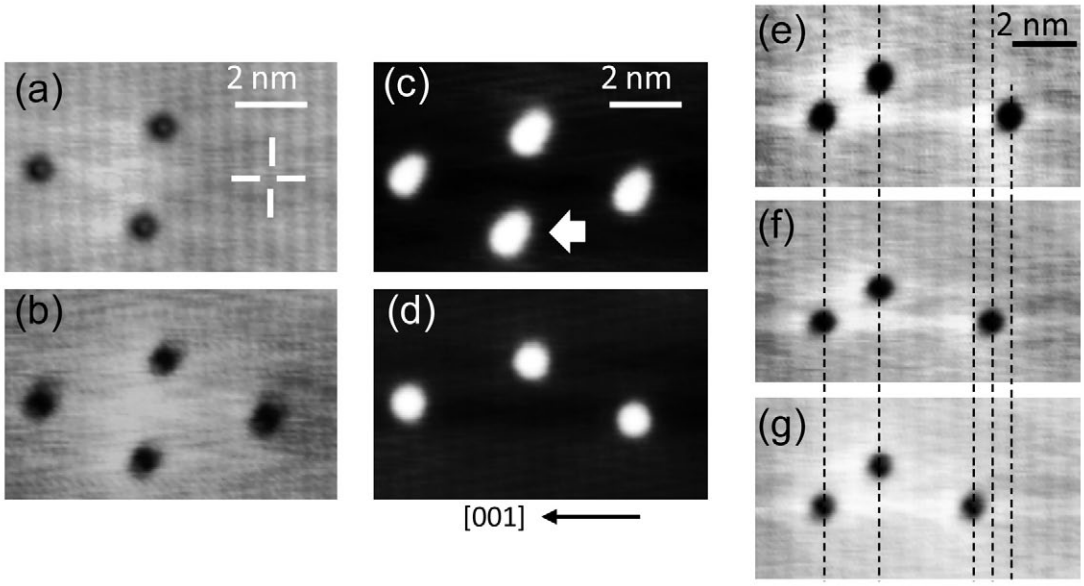

Fig. 1. STM images of In atoms on an InAs(110) surface. (a) and (b): In atoms are shown as black dots. When the STM tip approaches to the surface with the negative sample voltage (−1.0 V), an atom transfers from the tip to the surface. (c) and (d): In atoms are shown as white dots. When the tip approaches to a target atom with the positive sample voltage (+1.0 V), the atom transfers from the surface to the tip. (e)-(g): When the sample voltage is swept above a target atom, the atom hops horizontally in [001] direction by an In-As zigzag row.

Observation of Hysteretic Transport due to Dynamic Nuclear Spin Polarization in a GaAs Lateral Double Quantum Dot

Takashi Kobayashi[1,2], Kenichi Hitachi[1], Satoshi Sasaki[1,2], and Koji Muraki[1]
[1]Physical Science Laboratory, [2]Tohoku University

Electron spin dynamics in a semiconductor quantum dot (QD) is affected by the nuclear spin ensemble of the host material. This makes nuclear spin (NS) manipulation important in view of quantum information processing using physical qubits based on electron spins in QDs. Recently, we have observed a hysteretic transport signaling dynamic nuclear spin polarization (DNP) in a GaAs lateral double QD (DQD) regarded as a promising candidate for the physical implementation of the spin qubit because of its high controllability [1]. Magnetic-field dependence of this signal suggests strongly unbalanced DNP between two dots, which is applicable to a rapid manipulation of a spin qubit.

Figure 1 shows the DQD sample [(a)] and the dot current I_{dot} measured in the few-electron regime [(b)]. I_{dot} is clearly suppressed in the trapezoid region owing to the spin blockade (SB), where transport is blocked whenever parallel-spin electrons singly occupy both two dots.

In the SB region, electron spin relaxation results in leak current reflecting the spin relaxation mechanism [2]. To investigate this mechanism, we measured I_{dot} as a function of ε defined by the arrow in Fig. 1(b) and in-plane magnetic field $B_{||}$. While the I_{dot} spectrum obtained by ε sweeps at each value of $B_{||}$ [Fig. 2(a)] does not show any feature at $\varepsilon < 0$, clear I_{dot} enhancement appears over a wide range of ε and $B_{||}$ in that obtained by up sweeps of $B_{||}$ at each value of ε [Fig. 2(b)]. Figure 2(c), which displays I_{dot} measured by round sweeps of $B_{||}$, reveals that this I_{dot} enhancement is hysteretic with respect to the sweep direction of $B_{||}$. This result indicates DNP occurring for up sweeps of $B_{||}$, similarly to previous reports on DQDs of different materials and/or shapes [3]. Furthermore, the gradually escalating current level of this DNP signal with $B_{||}$ suggests strongly unbalanced DNP between the two dots, where NSs are polarized preferentially in one of the two dots.

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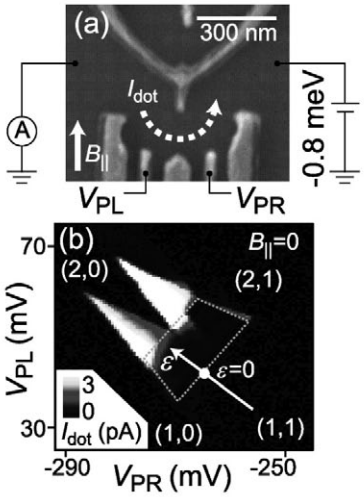

Fig. 1. (a) SEM image of the DQD sample. (b) I_{dot} spectrum in the few-electron regime. (n,m) denotes the occupation of the left and right dots.

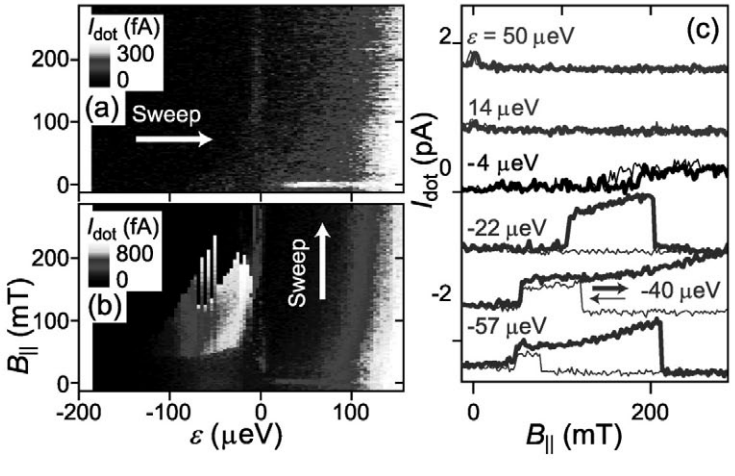

Fig. 2. ε and $B_{||}$ dependence of I_{dot} around the SB regime. (a) is obtained by ε sweeps at each value of $B_{||}$. (b) is obtained by up sweeps of $B_{||}$ at each value of ε. (c) I_{dot} obtained by round sweeps of $B_{||}$.

Mediation of Entanglement between a Microscopic Two Level System and a Macroscopic Resonator Using a Superconducting Flux Qubit

Alexander Kemp, Shiro Saito, William John Munro*, and Kouichi Semba
Physical Science Laboratory, *Optical Science Laboratory

Circuit quantum electrodynamics in superconducting circuits has demonstrated the coupling of superconducting qubits to microwave photons in a superconducting resonator, paving a way for scaling up the qubit system [1]. During these experiments, microscopic two level systems (TLS) coupled to the qubit were observed [2]. Here we report on the study of an entangled state of a microscopic TLS and a macroscopic resonator by way of a superconducting flux qubit [3].

A spectrum of the flux qubit depicted in fig. 1(a) shows two anti-crossings at 6.17 GHz and 8.95 GHz. These represent the coupling of the qubit to the TLS and the resonator, respectively. The coupling strengths were 55 MHz and 154 MHz. The qubit energy can be controlled by an external magnetic flux through the qubit. Using a flux shift pulse, we can bring the qubit on resonance with the TLS (or resonator) and create any entangled state between the qubit and the TLS (or resonator). Utilizing such pulses we realized an entangled state between the TLS and the resonator.

Figure 1(b) shows a pulse sequence to make this entangled state. First, a microwave π-pulse prepares the qubit in the excited state |100> (where the state is represented by |qubit, TLS, resonator>). Next a $\sqrt{\text{SWAP}}$ pulse brings the qubit on resonance with the TLS creating the entangled state (|100>+|010>) /$\sqrt{2}$. Then a SWAP pulse between the qubit and the resonator realizes the entangled state (|001>+|010>) /$\sqrt{2}$. The state then acquires a relative phase $\phi = \Delta E \tau/\hbar$ during a period of free evolution of a time τ. Here ΔE is the energy difference between the |001> and |010> levels. To observe this phase evolution we reverse our pulse sequence, we apply the SWAP pulse and then the $\sqrt{\text{SWAP}}$ pulse followed by the readout of the population of the qubits excited state P_{ex}. Figure 2 shows that P_{ex} as a function of τ oscillates with the frequency of $\Delta E/h$. This indicates an entangled state between the TLS and the resonator is realized during the free evolution.

In the future we will replace the TLS by a controllable quantum memory and scale up our superconducting qubits with long-lived quantum memories.

This work was supported by KAKENHI.

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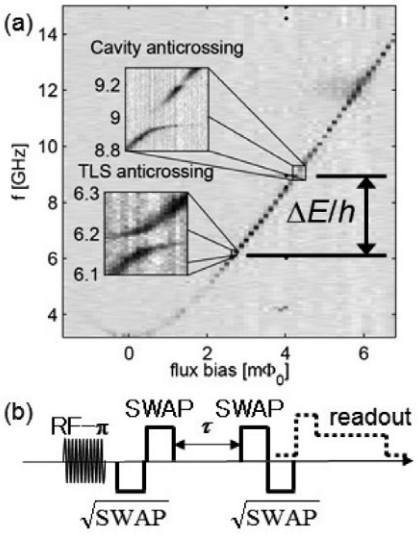

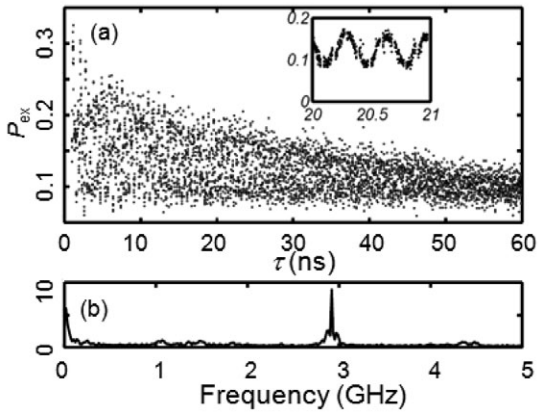

Left: Fig. 1. (a) Spectrum of a flux qubit. (b) Pulse sequence for the experiment.
Right: Fig. 2. (a) Switching probability P_{ex} as a function of τ. (b) Fourier spectrum of P_{ex}.

Coherent Coupling of a Gap-Tunable Flux Qubit to an Electron Spin Ensemble in Diamond

Xiaobo Zhu[1], Shiro Saito[1], Alexander Kemp[1], Kosuke Kakuyanagi[1], Shinichi Karimoto[1], Hayato Nakano[1], William J. Munro[2], Yasuhiro Tokura[1], Mark S. Everitt[3], Kae Nemoto[3], Makoto Kasu[4], Norikazu Mizuochi[5,6], and Kouichi Semba[1]
[1]Physical Science Laboratory, [2]Optical Science Laboratory, [3]National Institute of Informatics, [4]Materials Science Laboratory, [5]Osaka University, [6]PREST-JST

During the last several years, significant effort into superconducting quantum bits (qubits) based on Josephson junctions have been made. However, the experimentally reported coherence times are likely to be insufficient for future large-scale quantum computing. A natural solution is an engineered quantum memory based on atomic and molecular systems. An electron spin trapped at a nitrogen-vacancy (NV^-) center in diamond is known to have a very long coherent time and can be coupled via mutual inductance to a flux qubit. It is therefore an ideal candidate to acts as a quantum memory for our flux qubit.

We have designed and fabricated an upgraded flux qubit, whose gap can be tuned *in situ* by two high bandwidth control lines [1], giving two fundamental improvements: "gap control" and "σx coupling". Based on these fundamental improvements many new applications can be realized. For example, it opens up the possibility to realize a high fidelity coupling to other quantum systems and so demonstrate a quantum memory operation.

We glued an NV^- diamond sample on top of our superconducting circuit. We for the first time observed an anti-crossing structure at 2.88 GHz which clearly shows a ~70 MHz coupling between the NV^- spin ensemble and the gap-tunable flux qubit (Fig. 1). Furthermore we also observed the coherent exchange of a single quantum of energy between the flux qubit and a macroscopic ensemble consisting of about 6×10^7 NV^- centers (Fig. 2). This is the first step towards the realization of a long-lived quantum memory and hybrid devices coupling microwave and optical systems [2].

This work was supported by KAKENHI.

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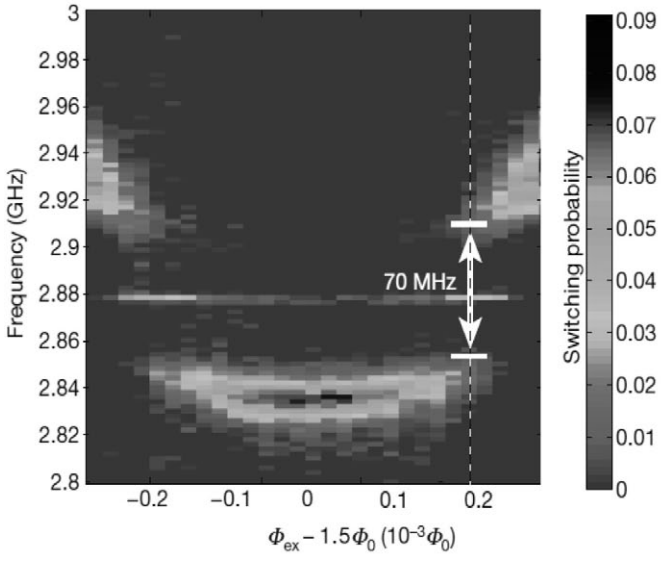

Fig. 1. Energy spectrum of the flux qubit coupled to an NV^- center ensemble.

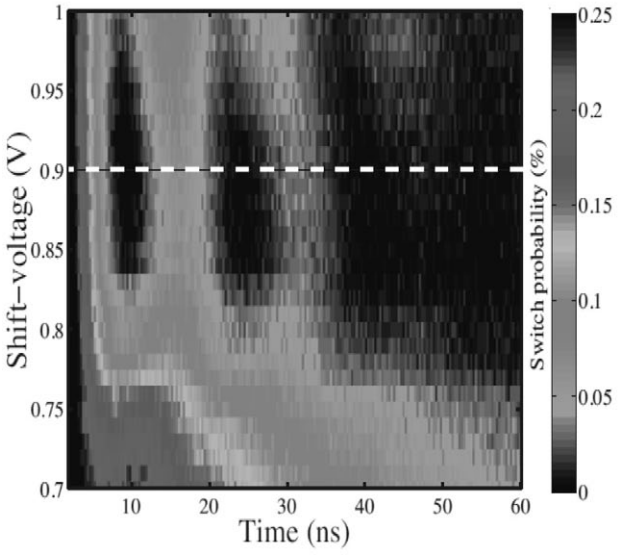

Fig. 2. Coherent oscillations of the flux qubit / NV^- center ensemble coupled system.

$In_{0.75}Ga_{0.25}As$ Quantum Point Contact Utilizing Wrap-Gate Geometry

Hiroshi Irie, Yuichi Harada, Hiroki Sugiyama*, and Tatsushi Akazaki
Physical Science Laboratory, *NTT Photonics Laboratories

Quantum nanostructures, such as quantum point contacts (QPCs) or quantum dots, in high-In-content $In_xGa_{1-x}As$ offer unique functionalities originated from its material properties. Firstly, by exploiting the strong spin-orbit interaction (SOI) in InGaAs, the electronic spin can be manipulated through the SOI. As an example, electrons moving through QPC experience the selective spin-flipping caused by SOI induced spin-splitting, which implies that the InGaAs QPC works as a spin-polarizer without the need of magnetic field [1]. Secondarily, InGaAs nanostructures are promising for the development of semiconductor/superconductor hybrid devices. Since high-In-content $In_xGa_{1-x}As$ forms low Schottky barriers (or no barrier for $x > 0.77$) against most metals, superconducting Cooper pairs can be effectively injected into InGaAs. Superconducting quantum point contact, a counterpart of the semiconducting QPC, has been intensively investigated to realize a quantum bit using Andreev bound states or to observe Majorana fermions that are induced at the interface between an s-wave superconducting electrode and one-dimensional channel with strong SOI.

In this study, we improved fabrication technique to realize QPCs in an $In_{0.75}Ga_{0.25}As$/InAlAs two-dimensional electron gas heterostructure [2]. The key challenge in realizing a well-behaved QPC is efficient electrostatic control of a one-dimensional channel using the gate electrode. The fabricated QPCs employ a 100-nm-wide mesa constriction and a gate electrode that wraps around the constriction for three-dimensional electric-field gating. Conformal aluminum-oxide growth by means of atomic layer deposition is employed to suppress gate leakage while minimizing the interface state density. Figure 1 shows an SEM image of the fabricated QPC and a schematic drawing of the cross-section. The wrap-gate QPCs show clear conductance steps, demonstrating the formation of one-dimensional channels with quantized transverse modes, as shown in Fig. 2. This technique can be easily extended to the fabrication of quantum dots and superconductor/QPC/superconductor junctions, which opens up a novel approach for the studies of spin-related phenomena in InGaAs-based quantum nanostructures.

This work was supported by KAKENHI.

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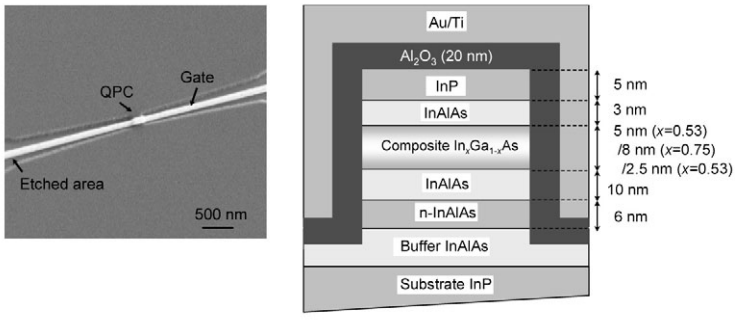

Fig. 1. SEM image and cross-sectional drawing of QPC.

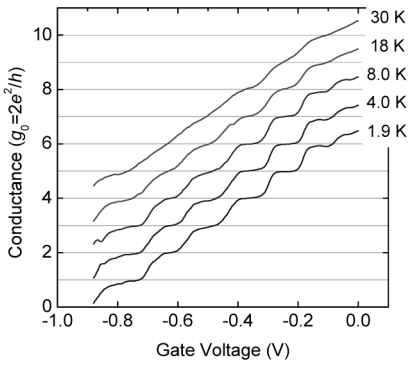

Fig. 2. Conductance vs. gate voltage.

Exploring Novel Quantum Phases of Bose-Fermi Mixtures Trapped in an Optical Lattice

Kensuke Inaba and Makoto Yamashita
Optical Science Laboratory

Recently, atomic gases trapped in a vacuum chamber can be cooled down to several nano-Kelvins regime, where the quantum effects govern physical properties of the system. The high controllability of atoms provides us with sophisticated tools for measuring the quantum phenomena. Thus, this system can be regarded as a quantum simulator [1], which attracts much interest of many researchers in various fields, such as condensed matter physics, elementary particle physics, quantum chemistry, and so on. In particular, the atoms trapped in an optical lattice, which is the artificially created periodic potential by laser interference, are expected to make great progress in condensed matter physics, because such fermionic atoms mimic electrons in a metallic crystal [2]. We can explore the pure quantum many-body effects by using this system without any lattice distortions and impurities. Interestingly, this controllable system allows us to expand the current knowledge in the electron systems.

Collaborating with the group at Kyoto University, we investigated the Bose-Fermi mixtures trapped in an optical lattice both theoretically and experimentally, and clarified appearance of novel quantum phases not observed in condensed matters [3]. Here, we introduce a part of our results on the attractively interacting Bose-Fermi mixtures. Kyoto University group measured the pair occupancies with photo-association spectroscopy by changing the number of fermionic atoms. We developed the numerical method for analyzing this system and applied it to the experiments. We show our results in Fig. 1(a) and (b), and briefly explain the proceeding of the measurements in Fig. 1(c). Our calculations show good quantitative agreements with experiments. We further analyzed the quantities that are difficult to be directly measured by the current experimental techniques. Based on these results, we clarified that the non-monotonic behavior of Bose-Bose pair occupancy seen in Fig. 1(b) results from the crossover among novel quantum phases. We also investigated the repulsively interacting system and found a different type of crossover.

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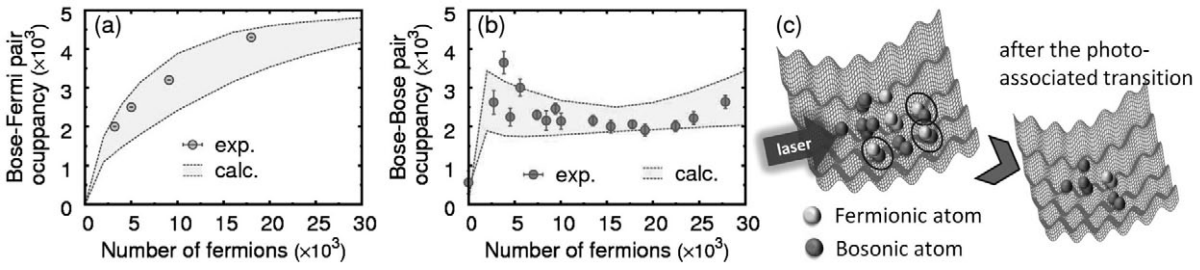

Fig. 1. (a) Bose-Fermi pair and (b) Bose-Bose pair occupancies observed by photo-association spectroscopy. The number of bosons is fixed at 5000. Numerical calculations consider the experimental ambiguity of estimated temperatures. (c) Schematic diagrams of the Bose-Fermi pair occupancy measurements. Irradiated laser induces photo-associated transition from a pair of atoms to a molecular state at each site, and the molecule immediately moves outside of the optical lattice. By counting the lost atoms, we can thus determine the Bose-Fermi pair occupancies. Another excitation laser is used for the Bose-Bose pair occupancy.

Enhanced Optical Nonlinearity in a Silicon Photonic Crystal Slow-Light Waveguide

Nobuyuki Matsuda, Ken-ichi Harada, Hiroki Takesue,
Eiichi Kuramochi, Hideaki Taniyama, and Masaya Notomi
Optical Science Laboratory

Slow light (SL) in an optical chip provides an enhanced light-matter interaction, thanks to the longitudinally compressed optical field and the prolonged interaction time between the medium and the slowly-propagating light within. We have already fabricated high-bandwidth SL waveguides using a 1-D chain of silicon photonic-crystal ultrahigh-Q (~ 1 million) nanocavities and demonstrated v_g less than c/100 in the telecom band [1]. This time we demonstrated SL enhancement of all-optical wavelength-conversion efficiency in our device via the four-wave-mixing (FWM) experiment [2].

Schematic of our SL waveguide (v_g = c/36, 0.42-mm long) is shown in Fig. 1. We input telecom-band pump and signal beam into the device and observed a new idler field that was created by the stimulated FWM, which arises from the third-order optical nonlinearity in the core material (Si). We plotted measured signal-to-idler wavelength conversion efficiency as a function of input pump power as shown in Fig. 2. The conversion efficiency was proportional to the the square of the pump power because the FWM is a two-photon absorption process. From the result, we obtained the value of nonlinear constant γ, which is the degree of waveguide nonlinearity, as 18,600 /W/m. The value is 10^7 times larger than that of standard single-mode fibers and even larger than 300 /W/m of a silicon wire waveguide (v_g = c/4.2) [3] and 2,930 /W/m of a photonic crystal SL waveguide that employed a line defect mode (v_g = c/30) [4]. The extremely high nonlinearity of our device is originating from SL enhancement ($(1/v_g)^2$ dependence of γ) and a strong spatial confinement of the SL mode due to wavelength-sized photonic crystal cavities. This value is the highest yet reported for silicon-core nonlinear waveguides with an integrated structure, indicating a potential to provide a new stage for integrated waveguide photonic devices with ultralow power consumption.

This work was supported by KAKENHI.

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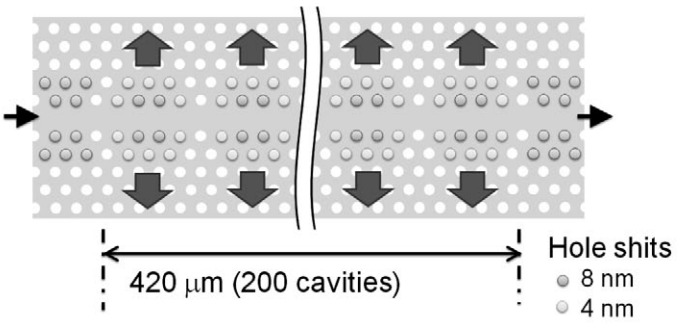

Fig. 1. Silicon photonic-crystal coupled-resonator optical waveguide.

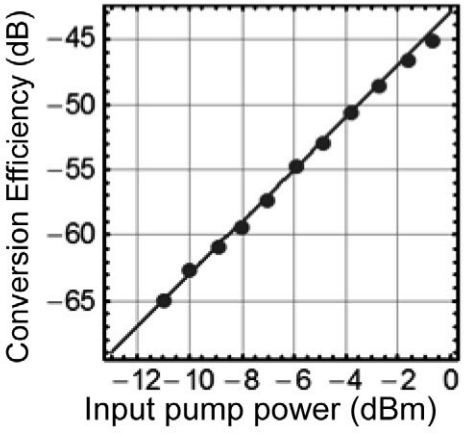

Fig. 2. Signal-to-idler wavelength conversion efficiency via the FWM.

Generation of Femtosecond Laser Pulses at 1-GHz Repetition Rate Derived from Continuous Wave Laser Diode

Tadashi Nishikawa and Atsushi Ishizawa
Optical Science Laboratory

Femtosecond pulse lasers with a gigahertz repetition rate are attractive for a variety of applications, including the analysis of nanomechanical and optomechanical systems, as a multiphoton tool for nanomedicine and nanobiotechnology, for high-speed asynchronous optical sampling, and as a carrier-envelope-offset-locked frequency comb with a wide mode spacing [1]. Conventional methods for generating a femtosecond pulse train are based on a passive mode-locking technique. However, since the cavity length must correspond to the repetition rate, it is difficult to obtain femtosecond pulses with a high repetition rate exceeding 1GHz. Moreover, the repetition rate and wavelength have limited tunability. We propose a simple method to generate GHz repetition rate optical pulses with a widely selectable repetition rate and wavelength by using commercial optical phase-modulators (PMs), a commercial intensity-modulator (IM), and a standard single-mode fiber (SMF).

The phase of the light from a CW laser diode (LD) with a center wavelength of 1552 nm are modulated with PMs driven by an external RF synthesizer at modulation frequency of 25 GHz. This process causes repetitive up- and down-chirping at 25 GHz. The linear part of the down-chirping is selectively gated with the IM, resulting in a flat optical frequency comb with a 24-nm bandwidth. After chirping compensation with a SMF, we obtained a 230-fs pulse at 25 GHz. After an optical gate, which reduces the repetition rate from 25 GHz to 1 GHz (or 250 MHz), the optical pulse train is amplified up to an average power of 1 W in an erbium-doped fiber amplifier (EDFA). Since the laser peak intensity is estimated to be more than several kilowatts in the EDFA, spectral broadening occurs by self-phase modulation. Then, the chirped pulse is compressed by 1-m-long glass block. We succeeded in the generation of a 1-W, 120-fs optical pulse at 1 GHz and a 1-W, 80-fs optical pulse at 250 MHz [2]. Figure 1 shows the spectrum and autocorrelation trace for the latter case. As far as we know, these are the shortest pulses ever achieved for these repetition rates using a CW LD as a seed light source. Our scheme could provide a sub-100-fs laser with widely tunable repetition rate and wavelength by changing the modulation frequency of the RF synthesizer and the wavelength of a tunable laser diode. These features mean that our proposed laser system has the potential to become a powerful tool for a variety of applications.

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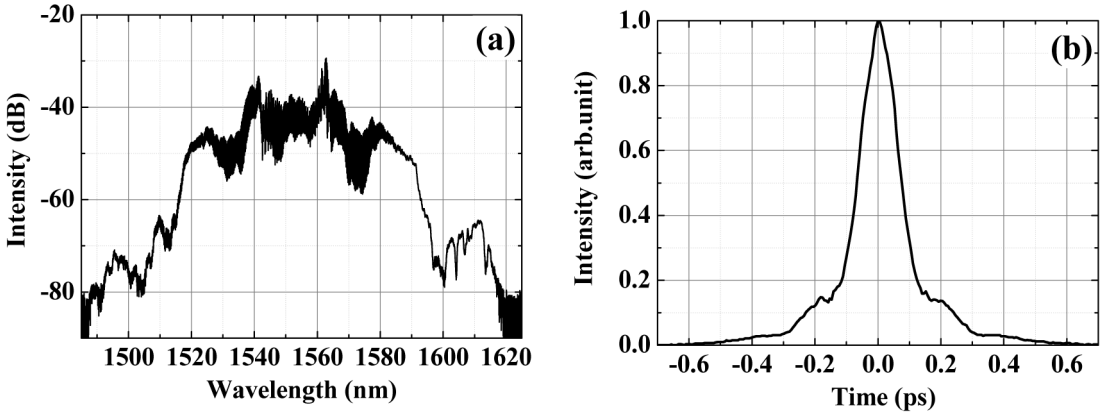

Fig. 1. (a) Spectrum and (b) autocorrelation trace obtained using the optical gate at 250 MHz.

Transport and Manipulation of Electron Spins Using Surface Acoustic Waves

Haruki Sanada, Hideki Gotoh, Koji Onomitsu*, and Tetsuomi Sogawa
Optical Science Laboratory, *Physical Science Laboratory

Transporting electron spins in semiconductors will be a crucial technique both for fundamental research on spin-orbit interactions [1] and for the spintronics applications that need spin information transfer [2]. We have investigated the spin dynamics of electrons traveling with *moving wires* and *dots* formed by surface acoustic waves (SAWs) [3].

The *moving wires* and *dots* are generated in a 20-nm-thick GaAs/AlGaAs(001) quantum well (QW) grown by molecular beam epitaxy. Interdigital transducers (IDTs) designed for operation at a SAW wavelength of 2.55 μm were processed on the sample. Depending on the IDT's direction, Rayleigh SAWs propagate along [–110] or [110] with a velocity v_{SAW} = 3 km/s. The single SAW beams produce *moving wires*, which are formed by the one-dimensional lateral confinement of the SAW-induced piezoelectric potential. The interference between the two orthogonal SAW beams forms *moving dots* traveling along [010] with a velocity of $\sqrt{2}\, v_{SAW}$.

To measure the spin dynamics during transport, we employed Kerr microscopy with a pump-probe technique. A circularly polarized pump light generated spin-polarized electrons at a fixed position on the sample; and a linearly polarized probe light, which can be scanned in the QW plane, was used to detect the magneto-optic Kerr effect. Since the Kerr rotation angle θ_K is proportional to the spin density at the probe position, we can obtain two-dimensional images of spin distribution under SAWs.

Figure 1 shows the two-dimensional images of the spin transport measured in the absence of an external magnetic field. For both *moving wires* and *dots*, we successfully extracted the precession behavior induced by the spin-orbit interaction. We also found that the spin precession frequency for the *moving dots* depends on the SAW intensity (Fig. 2). The theoretical analysis of the data revealed the existence of SAW-induced spin-orbit interactions, indicating that the spin precession angle is acoustically tunable. These techniques will provide the versatility needed for spin manipulation in future spintronics applications.

This work was partly supported by KAKENHI.

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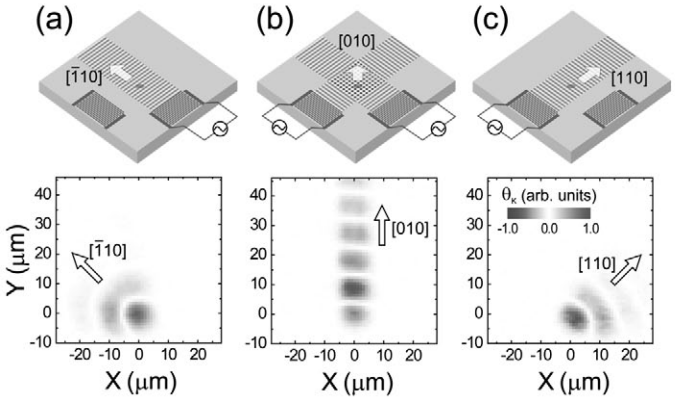

Fig. 1. Two-dimensional images of spin densities for *moving wires* traveling along [–110] (a), [110] (c), and for *moving dots* traveling along [010] (b).

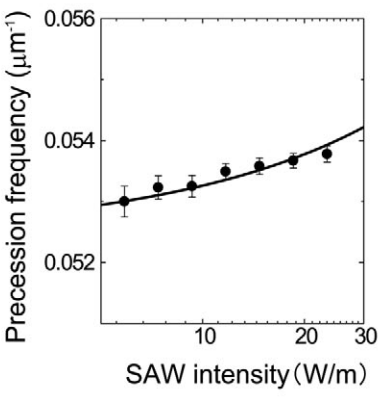

Fig. 2. SAW intensity dependence of the precession frequency for *moving dots*. The line is a theoretical fit.

Bonding and Anti-Bonding Orbitals in Raman Spectroscopy for Graphene Edge

Ken-ichi Sasaki, Keiko Kato, Yasuhiro Tokura, and Satoru Suzuki*
Optical Science Laboratory, *Materials Science Laboratory

Graphene has several notable properties not seen in the conventional semiconductor. For example, there is a degree of freedom known as pseudospin. It is a general idea regarding the superposition of bonding and antibonding orbitals. Normally bonding orbital is more stable than antibonding orbital in energy, however, graphene is a special material in which bonding and antibonding orbitals are degenerate. As a result, various types of superposition are realizing at an energy contour surface. The direction of pseudospin is defined by the superposition of bonding and antibonding orbitals in the same manner as the direction of spin is determined by the superposition of up and down spins. We are pursuing the possibility of pseudospintronics of graphene.

As it is the first stage of spintronics to distinguish between up and down spins, it is an important stage of pseudospintronics to distinguish between up and down pseudospins. While spin direction is changed by a magnetic field, pseudospin direction is changed by a stress. In material, there exists an internal strain called phonon, and the pseudospin direction is governed by the interaction between electron and phonon. Raman spectroscopy is suitable for investigating the pseudospin. Here, we report on our study, in which the two pseudospins that correspond to bonding and antibonding orbitals are automatically selected in the Raman spectroscopy for graphene edge.

In the Raman spectrum taken at a graphene edge, it is commonly observed that the D band appears as a prominent peak [1]. A notable feature of the D band is that there is a strong dependence on the polarization of light: when the polarization is parallel to the edge, the intensity is the maximum, and it is suppressed for perpendicular polarization. We clarified that this polarization dependence originates from the pseudospin dependence of electron-phonon interaction. Namely, because the D band is a special (strain) phonon mode that consists only of the bond stretching motion, the bonding and antibonding orbitals couple selectively to the D band [2]. This means that exciting the D band at graphene edge is the same as selecting the up and down pseudospins (bonding and antibonding orbitals) among all directions of pseudospins [Fig. 1(a)].

In addition, we predict that the D band splits into two peaks [Fig. 1(b)]. The higher (lower) frequency peak originates from up (down) pseudospin. By this splitting, it is possible to distinguish between up and down pseudospins. Although there is no report on the splitting of the D band at graphene edge yet, the splitting of the D band has been observed in defective carbon nanotubes [3].

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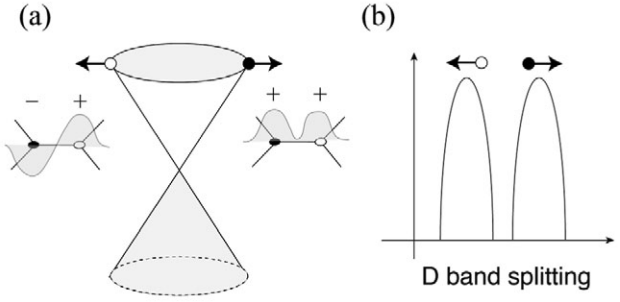

Fig. 1. (a) The energy dispersion of graphene (Dirac cone). The solid and empty circles represent the electronic states (with bonding and antibonding orbitals) that can selectively excite the D band phonon. The arrows correspond to their pseudospin directions. (b) The splitting of the D Raman band.

Ultrahigh-Q Nanocavities Written with a Nanoprobe

Atsushi Yokoo, Takasumi Tanabe, Eiichi Kuramochi, and Masaya Notomi
Optical Science Laboratory

High-Q nanocavities have been extensively studied recently because they are considered key elements in low-power photonic devices and integrated circuits. These high-Q nanocavities in photonic crystals were fabricated by a combination of high-resolution electron-beam lithography and dry etching techniques. However, this means that the photonic crystal device components should be incorporated in the CAD data before the fabrication process begins. It is difficult to add other components to photonic crystals once they have been fabricated.

We propose employing the selective oxidation of silicon photonic crystals by using the scanning nanoprobe of an atomic force microscope (AFM) to form an ultrahigh-Q nanocavity in a line defect of a 2D Si photonic crystal slab as shown in Fig. 1 [1]. Selective anodic oxidation produces an ultrasmall oxide pattern on a Si surface if we apply a voltage between the probe's conductive tip and the target, which leads to local modification of the thickness and effective refractive index of a Si slab. This process is sometimes referred to as scanning-probe lithography (SPL) or AFM lithography. In this strategy, we utilize the fact that a very small spatial index modulation ($\Delta n/n < 0.1$ %) changes the mode-gap edge frequency of the modified area to create barrier regions, while the unmodified area retains its original mode-gap edge frequency [2]. We evaluate peak width of cavity resonance of a photonic crystal sample post-modulated by SPL and HF wet etching. As a result, an ultrahigh-Q (>1 million) nanocavities with a mode volume of 0.2 μm^3 can be formed by employing scanning probe lithography on a pre-patterned line defect in a silicon photonic crystal as shown in Fig. 2. We confirmed that a photon lifetime of the cavity is around 1.25 ns. This is the first realization of ultrahigh-Q nanocavities by the post-process modification of photonic crystals. With this method, we can form an ultrahigh-Q nanocavity with controllable cavity parameters at an arbitrary position along a line defect. Furthermore, the fabricated nanocavity achieves ultra-low power all-optical bistable operation owing to its large cavity enhancement effect. The threshold power for the bistable operation is close to the values obtained for conventional photonic crystal nanocavity devices. This demonstration indicates the possibility of realizing photonic integrated circuits on demand, where various circuit patterns are written with a nanoprobe on a universal photonic crystal substrate.

[1] A. Yokoo, T. Tanabe, E. Kuramochi, and M. Notomi, Nano Lett. **11** (2011) 3634.
[2] M. Notomi and H. Taniyama, Optics Express **16** (2008) 18657.

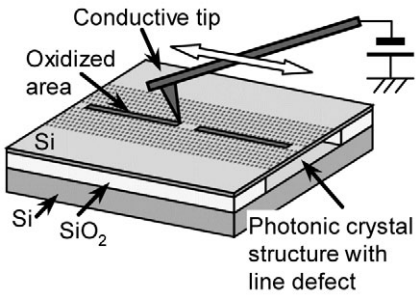

Fig. 1. Schematic of nanocavity formation by SPL applied to a line defect in photonic crystal.

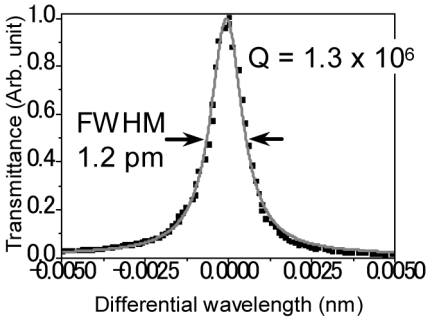

Fig. 2. Cavity resonance of a photonic crystal sample post-modulated by SPL and HF wet etching. (Q-factor : 1.3 x 10^6)

Ultralow-Power All-Optical RAM Chip Based on Nanocavities

Kengo Nozaki, Akihiko Shinya, Shinji Matsuo*, Yasumasa Suzaki*, Toru Segawa*,
Tomonari Sato*, Ryo Takahashi*, and Masaya Notomi
Optical Science Laboratory, *NTT Photonics Laboratories

An optical random-access memory (o-RAM) will enable us to develop various high-speed logic elements with a small power consumption [1], and is expected to play a key role in future optical routers in which high-bit-rate optical packets are processed without E-O/O-E conversion. A PhC nanocavity is a possible candidate for an o-RAM because of its ultrasmall size, ultralow power consumption, and large-scale integrability on a chip.

We achieved a novel buried heterostructure (BH) with which to form a PhC nanocavity, as shown in Fig. 1(a), where an ultra-compact InGaAsP is buried in an InP-PhC waveguide [2]. This structure allowed us to strongly confine both photons and carriers, enabling a bistable behavior with very small optical power, as shown in Fig. 1(b). Thus memory state switching between the "on" and "off" states can be successfully obtained with a combination of CW bias light and optical pulse input. Operation power was only 30 nW, which is several orders of magnitude lower than of the power required by previously reported o-RAMs.

To demonstrate the feasibility for integration, we fabricated a four-bit memory array integrated in the same chip and demonstrated a four-bit RAM operation as shown in Fig. 1(c). The 40-Gb/s data ("1101" or "1010") were first spatially demultiplexed by an all-optical serial-to-parallel converter, and then stored in four different cavities. Finally, the stored four-bit data were successfully read by injecting read pulses after a buffering time of 500 ns. There has been no previous report of integrated nanophotonics and our work is the first demonstration of "Integrated o-RAM chip".

This work was supported by the National Institute of Information and Communications Technology (NICT).

[1] M. Notomi et al., IET Circuits Devices & Systems **5** (2011) 84.
[2] K. Nozaki et al., Nature Photon. **6** (2012) 248.

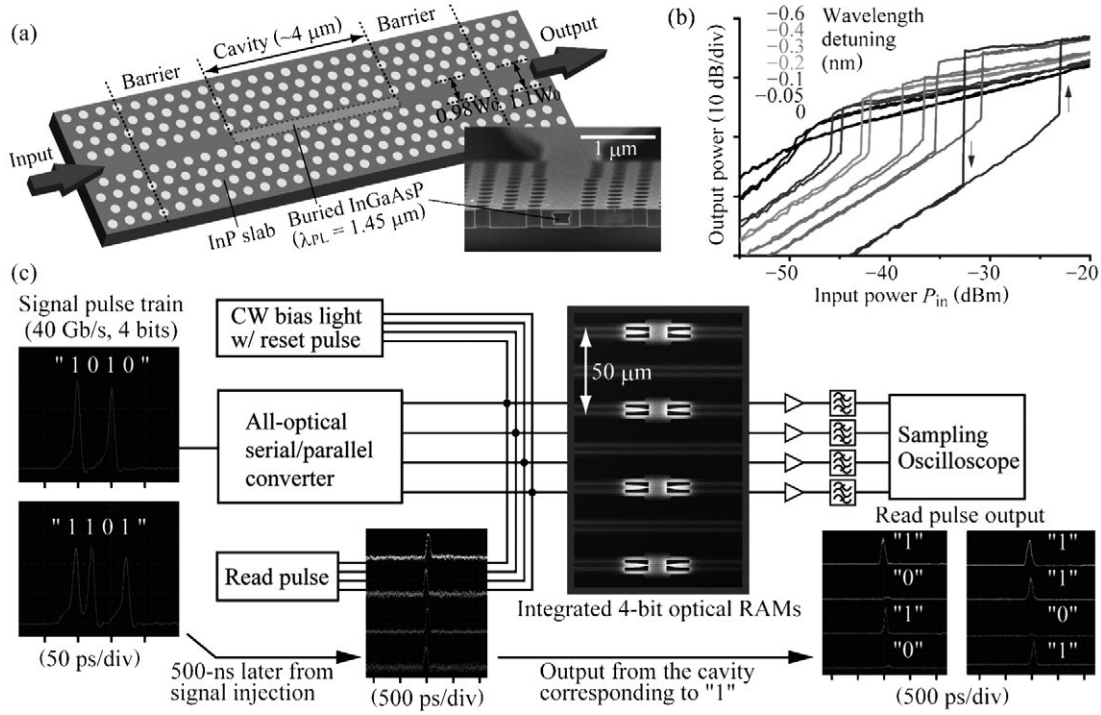

Fig. 1. (a) Optical RAM element based on photonic crystal nanocavity having compact buried heterostructure. (b) Optical bistability on optical input/output characteristic. (c) Integrated optical RAM operation for 40-Gb/s, 4-bit signal train by parallely-integrated nanocavities on a chip.

Ⅱ. Data

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BRL Director Award Award for Achievements	K. Nozaki A. Shinya M. Notomi Y. Suzaki T. Segawa T. Sato S. Matsuo R. Takahashi	Realization of ultralow-power 4-bit optical RAM subsystem based on integrated photonic crystal nanocavities	Mar. 28, 2012
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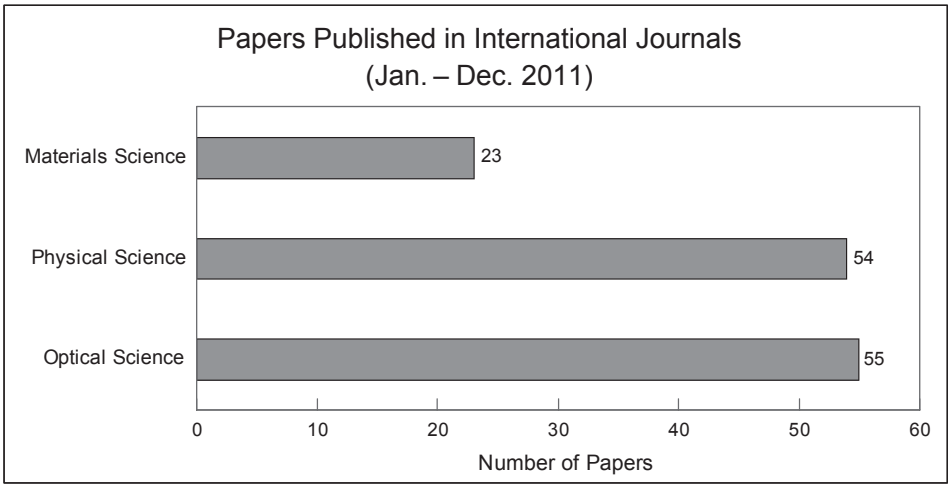

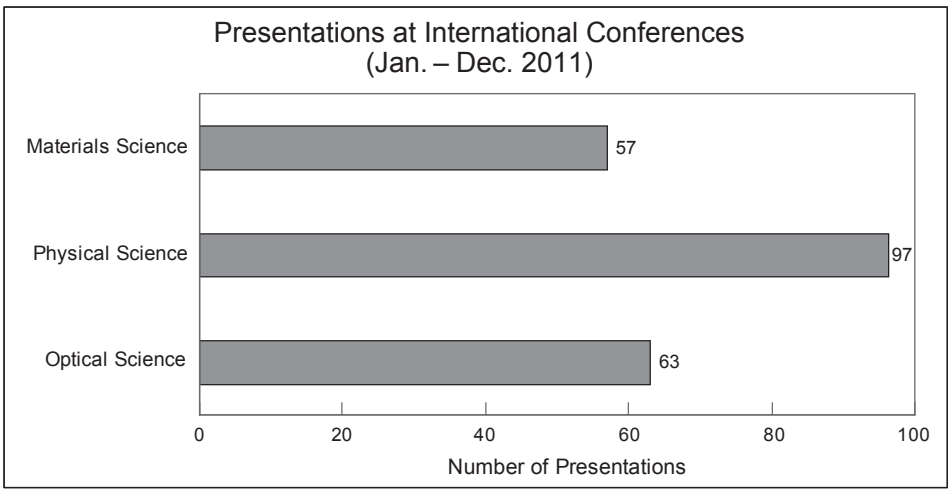

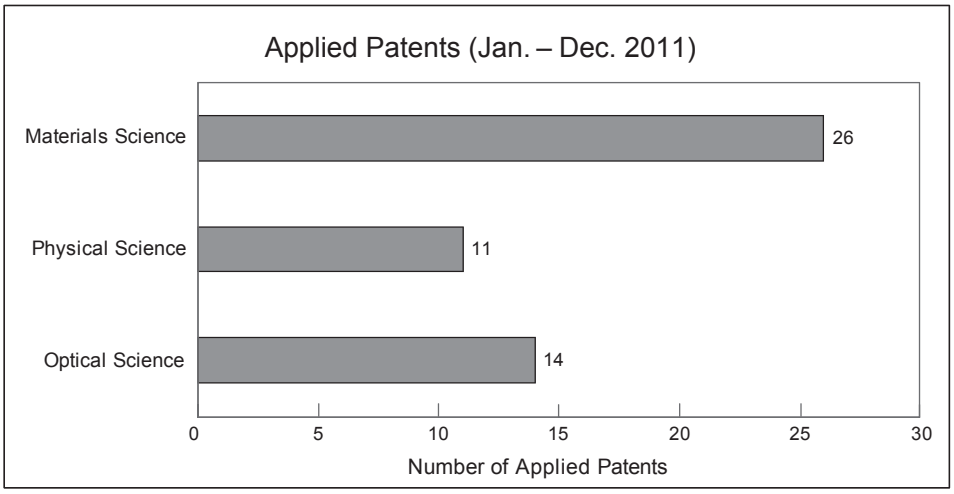

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Japanese Journal of Applied Physics	1.024	13
Physical Review Letters	7.622	12
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Applied Physics Express	2.778	5
Physical Review A	2.861	4
Nature Physics	18.43	3
Nano Letters	12.219	3
New Journal of Physics	3.849	3
Nature	36.104	2
Nanotechnology	3.652	2
Nature Nanotechnology	30.324	1
ACS Nano	9.865	1
Journal of the American Chemical Society	9.023	1
Small	7.336	1
Proceedings of the IEEE	5.151	1
Carbon	4.896	1
Journal of Physical Chemistry C	4.524	1
Langmuir	4.269	1
Nature Communications	-	1

*IF2010: Impact Factor 2010 (Journal Citation Reports, 2010)

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Conferences	Numbers
International Symposium on Nanoscale Transport and Technology	37
2011 International Conference on Solid State Devices and Materials	19
Electronic Properties of Two-Dimensional Systems 19	12
24th International Microprocesses and Nanotechnology Conference	5
38th International Symposium on Compound Semiconductors	5
Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference	5
International Symposium on Surface Science	5
22nd European Conference on Diamond, Diamond-Like Materials, Carbon Nanotubes and Nitrides	4
24th International Symposium on Superconductivity	4
Biophysical Society 55th Annual Meeting	4
ERATO Macroscopic Quantum Control Conference on Ultracold Atoms and Molecules	4
Frontiers in Nanoscale Science and Technology	4
Quantum Nanostructure and Nanoelectronics 2011	4

List of Invited Talks at International Conferences (2011)

I. Materials Science Laboratory

(1) H. Hibino, S. Tanabe, and H. Kageshima, "Growth and characterization of graphene on SiC", Graphene Workshop in Tsukuba 2011, Tsukuba, Japan (Jan. 2011).

(2) H. Hibino, S. Tanabe, and H. Kageshima, "Growth, structure, and transport properties of epitaxial graphene on SiC " 8th International Symposium on Atomic Level Characterizations for New Materials and Devices '11 (ALC'11) Seoul, Korea (May 2011).

(3) M. Kasu, K. Hirama, and Y. Taniyasu "High-thermal-efficiency AlGaN/GaN HEMTs on diamond", Asia-Pacific Workshop on Fundamentals and Applications of Advanced Semiconductor Devices, Daejeon, Korea (June 2011).

(4) H. Hibino, S. Tanabe, and H. Kageshima, "Growth and electronic transport properties of monolayer and bilayer graphene on SiC", XX International Material Research Congress 2011 (IMRC 2011), Cancun, Mexico (Aug. 2011).

(5) M. Kasu, K. Hirama, and Y. Taniyasu, "Nitride/diamond heterostructures -from growth to devices-", 22nd European Conference on Diamond, Diamond-Like Materials, Carbon Nanotubes and Nitrides (Diamond 2011), Garmisch-Partenkirchen, Germany (Sep. 2011).

(6) A. Shimada, T. Iwata, N. Nakano, and K. Torimitsu, "CMOS LSI for excitation and measurement of neural activity with microelectrode array", 2011 International Conference on Solid State Devices and Materials, Nagoya, Japan (Sep. 2011).

(7) M. Kasu and K. Hirama, "Diamond-based Electronic Device Technologies", International Conference on Carbon-based Nano-Materials and Devices, Suzhou, China (Oct. 2011).

(8) H. Hibino, S. Tanabe, and H. Kageshima, "Carrier transport in epitaxial graphene grown on SiC(0001)", 3rd International Symposium on the Science and Technology of Epitaxial Graphene (STEG3), Saint Augustine, U.S.A. (Oct. 2011).

(9) H. Omi, "Surface plasmon of gold nanorods in solutions", BIT's 1st Annual World Congress of Nano-S&T, Dalian, China (Oct. 2011).

(10) Y. Krockenberger, "Sr_2RuO_4 thin films: What's next?", International Workshop for Young Researchers on Topological Quantum Phenomena in Condensed Matter with Broken Symmetries, Shiga, Japan (Nov. 2011).

(11) K. Furukawa and J. Durao, "Donor-to-Acceptor Distance Dependent Fluorescence Resonance Energy Transfer Efficiency for Multiple Donors and Acceptors System Confined within 2-Dimensional Fluid of Supported Lipid Bilayer", International Symposium on Surface Science (ISSS-6), Funabori, Japan (Dec. 2011).

(1) H. Okamoto, D. Ito, K. Onomitsu, H. Sanada, H. Gotoh, T. Sogawa, and H. Yamaguchi, "Carrier-mediated opto-mechanical coupling in GaAs cantilevers", Frontiers in Nanoscale Science and Technology Workshop (FNST2011), Saitama, Japan (Jan. 2011).

(2) H. Nakano, "Time-evolution during superconducting qubit measurement process", International Symposium "Nanoscience and Quantum Physics 2011" (nanoPHYS'11), Tokyo, Japan (Jan. 2011).

(3) S. Saito, "Entanglement between macroscopic resonator and microscopic two level system through a flux qubit", The Third International Workshop on Dynamics and Manipulation of Quantum Systems (DMQS2010), Tokyo, Japan (Feb. 2011).

(4) H. Nakano, "Energy flow and information flow in qubit measurement process", International Conference in Quantum Bio-Informatics Center (QBIC2011), Chiba Japan (Mar. 2011).

(5) Y. Ono, M.A.H. Khalafalla, J. Noborisaka, G.P. Lansburgen, and A. Fujiwara, "Dopants in silicon transistors: transport and photoemission", CMOS Emerging Technologies Workshop, Whistler, BC, Canada (June 2011).

(6) T. Shinada, M. Hori, Y. Ono, A. Komatsubara, K. Kumagai, T. Tanii, T. Endoh, and I. Ohdomari, "Control of dopant distribution by dingle-ion implantation and its impact on transconductance of FETs", 2011 Asia-Pacific Workshop on Fundametals and Applications of advanced Semiconductor Devices (AWAD2011), Daejeon, Korea (June 2011).

(7) T. Koga, T. Matsuura, S. Faniel, S. Souma, S. Mineshige, Y. Sekine, and H. Sugiyama, "Determination of spin-orbit coefficients and application to the spin-filter devices using InGaAs/InAlAs heterostructures", 2011 Asia-Pacific Workshop on Fundamentals and Applications of Advanced Semiconductor Devices (AWAD2011), Daejeon, Korea (June 2011).

(8) H. Yamaguchi, I. Mahboob, H. Okamoto, and K. Onomitsu, "Heterostructure-based parametric resonator and its applications", The Second International Seminar on Nano-Electro-Mechanical Systems (NEMS2011), Toulouse, France (July 2011).

(9) L. Tiemann, G. Gamez, N. Kumada, and K. Muraki, "The spin polarization of the $\nu = 5/2$ fractional quantum Hall state", The 19th international Conference on Electronic Properties of Two-Dimensional Electron Systems (EP2DS19), Tallahassee, Florida, U.S.A. (July 2011).

(10) H. Okamoto, D. Ito, T. Watanabe, K. Onomitsu, H. Sanada, H. Gotoh, T. Sogawa, and H. Yamaguchi, "Carrier-mediated opto-mechanical coupling in GaAs micromechanical resonators", 17th International Conference on Electron Dynamics in Semiconductors, Optoelectronics and Nanostructures (EDISON 17), Santa Barbara, CA, U.S.A. (Aug. 2011).

(11) L. Tiemann, G. Gamez, N. Kumada, and K. Muraki, "The spin polarization of the $\nu = 5/2$ fractional quantum Hall state", 26th International Conference on Low Temperature Physics (LT26), Beijing, China (Aug. 2011).

(12) X. Zhu, S. Saito, A. Kemp, K. Kakuyanagi, S. Karimoto, H. Nakano, W. J. Munro, Y. Tokura, M. S. Everitt, K. Nemoto, M. Kasu, N. Mizuochi, and K. Semba, "Coupling an ensemble to a superconducting qubit", 26th International Conference on Low Temperature Physics (LT26), Beijing, China (Aug. 2011).

(13) K. Semba, "Toward hybrid quantum systems ~ A quest for a quantum memory ~", Shonan Workshop Report on "Hybrid Quantum Devices", Kanagawa, Japan (Nov. 2011).

(14) K. Semba, "Coherent coupling of a superconducting flux qubit to an ensemble of NV-centers in diamond", Quantum Technologies: Information, Communication and Computation, Tokyo, Japan (Nov. 2011).

(15) T. Yamaguchi, H. Yamaguchi, and T. Iyoda,"Directed self-assembly of block copolymers toward single-digit nanolithography", 24th International Microprocesses and Nanotechnology Conference (MNC2011), Kyoto, Japan (Oct. 2011).

(16) K. Muraki, "NMR measurement of the spin polarization in the $\nu = 5/2$ fractional quantum Hall state and in the N = 1 Landau level", Microsoft Station Q Fall Meeting, Santa Barbara, CA, U.S.A. (Dec. 2011).

III. Optical Science Laboratory

(1) K. Tateno, G. Zhang, H. Gotoh, and T. Sogawa," Characterization of InP-related Nanowires", Frontiers in Nanoscale Science & Technology (FNST2011), Saitama, Japan (Jan. 2011).

(2) M. Notomi, "Bi-layer Photonic Crystals for Optomechanics", SPIE Photonics West 2011, California, U.S.A. (Jan. 2011).

(3) W.J. Munro, "Universal Continuous variable quantum computation: what is needed?", Royal Society International Scientific Seminar on Continuous Variable Quantum Computation: Prospects and Challenges (CVQC), Milton Keynes, U.K. (Feb. 2011).

(4) M. Notomi, "fJ/bit nanophotonics for future ICT", International Conference of Nanophotonics, Shanghai, China (May 2011).

(5) M. Notomi, "fJ/bit nanophotonics for future ICT", The 10th Japan-Sweden QNANO Workshop, Visby, Sweden (June 2011).

(6) H. Takesue, "Entanglement generation using silicon wire waveguide", IEEE Summer Topicals, Montreal, Canada (July 2011).

(7) K. Nozaki, T. Tanabe, A. Shinya, S. Matsuo, G. Sato, E. Kawaguchi, H. Taniyama, and M. Notomi, "Photonic crystal nanocavities toward on-chip low-power nanophotonic devices", IQEC/CLEO PR, Sydney, Australia (Aug. 2011).

(8) S.J. Devitt, A.M. Stephens, W.J. Munro, and K. Nemoto, "The Optical Quantum Computer", SPIE, San Diego, U.S.A. (Aug. 2011).

(9) W.J. Munro, S.J. Devitt, and K. Nemoto, "Designing quantum repeaters and networks", SPIE, San Diego, U.S.A. (Aug. 2011).

(10) M. Notomi, "fJ/bit photonics platoform based on photonic crystals", SPIE, San Diego, U.S.A. (Aug. 2011).

(11) K. Azuma, "Quantum repeaters and computation built on a single module", Quantum Science Symposium 2011, Massachusetts, U.S.A. (Sep. 2011).

(12) M. Notomi, K. Nozaki, S. Matsuo, A. Shinya, G. Sato, and H. Taniyama, "fJ/bit Integrated Nanophotonics based on photonic Crystals", ECOC, Geneva, Switzerland (Sep. 2011).

(13) Y. Tokura, "Spin orbit interaction and spin accumulation in quantum dot systems", PIERS2011, Suzhou, China (Sep. 2011).

(14) H. Takesue, "Quantum communication experiments using superconducting single-photon detectors", International Workshop on Nanowire Superconducting Single-Photon Detectors (NSSPD), Eindhoven, Netherlands (Sep. 2011).

(15) T. Kubo, "Measurement Induced Backaction by Coupling with an Environment Containing a Quantum Dot as a Nanosensor", BIT's 1st Annual world Congress of Nano-S&T, Dalian, China (Oct. 2011).

(16) M. Notomi, E. Kuramochi, H. Taniyama, T. Tanabe, K. Nozaki, A. Shinya, S. Matsuo, G. Sato, and E. Kawaguchi, "Modulated mode-gap cavities in various forms", IEEE Photonics Conference, Arlington, U.S.A. (Oct. 2011).

(17) M. Notomi, "Integrated Nanophotonics for Green ICT", 12th RIES International Symposium, Hokkaido, Japan (Nov. 2011).

(18) A. Yokoo, T. Tanabe, E. Kuramochi, and M. Notomi, "Nano-fabrication for photonic crystal functional device", 11th International Symposium on Advanced Orgainc Photonics, Seoul, Korea (Nov. 2011).

(19) M. Notomi, K. Nozaki, S. Matsuo, A. Shinya, T. Sato, and H. Taniyama, "fJ/bit Integrated Nanophotonics Based on Nanocavities", SPIE Asia Communications and Optics Conference (ACP 2011), Shanghai, China (Nov. 2011).

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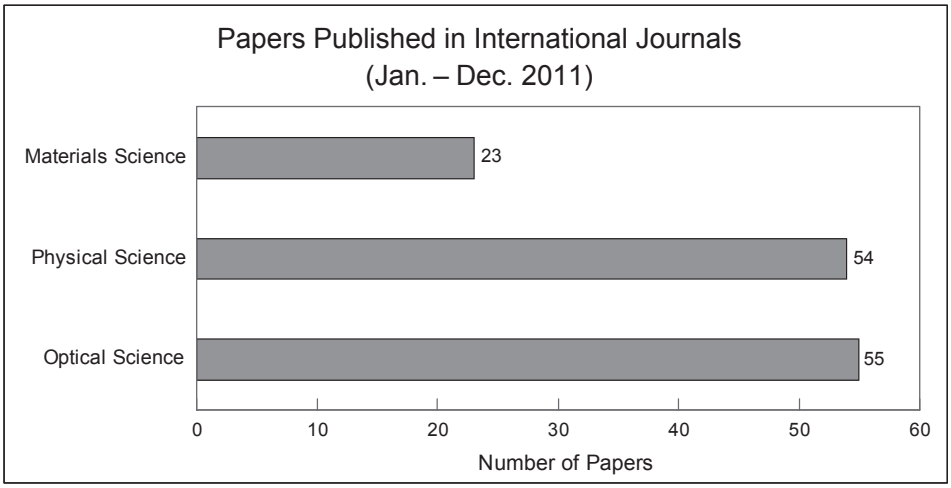

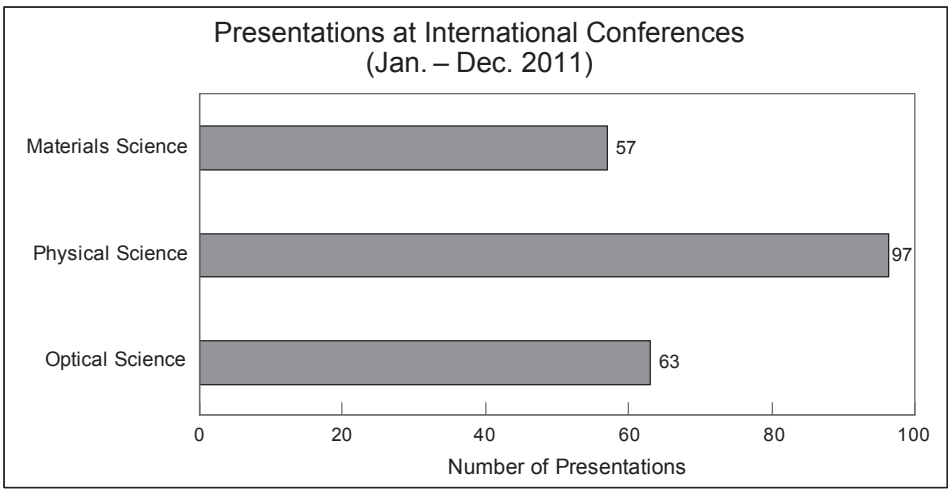

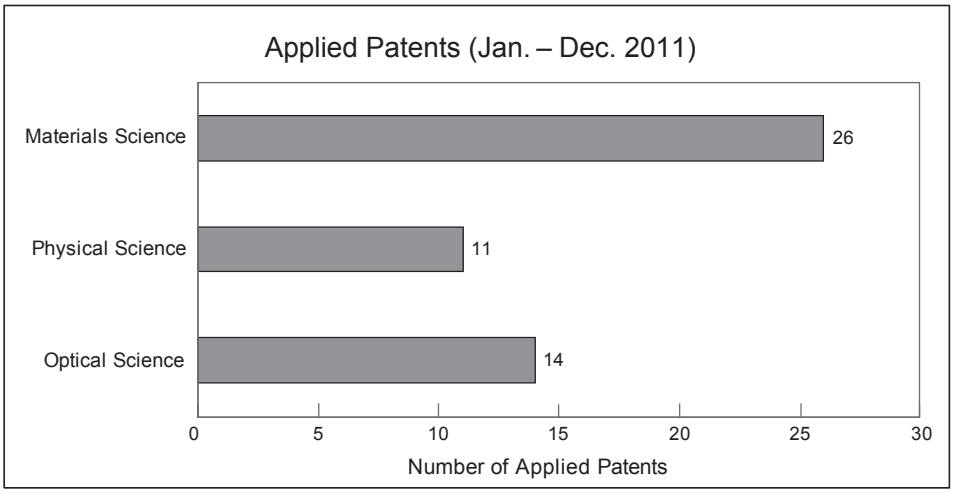

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Nanotechnology	3.652	2
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ACS Nano	9.865	1
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24th International Microprocesses and Nanotechnology Conference	5
38th International Symposium on Compound Semiconductors	5
Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference	5
International Symposium on Surface Science	5
22nd European Conference on Diamond, Diamond-Like Materials, Carbon Nanotubes and Nitrides	4
24th International Symposium on Superconductivity	4
Biophysical Society 55th Annual Meeting	4
ERATO Macroscopic Quantum Control Conference on Ultracold Atoms and Molecules	4
Frontiers in Nanoscale Science and Technology	4
Quantum Nanostructure and Nanoelectronics 2011	4

List of Invited Talks at International Conferences (2011)

I. Materials Science Laboratory

(1) H. Hibino, S. Tanabe, and H. Kageshima, "Growth and characterization of graphene on SiC", Graphene Workshop in Tsukuba 2011, Tsukuba, Japan (Jan. 2011).

(2) H. Hibino, S. Tanabe, and H. Kageshima, "Growth, structure, and transport properties of epitaxial graphene on SiC " 8th International Symposium on Atomic Level Characterizations for New Materials and Devices '11 (ALC'11) Seoul, Korea (May 2011).

(3) M. Kasu, K. Hirama, and Y. Taniyasu "High-thermal-efficiency AlGaN/GaN HEMTs on diamond", Asia-Pacific Workshop on Fundamentals and Applications of Advanced Semiconductor Devices, Daejeon, Korea (June 2011).

(4) H. Hibino, S. Tanabe, and H. Kageshima, "Growth and electronic transport properties of monolayer and bilayer graphene on SiC", XX International Material Research Congress 2011 (IMRC 2011), Cancun, Mexico (Aug. 2011).

(5) M. Kasu, K. Hirama, and Y. Taniyasu, "Nitride/diamond heterostructures -from growth to devices-", 22nd European Conference on Diamond, Diamond-Like Materials, Carbon Nanotubes and Nitrides (Diamond 2011), Garmisch-Partenkirchen, Germany (Sep. 2011).

(6) A. Shimada, T. Iwata, N. Nakano, and K. Torimitsu, "CMOS LSI for excitation and measurement of neural activity with microelectrode array", 2011 International Conference on Solid State Devices and Materials, Nagoya, Japan (Sep. 2011).

(7) M. Kasu and K. Hirama, "Diamond-based Electronic Device Technologies", International Conference on Carbon-based Nano-Materials and Devices, Suzhou, China (Oct. 2011).

(8) H. Hibino, S. Tanabe, and H. Kageshima, "Carrier transport in epitaxial graphene grown on SiC(0001)", 3rd International Symposium on the Science and Technology of Epitaxial Graphene (STEG3), Saint Augustine, U.S.A. (Oct. 2011).

(9) H. Omi, "Surface plasmon of gold nanorods in solutions", BIT's 1st Annual World Congress of Nano-S&T, Dalian, China (Oct. 2011).

(10) Y. Krockenberger, "Sr_2RuO_4 thin films: What's next?", International Workshop for Young Researchers on Topological Quantum Phenomena in Condensed Matter with Broken Symmetries, Shiga, Japan (Nov. 2011).

(11) K. Furukawa and J. Durao, "Donor-to-Acceptor Distance Dependent Fluorescence Resonance Energy Transfer Efficiency for Multiple Donors and Acceptors System Confined within 2-Dimensional Fluid of Supported Lipid Bilayer", International Symposium on Surface Science (ISSS-6), Funabori, Japan (Dec. 2011).

(1) H. Okamoto, D. Ito, K. Onomitsu, H. Sanada, H. Gotoh, T. Sogawa, and H. Yamaguchi, "Carrier-mediated opto-mechanical coupling in GaAs cantilevers", Frontiers in Nanoscale Science and Technology Workshop (FNST2011), Saitama, Japan (Jan. 2011).

(2) H. Nakano, "Time-evolution during superconducting qubit measurement process", International Symposium "Nanoscience and Quantum Physics 2011" (nanoPHYS'11), Tokyo, Japan (Jan. 2011).

(3) S. Saito, "Entanglement between macroscopic resonator and microscopic two level system through a flux qubit", The Third International Workshop on Dynamics and Manipulation of Quantum Systems (DMQS2010), Tokyo, Japan (Feb. 2011).

(4) H. Nakano, "Energy flow and information flow in qubit measurement process", International Conference in Quantum Bio-Informatics Center (QBIC2011), Chiba Japan (Mar. 2011).

(5) Y. Ono, M.A.H. Khalafalla, J. Noborisaka, G.P. Lansburgen, and A. Fujiwara, "Dopants in silicon transistors: transport and photoemission", CMOS Emerging Technologies Workshop, Whistler, BC, Canada (June 2011).

(6) T. Shinada, M. Hori, Y. Ono, A. Komatsubara, K. Kumagai, T. Tanii, T. Endoh, and I. Ohdomari, "Control of dopant distribution by dingle-ion implantation and its impact on transconductance of FETs", 2011 Asia-Pacific Workshop on Fundametals and Applications of advanced Semiconductor Devices (AWAD2011), Daejeon, Korea (June 2011).

(7) T. Koga, T. Matsuura, S. Faniel, S. Souma, S. Mineshige, Y. Sekine, and H. Sugiyama, "Determination of spin-orbit coefficients and application to the spin-filter devices using InGaAs/InAlAs heterostructures", 2011 Asia-Pacific Workshop on Fundamentals and Applications of Advanced Semiconductor Devices (AWAD2011), Daejeon, Korea (June 2011).

(8) H. Yamaguchi, I. Mahboob, H. Okamoto, and K. Onomitsu, "Heterostructure-based parametric resonator and its applications", The Second International Seminar on Nano-Electro-Mechanical Systems (NEMS2011), Toulouse, France (July 2011).

(9) L. Tiemann, G. Gamez, N. Kumada, and K. Muraki, "The spin polarization of the $\nu = 5/2$ fractional quantum Hall state", The 19th international Conference on Electronic Properties of Two-Dimensional Electron Systems (EP2DS19), Tallahassee, Florida, U.S.A. (July 2011).

(10) H. Okamoto, D. Ito, T. Watanabe, K. Onomitsu, H. Sanada, H. Gotoh, T. Sogawa, and H. Yamaguchi, "Carrier-mediated opto-mechanical coupling in GaAs micromechanical resonators", 17th International Conference on Electron Dynamics in Semiconductors, Optoelectronics and Nanostructures (EDISON 17), Santa Barbara, CA, U.S.A. (Aug. 2011).

(11) L. Tiemann, G. Gamez, N. Kumada, and K. Muraki, "The spin polarization of the $\nu = 5/2$ fractional quantum Hall state", 26th International Conference on Low Temperature Physics (LT26), Beijing, China (Aug. 2011).

(12) X. Zhu, S. Saito, A. Kemp, K. Kakuyanagi, S. Karimoto, H. Nakano, W. J. Munro, Y. Tokura, M. S. Everitt, K. Nemoto, M. Kasu, N. Mizuochi, and K. Semba, "Coupling an ensemble to a superconducting qubit", 26th International Conference on Low Temperature Physics (LT26), Beijing, China (Aug. 2011).

(13) K. Semba, "Toward hybrid quantum systems ~ A quest for a quantum memory ~", Shonan Workshop Report on "Hybrid Quantum Devices", Kanagawa, Japan (Nov. 2011).

(14) K. Semba, "Coherent coupling of a superconducting flux qubit to an ensemble of NV-centers in diamond", Quantum Technologies: Information, Communication and Computation, Tokyo, Japan (Nov. 2011).

(15) T. Yamaguchi, H. Yamaguchi, and T. Iyoda,"Directed self-assembly of block copolymers toward single-digit nanolithography", 24th International Microprocesses and Nanotechnology Conference (MNC2011), Kyoto, Japan (Oct. 2011).

(16) K. Muraki, "NMR measurement of the spin polarization in the $\nu = 5/2$ fractional quantum Hall state and in the N = 1 Landau level", Microsoft Station Q Fall Meeting, Santa Barbara, CA, U.S.A. (Dec. 2011).

III. Optical Science Laboratory

(1) K. Tateno, G. Zhang, H. Gotoh, and T. Sogawa," Characterization of InP-related Nanowires", Frontiers in Nanoscale Science & Technology (FNST2011), Saitama, Japan (Jan. 2011).

(2) M. Notomi, "Bi-layer Photonic Crystals for Optomechanics", SPIE Photonics West 2011, California, U.S.A. (Jan. 2011).

(3) W.J. Munro, "Universal Continuous variable quantum computation: what is needed?", Royal Society International Scientific Seminar on Continuous Variable Quantum Computation: Prospects and Challenges (CVQC), Milton Keynes, U.K. (Feb. 2011).

(4) M. Notomi, "fJ/bit nanophotonics for future ICT", International Conference of Nanophotonics, Shanghai, China (May 2011).

(5) M. Notomi, "fJ/bit nanophotonics for future ICT", The 10th Japan-Sweden QNANO Workshop, Visby, Sweden (June 2011).

(6) H. Takesue, "Entanglement generation using silicon wire waveguide", IEEE Summer Topicals, Montreal, Canada (July 2011).

(7) K. Nozaki, T. Tanabe, A. Shinya, S. Matsuo, G. Sato, E. Kawaguchi, H. Taniyama, and M. Notomi, "Photonic crystal nanocavities toward on-chip low-power nanophotonic devices", IQEC/CLEO PR, Sydney, Australia (Aug. 2011).

(8) S.J. Devitt, A.M. Stephens, W.J. Munro, and K. Nemoto, "The Optical Quantum Computer", SPIE, San Diego, U.S.A. (Aug. 2011).

(9) W.J. Munro, S.J. Devitt, and K. Nemoto, "Designing quantum repeaters and networks", SPIE, San Diego, U.S.A. (Aug. 2011).

(10) M. Notomi, "fJ/bit photonics platoform based on photonic crystals", SPIE, San Diego, U.S.A. (Aug. 2011).

(11) K. Azuma, "Quantum repeaters and computation built on a single module", Quantum Science Symposium 2011, Massachusetts, U.S.A. (Sep. 2011).

(12) M. Notomi, K. Nozaki, S. Matsuo, A. Shinya, G. Sato, and H. Taniyama, "fJ/bit Integrated Nanophotonics based on photonic Crystals", ECOC, Geneva, Switzerland (Sep. 2011).

(13) Y. Tokura, "Spin orbit interaction and spin accumulation in quantum dot systems", PIERS2011, Suzhou, China (Sep. 2011).

(14) H. Takesue, "Quantum communication experiments using superconducting single-photon detectors", International Workshop on Nanowire Superconducting Single-Photon Detectors (NSSPD), Eindhoven, Netherlands (Sep. 2011).

(15) T. Kubo, "Measurement Induced Backaction by Coupling with an Environment Containing a Quantum Dot as a Nanosensor", BIT's 1st Annual world Congress of Nano-S&T, Dalian, China (Oct. 2011).

(16) M. Notomi, E. Kuramochi, H. Taniyama, T. Tanabe, K. Nozaki, A. Shinya, S. Matsuo, G. Sato, and E. Kawaguchi, "Modulated mode-gap cavities in various forms", IEEE Photonics Conference, Arlington, U.S.A. (Oct. 2011).

(17) M. Notomi, "Integrated Nanophotonics for Green ICT", 12th RIES International Symposium, Hokkaido, Japan (Nov. 2011).

(18) A. Yokoo, T. Tanabe, E. Kuramochi, and M. Notomi, "Nano-fabrication for photonic crystal functional device", 11th International Symposium on Advanced Orgainc Photonics, Seoul, Korea (Nov. 2011).

(19) M. Notomi, K. Nozaki, S. Matsuo, A. Shinya, T. Sato, and H. Taniyama, "fJ/bit Integrated Nanophotonics Based on Nanocavities", SPIE Asia Communications and Optics Conference (ACP 2011), Shanghai, China (Nov. 2011).

Research Activities in NTT-BRL
Editorial Committee

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