Research Activities
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NTT Basic Research Laboratories

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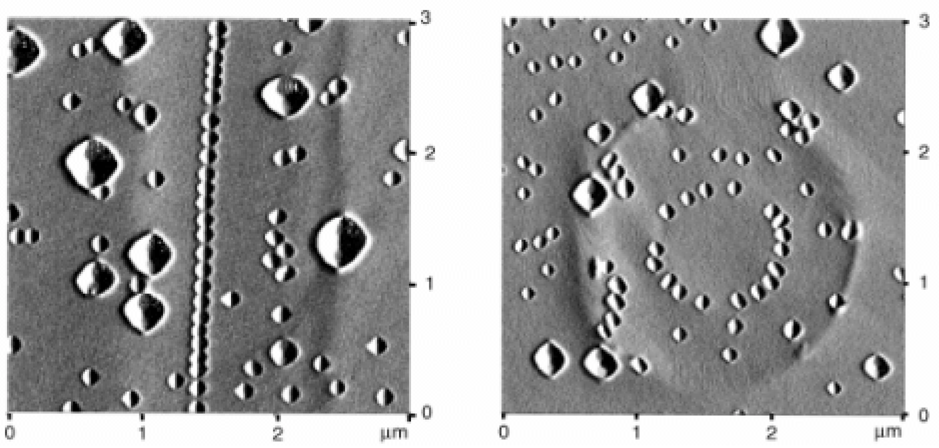
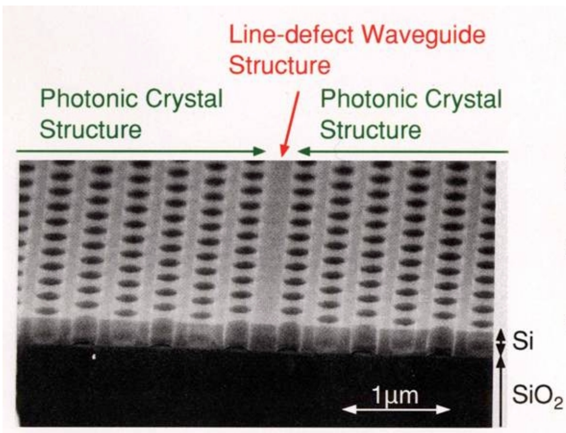
Basic Research Laboratories



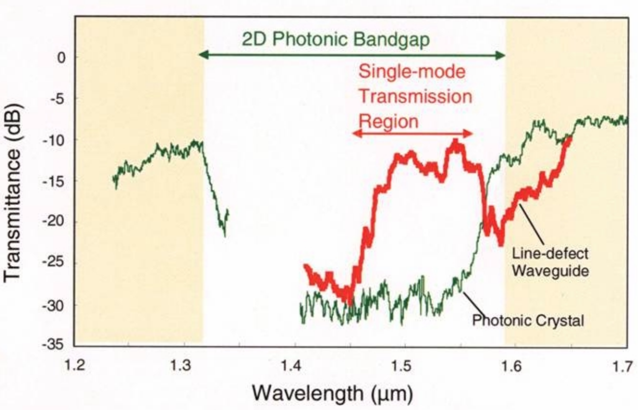
Atomic Force Microscopy Images

Semiconductor Surface with Strain Control

We have succeeded in obtaining a strain distribution controlled Si(001) substrate by forming silicon oxide inclusions below the surface, for the first time. Strained epitaxial growth of Ge on Si(001) produces three dimensional islands whose location and size distribution are well-controlled. (Page.13)



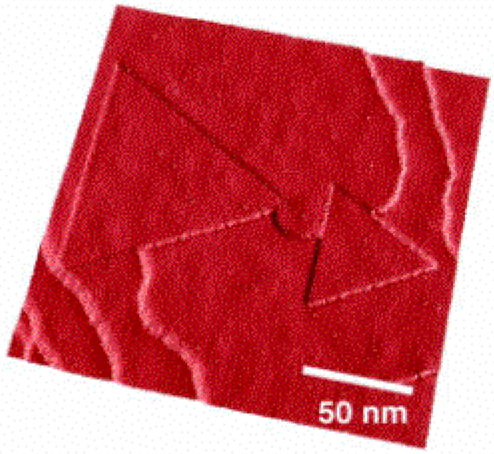
SEM Viewgraph of Fabricated Line-Defect Waveguide Structure



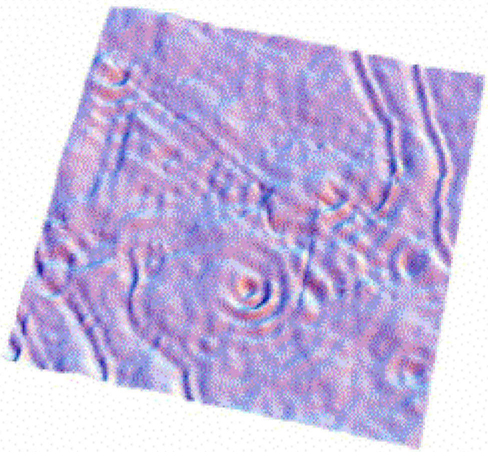
Tranmission Spectra

Successful Fabrication of 2D Photonic Crystals

A photonic crystal is a periodical structure composed of different refractive-index materials and its use is expected to lead to the development of future ultra-small-sized optical integrated cirsuits. Using SOI (Silicon On Insulator) structures, we have demonstrated 2D photonic crystal and line-defect structures with good transmission characteristics for the first time. (Page.19)



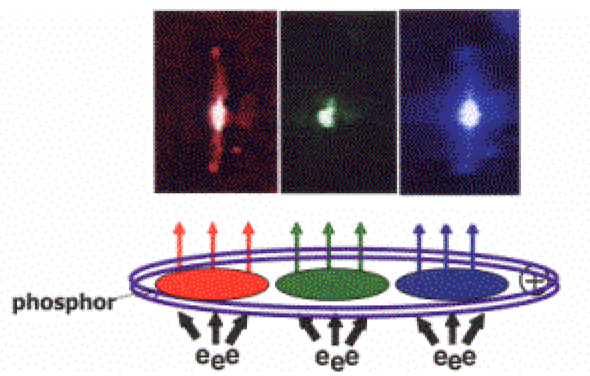
Topography

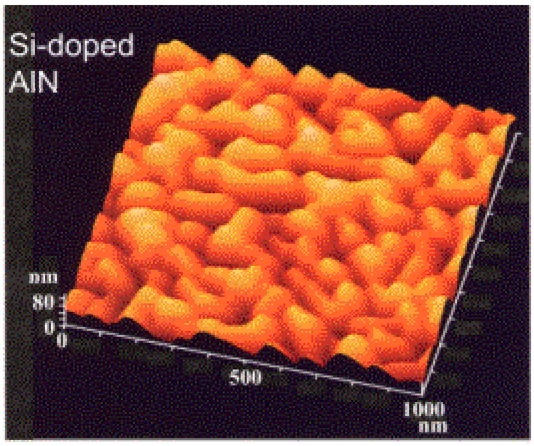


Local Density of States (LDOS)
(Friedel Oscillation)

Friedel Oscillations in 2D Electron Gas Systems at Semiconductor Surfaces

The feature of electrons as *matter waves*, one of the most significant conclusions from quantum mechanics, should be taken into account and controlled to engineering the electron transport in a nanoscale world. We have successfully imaged the electron waves (Friedel Oscillations) by applying a scanning tunneling microscopy (STM) for epitaxially grown semiconductor surfaces. Wavy LDOS patterns due to the electron wave interferences are clearly imaged in the vicinity of an isolated defect and inside of triangle nanostructures. (Page.22)





Large Electron-Field Emission from Aluminum Nitrides

We have found large electron-field emission from heavily Si-doped AlN with negative electron affinity. In a basic display structure, we observed red, green, blue light emission from phosphors excited by field-emitted electrons. Its luminance was intense enough for a practical display. (Page.23)

Preface

The mission of NTT Basic Research Laboratories is to create, by exploring the frontier of technology and creating a world-renown body of academic knowledge, technology innovations that will come into play in perhaps 10 or 20 years. Hence, in line with our enterprise strategy, we are developing new principles and concepts for the innovative technologies that will lead to NTT-group competitiveness and provide the infrastructure of the IT society in the 21st century. Nanotechnologies have attracted world attention over since the U.S. government announced their significance in its national strategy. We have been systematic studying nanoscience and nanotechnology for many years. The social and industrial expectations to the nanoscience and nanotechnology are a good incentive for us.

The fields of nanoscience and nanotechnology are further reflected in our research planning policy. We are aiming at breakthroughs that overcome the speed, capacity, power-consumption, size, and security barriers to the future network. So, we are pushing research of quantum information processing, ultimate electron devices, optical integrated circuits, and trying to artificially create new materials. To carry out more effective research, we are collaborating with outside parties based on our open-door policy, and actively harness outside talent. In particular, we now have an Advisory Board that does peer reviews and evaluates our laboratories. The first Advisory Board meeting convened this past February. We are now working to improve management based on the Advisory Board's suggestions.

This booklet, "Research Activities in NTT Basic Research Laboratories," is published annually to provide an overview of the research activities of the NTT Basic Research Laboratories. This volume reviews activities that have been conducted during fiscal year 2000. I hope this booklet will lead to the exchange of scientific information and promote mutual understanding among all scientists.

August 2001

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Member List

As of March 31, 2001
(*/ left NTT BRL in the middle of the year)

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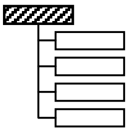

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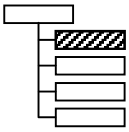

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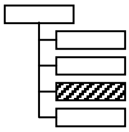

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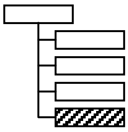

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Distinguished Technical Members

Yoshiro Hirayama was born in Kanagawa on July 18, 1955. He received the B.E., M.S. and Ph.D. degrees in electrical engineering from the University of Tokyo in 1978, 1980 and 1983, respectively. He joined NTT Basic Research Laboratories in 1983. He was a guest scientist in Max-Planck-Institut für Festkörperforschung, Stuttgart, Germany during 1990-1991. Since 1983 he has engaged in the study of semiconductor fine structures fabricated by focused-ion-beam technique, transport characteristics of semiconductor mesoscopic systems and ballistic transport in high-mobility semiconductors. His current interests are transport properties of semiconductor layer and nano structures including carrier interaction phenomena. He is a research coordinator of NEDO international joint research project (NTDP-98) since 1998, and also a coordinator of CREST research team for interacting carrier electronics since 1999. He is an associate editor of Japanese Journal of Applied Physics, and a member of the Japan Society of Applied Physics, the Physical Society of Japan and IEEE.

Toshiki Makimoto was born in Tokyo on January 16, 1960. He received the B.E., M.S. and Ph.D. degrees in electrical engineering from the University of Tokyo in 1983, 1985 and 1993, respectively. He joined NTT Basic Research Laboratories in 1985. He was a visiting researcher in University of California, Santa Barbara, USA during 1993-1994. Since 1985, he has engaged in epitaxial growth of III-V compound semiconductors using metalorganic vapor phase epitaxy (MOVPE) and flow-rate modulation epitaxy (FME), *in-situ* monitoring of epitaxial growth using surface photo-absorption (SPA), characterization of heavily doped semiconductors, heterojunction bipolar transistors (HBTs), and nano-structure selective area growth using scanning tunnel microscopy (STM). His current interests are epitaxial growth of nitride semiconductors and nitride semiconductor devices. He is a member of the Japan Society of Applied Physics and Materials Research Society.

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Prof. Klaus-J. Friedland	Paul-Drude-Institut für Festkörperelektronik, Germany March – April, 2000
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Prof. Michael B. Santos	University of Oklahoma, USA August – December, 2000
Prof. Joseph Imry	Weizman Institute of Science, Israel August – September, 2000
Prof. Yshai Avishai	Ben-Gurion University, Israel September – October, 2000
Prof. Thomas Schäpers	Institut für Shinchten und Grenzflächen Forschungszentrum Jülich, German October, 2000 – February, 2001
Prof. Alexander Khaetskii	Institute of Microelectronics Technology of the USSR Academy of Sciences, Russia September – November, 2000
Prof. Stoyan Stoyanov	Institute of Physical Chemistry, Bulgarian Academy of Science, Bulgaria November, 2000 – January, 2001

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Wilfred van der Wiel	Delft University of Technology, The Netherlands (May 00 – Aug. 00)
Barbara Ressel	Charles University, Italy (May 00 – June 00)
Enjalbert Fabrice	Ecole Nationale Supérieure de Physique de Grenoble (ENSPG), France (June 00 – Sep. 00)
Federico Rosei	University of Rome, Italy (July 00 – Sep. 00)
Marlies Comelia Goorden	Delft University of Technology, The Netherlands (Aug. 00 – Nov. 00)
Remi Dreyfus	Ecole Supérieure de Physique et de Chimie Industrielles de la ville de Paris (ESPCI), France (July 00 – Dec. 00)
Claire Akiko Kikuchi	Ecole Supérieure de Physique et de Chimie Industrielles de la ville de Paris (ESPCI), France (Aug. 00 – Dec. 00)
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Elise Laffosse	Institut National Des Sciences Appliquées, France (Mar. 01 – Aug. 01)

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Yusuke Asari	Waseda University, Japan (July 00 – Mar. 01)
Shinichi Amaha	Tokyo University, Japan (Apr. 00 – Mar. 01)
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Michihisa Yamamoto	Tokyo University, Japan. (Apr. 01 – Mar. 01)
Masahiro Wada	Waseda University, Japan (Apr. 00 – Mar. 01)

Ⅰ. Research Topics

Overview of Device Physics Research

Toshio Ogino
Device Physics Laboratory

Evolution of information technology is based on semiconductor devices of ultrahigh speed, low power dissipation, and ultrahigh density. The ultimate goal of silicon integrated system will be the control of a single electron in device functioning and control of a single atom in the fabrication process. Towards single electron control, we are proceeding with research on single electron transistors, single hole transfer devices, nanofabrication processes required for production of nano-scaled devices, and modeling of the Si oxidation process. Towards single atom control, we are developing a new approach of wafer-scale integration of self-organized nanostructures based on surface structure control. As a common basis for these goals, we are investigating new techniques for characterization of materials and device structures.

The single electron transistor is a device whose power dissipation is expected to be the minimum possible. We have already succeeded in fabricating an inverter that is a basic logic circuit element. In 2000, we fabricated an adder using our single electron transistors and demonstrated its operation. In addition to single electron circuits, we invented a single hole transfer device that is completely unprecedented. In this device, electrons and holes are spatially separated and the transport of a single hole is detected by the electron current. The single electron transistor was also applied to a new multiple-valued memory. We proceeded with characterization of the inside structure of the single electron transistor using scanning electron microscopy and considered theoretically the mechanism of single electron operation.

The most important process in Si technology is thermal oxidation of Si. We have shown that oxidation behavior under various oxidation conditions can be interpreted by the universal model for thermal oxidation which was proposed by this laboratory.

Towards room temperature operation of single electron devices, we are developing nanofabrication processes including electron beam lithography and resist processes. In nano-scale devices, pattern formation without roughness is indispensable. We have clarified the roughness generation mechanism and developed a new resist which can form a pattern with a very small roughness.

Conventional semiconductor devices are fabricated using resist patterns that are transferred from masks. On the other hand the "bottom-up process", in which device structures are fabricated from atomic structures on the substrate surface, attracts much attention. Towards realization of this process, we are investigating wafer-scale control of atomic structures on silicon surfaces. The dynamics of atomic steps and reconstructed domains were analyzed using scanning electron microscopy and low-energy electron microscopy. In order to control the arrangement of self-organized nanostructures, we have developed a novel technique to control the strain distribution on silicon surfaces: oxide inclusions are used to generate strain. We investigated the growth mechanism of Ge nanowires on Si surfaces. A new technique to form functional nanoparticles on Si surfaces has been proposed. By way of new materials research, we have started research on the growth and characterization of carbon nanotubes. We have established a novel characterization technique to observe the atomic structure of semiconductor surfaces during vapor-phase growth. This technique was applied to the analysis of the reconstruction of InP surfaces in a hydrogen ambient.

Manipulation of Elementary Charge in a Silicon Charge-Coupled Device

Akira Fujiwara and Yasuo Takahashi
Device Physics Laboratory

Single-electron (SE) devices have been attracting much attention in light of the underlying physics and the application to future integrated circuits. Though the manipulation of single electrons becomes possible in the so-called SE pump consisting of coupled conductive islands, the fabrication is no easy because it needs the integration of multiple tunnel capacitors. The SE manipulation has not yet been performed in Si devices. Recently we have developed a novel-type SE device oriented for large-scale integration [1]; it is the SE charge-coupled device (CCD), in which a single hole was stored and transferred at 25K. For sensing the hole, we demonstrate a new scheme based on the electron-hole system in Si nanostructures.

Figure 1(a) shows a top-view SEM image of the device. It is a closely packed array of two Si-wire MOSFETs with fine poly-Si gates. The Si wire is T-shaped so that each end is connected to three n-type electrodes, enabling us to detect the electron currents through each MOSFET separately. Figure 1(b) and (c) describe how the single hole is stored and transferred between the two Si channels, and is sensed by the electron currents. The hole is generated by illumination. Its storage and transfer are done simply by applying the negative voltages to the poly-Si gates and controlling them like the CCD. For the sensing, the hole and the electrons are kept apart by the large electric field across the Si wire, and therefore do not recombine soon. Since the wire diameter is as small as 15-20 nm, the electron current is highly sensitive to the number of holes (n_h), thus realizing the elementary-charge sensitivity.

The results for the single-hole manipulation are shown in Fig. 2. The sensing and the transfer of the single hole were repeated a few times. The sensing currents alternately have a high level. This means that the single hole was successfully transferred back and forth between the two Si-wire MOSFETs.

[1] A. Fujiwara and Y. Takahashi, Nature **410** (2001) 560.

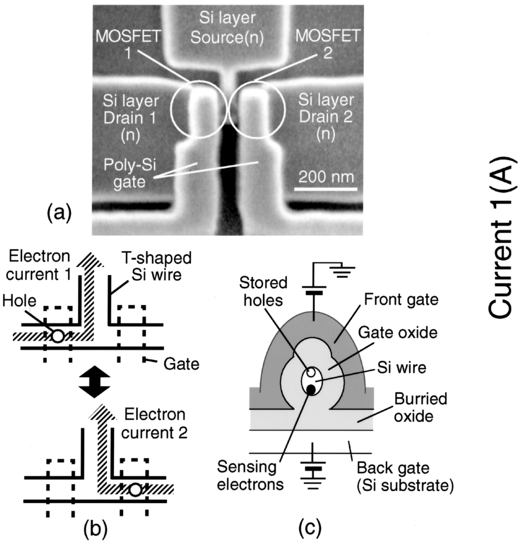

Fig. 1. (a) Top-view SEM image of the device.
(b) Transfer and sensing of the single hole.
(c) Cross-sections of the Si wire.

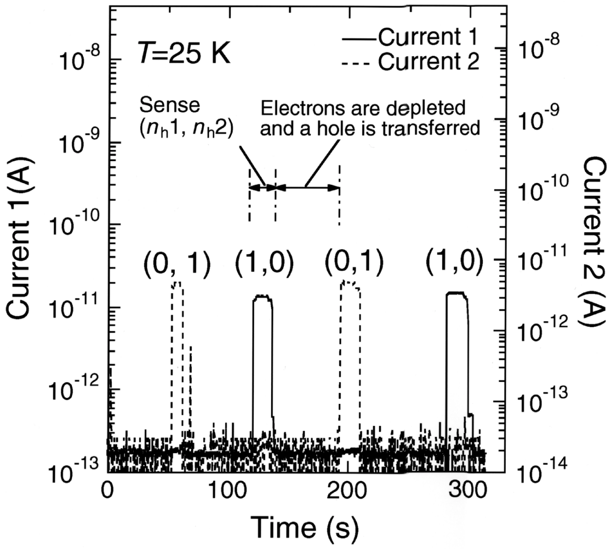

Fig. 2. Manipulation of a single hole between the two MOSFETs.

Sub-10-nm Electron Beam Lithography Using Inorganic Resist

Kenji Yamazaki, M. S. M. Saifullah*, Toru Yamaguchi, and Hideo Namatsu
Device Physics Laboratory

In order to make high performance nanodevices like single-electron devices working at room temperature, nanofabrication at the scale of sub-10 nm is necessary. To enable that, electron beam (EB) nanolithography on inorganic resists has been tried by many groups. The sensitivity of conventional inorganic resists, however, is too low for these resist to be applied to make high-performance nanodevices.

We have developed a new organic/inorganic composite resist that has much higher sensitivity than conventional inorganic resists and sufficient resolution for our purpose. This resist is a chelete compound of a metal alchoxide chemically modified by a β-diketone [1]. EB exposure causes separation of the diketone from the compound, which is followed by spontaneous crosslinkage of the alchoxide. Thus, it can be used as a negative-tone resist to an EB. As the primary reaction due to the EB occurs at the organic ketone part, not at inorganic parts, this resist is more than a hundred times more sensitive to the EB, compared to conventional inorganic resists. The resist enables finer patterning and provides small line-edge roughness due to its structure being as small as a few nanometers.

We have evaluated this resist using our EB nanolithography system at 100-kV acceleration voltage. Besides its small beam size, this system has high stability and reproducibility for sub-10-nm scale lithography. For example, the beam positioning error is less than 2 nm for 10 minutes, and the reproducibility of the stage position is as good as 1-2 nm after 500 stage movements [2].

Figure 1 shows fine lines of the resist exposed to the EB using the system. The width of the lines formed at the center of the main deflection field is about 8 nm. We could also obtain fine lines as narrow as about 10 nm on the boundary of a 320-μm-square mainfield. Good reproducibility and low fluctuation of linewidth are obtained, and the linewidths at the center and the boundary of the field correspond to the diameters of the EB simulated there. These results mean the resist pattern strictly reflects the distribution of the energy absorbed in resist.

[1] M. S. M. Saifullah et al., Jpn. J. Appl. Phys. **38** (1999) 7052.
[2] K. Yamazaki et al., Proc. SPIE. **3997** (2000) 458.

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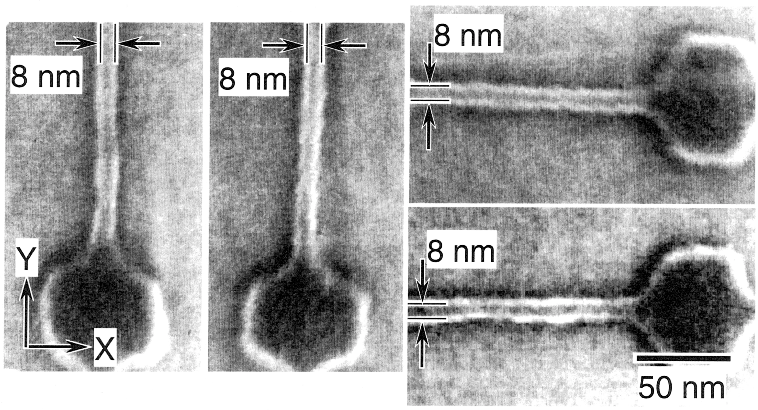


Fig. 1. 8-nm-wide lines of composite resist formed at the center of the mainfield. Lines were reproducibly formed with small line edge roughness along both x- and y- axis.

Semiconductor Surface with Strain Control

Hiroo Omi, David Bottomley, and Toshio Ogino
Device Physics Laboratory

Looking to the long term future of Si semiconductor technology, we have proposed, fabricated and demonstrated strain distribution control on the planar Si wafer scale for advanced nanostructure self-assembly. Self-assembled growth attracts much attention because it is free from the optical lithography minimum feature size limit. In most research to date on nanostructure formation on Si surfaces, the substrate was not subjected to advanced preparation procedures. Preparation typically consisted of chemical etching followed by thermal treatment in ultra high vacuum. The size variation of Ge or Ge_xSi_{1-x} alloy nanostructures grown coherently on the surface was appreciable, with no localization control. As a result the structures are difficult to utilize effectively in commercial applications.

Here we apply commercially-viable industrially-proven processes to prepare the Si wafer for advanced nanostructure fabrication. Pre-deposited layers on the surface of the wafer are patterned using optical lithography; oxygen ions are implanted; the sample is subjected to a 1325°C anneal, and finally the pattern is removed in a chemical etch. The oxide inclusions are completely stable up to at least 1325°C and are therefore compatible with further fabrication processes. The O ion implantation and annealing approach is a spinoff from the silicon on insulator (SOI) field, specifically the separation by implanted oxygen (SIMOX) process invented 23 years ago at NTT.

Strained epitaxial growth of Ge on the Si(001) substrate surface at 550°C in ultra high vacuum produces three dimensional islands whose location and size distribution are well-controlled (Fig. 1). Ge grows forming three dimensional islands surrounded by a wetting layer. The growth mode occurs to reduce the combined surface energy and elastic energy of the system. Growth on a line pattern produces aligned, closely-spaced islands with a highly uniform size distribution (Fig. 1(a)). In Fig. 1(b), the islands have self-organized into a ring at the centre of the implanted region.

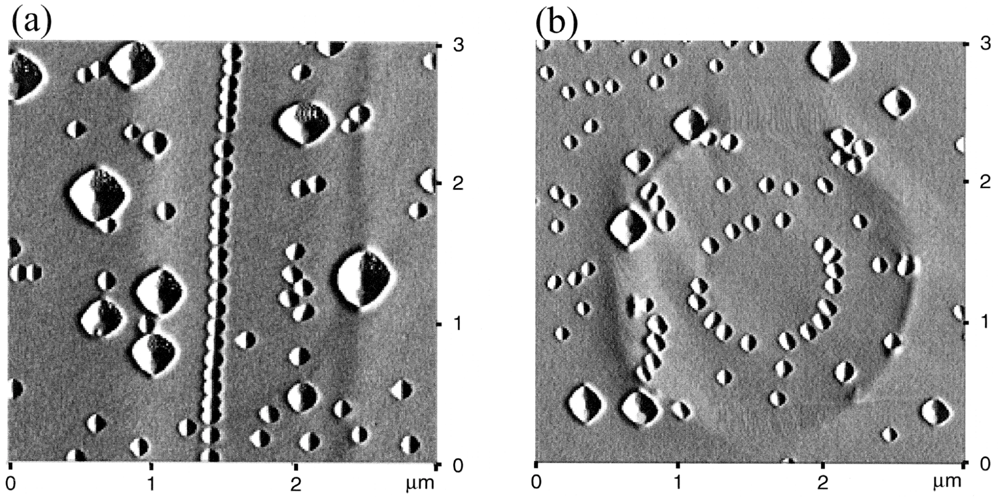


Fig. 1. Atomic force microscopy images of the surface after growth of Ge (a) on a 700 nm implantation width line pattern (b) on a 2 μm implantation diameter hole pattern.

Observation of Indium Phosphide Surface Structures in Metalorganic Vapor Phase Epitaxy

Tomoaki Kawamura and Yoshio Watanabe
Device Physics Laboratory

Understanding surface structures is one of the fundamental issues in epitaxial growth. Reflection high energy electron diffraction is routinely used in molecular beam epitaxy (MBE). In metalorganic vapor phase epitaxy (MOVPE), optical tools, such as reflectance difference spectroscopy (RDS) and surface photoabsorption (SPA), are used. However, surface structures in MOVPE growth are still uncertain because of the low spatial resolution owing to the longer wavelength of visible light.

A crystallographic structure analysis by using x-ray diffraction is known as a powerful tool for determining the atomic arrangement in bulk crystals, and has also been applied in analyses of surface structures in liquid and gaseous environments. Additionally, owing to the low interference between x-rays and materials, a quantitative treatment of measurement is possible, and this makes the analysis procedure easier. To investigate fundamentals of epitaxial growth in the gas phase, we developed an in situ x-ray diffractometer that combines an x-ray goniometer and reactor chamber [1], and used it to analyze surface structures of indium phosphide (InP) [2].

Due to high partial pressure of V-elements, it is difficult to obtain good-quality epitaxial films in MBE, and surface structures in the growth environment are poorly understood. We investigated InP (001) surfaces grown by MOVPE in a hydrogen environment. Figure 1 shows intensity distribution of a reconstructed InP (001) surface in reciprocal space. Filled symbols show the points where Bragg diffraction was observed, and crosses show where there were no diffraction. Open circles indicate points where we cannot observe Bragg diffractions because of the bulk Bragg diffraction. Obviously, fractional diffractions of (1/2 n) along the [-110] direction and integral diffraction spots along the [110] direction were observed, suggesting (2×1) periodicity on the surface. Additionally, intensity variation along (1/2 m), (3/2 m) was observed, suggesting the surface model shown in Fig. 2.

[1] T. Kawamura et al., J. Cryst. Growth **221** (2000) 106.
[2] T. Kawamura et al., Appl. Phys. Lett. **77** (2000) 996.

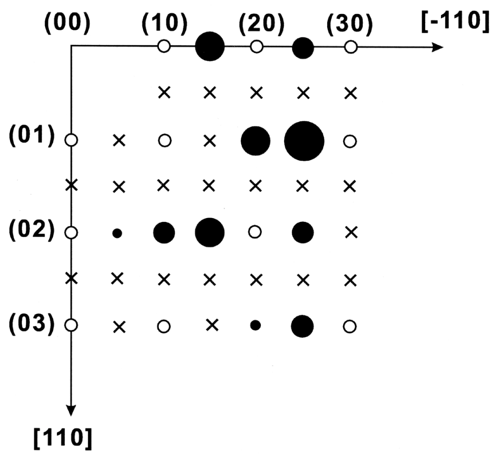


Fig. 1. Intensity distribution in reciprocal space.

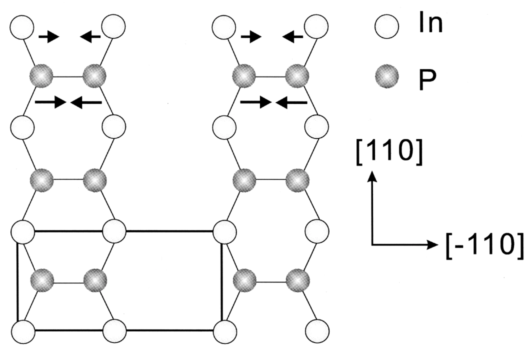


Fig. 2. Model of (2×1) InP (001).

Overview of Materials Science Research

Hideaki Takayanagi
Materials Science Laboratory

The Materials Science Laboratory (MSL) aims at producing new materials by controlling the arrangement and coupling among atoms and molecules. By producing such materials, MSL also aims to discover new quantum phenomena and to create new concepts. Toward these goals, the following four MSL groups investigate a wide variety of materials, from inorganic to organic. The important feature of MSL is the effective sharing of nanofabrication and precise measurement techniques developed originally in each group.

Molecular and Bio-Science Research Group

Creating new organic materials based on the manipulation of single molecules, and researching into information processing devices based on neural functions.

Superconducting Thin Films Research Group

Creating new high-Tc superconductors using the molecular beam epitaxy method.

Superconducting Quantum Physics Research Group

Controlling quantum bits in superconductor as a step towards quantum computing, and creating new magnetic devices using quantum dot arrays.

Nano-Structure Materials Research Group

Developing optical devices for the next generation using photonic crystals.

The four major results obtained in fiscal year 2000 are as follows.

1. The real-time monitoring of glutamate (Glu), which are typical neurotransmitters in the cerebral cortex. By fabricating a special electrochemical Glu sensor array, we have succeeded in real-time and multi-site monitoring of this neurotransmitter. This can be regarded as the first step towards understanding the complex neural network in the brain.
2. High-quality electron-doped cuprate superconducting thin films were prepared by molecular beam epitaxy (MBE) method for the first time. A reduction of the synthesis temperature in MBE makes it possible to synthesize a high-quality thin firm, which cannot be prepared by conventional methods. By investigating the properties of the films, we should find a clear guiding principle for the search for new electron-doped superconductor.
3. Ferromagnetism in quantum dot superlattices was theoretically predicted. A quantum dot artificial crystal comprising 0.104-μm-wide InAs quantum wires has flat band characteristics. By changing the electron filling of the band, we show that the crystal can be switched from a ferromagnetic to a paramagnetic state and vise versa.
4. The single-mode, low-loss transmission was achieved in a two dimensional photonic crystals. A photonic crystal, which is an artificial periodical structure consisting of different refractive-index materials, is expected to lead to smaller optical devices and larger scales of integration. We proposed and fabricated line-defect two-dimensional photonic crystals on the SOI (silicon on insulator) structures, and demonstrated the capability of low-loss transmission under the single-mode condition.

The details of these accomplishments will be described in the following pages.

Real-Time Monitoring of Neural Activity in the Brain

Nahoko Kasai, Yasuhiko Jimbo, and Keiichi Torimitsu
Materials Science Laboratory

The brain, which consists of neurons and many other different types of cell in a complex network, provides efficient functions including transfer, storage and other forms of processing of a large quantity of information. Numerous attempts have been made to understand these functions, however, few studies have been able to obtain real-time two- or three-dimensional information with precision and high special resolution, which is essential if we are to comprehend how the brain operates.

The release of neurotransmitters from neurons and their distribution are also important issues in terms of understanding the mechanisms of memory and learning. However, few studies have succeeded in monitoring the distribution of neurotransmitters themselves. Rather, reports have described the distribution of receptor subunits, which do not inform us of the activity of the receptor and its dynamics. We focus on glutamate (Glu), one of the neurotransmitters in the cortex or hippocampus and have monitored the real-time Glu concentration with a view of imaging and animating its two-dimensional distribution.

In this study, we have succeeded in monitoring the Glu concentration at multiple positions in a hippocampal slice simultaneously [1]. We fabricated an electrochemical Glu sensor array by modifying an electrode array (each size: 50×50 μm^2) with enzymes and an electron transfer mediator. We then placed the cultivated slice on the array and measured the Glu concentration at selected sensors in the array. When we introduced a stimulant into the external medium, the sensors indicated the different amounts of Glu released as a result of the receptor stimulation (Fig. 1). This result demonstrates the diversity of the receptors, their distribution and their dynamics. Our glutamate sensor array could prove to be a powerful tool for understanding the role of glutamate in the brain. We will continue our work in order to realize the imaging of its distribution.

[1] N. Kasai et al., Neurosci. Lett. **304** (2001) 112.

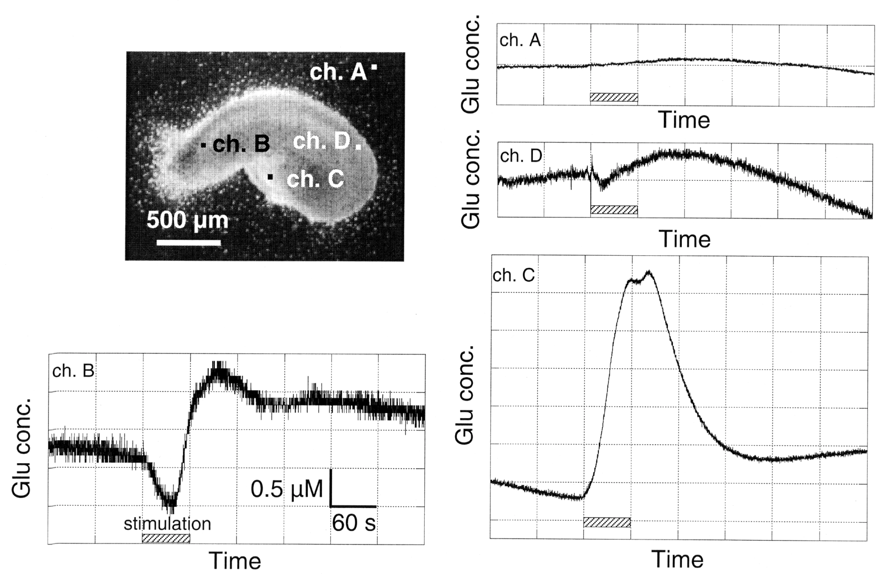


Fig. 1. Glutamate concentration profiles at different positions in hippocampus.

Electron-Doped High-T_C Superconducting Thin Films Grown by Molecular Beam Epitaxy

Shin-ichi Karimoto and Michio Naito
Materials Science Laboratory

High-T_C superconductors are classified as hole-doped or electron-doped and there seems to be apparent asymmetry between the two classes. Hole-doped superconductors are major, and their highest T_C is 135 K. Electron-doped superconductors are minor (only two kinds), and their highest T_C is 40 K. This raises two important questions: why these T_C values are so different, and whether or not superconductivity mechanism is the same. To answer these questions, it is highly desirable to find new electron-doped superconductors and obtain high-quality single-crystalline thin films. Recently, we have succeeded in the MBE-growth of single-crystalline films of the following two electron-doped superconductors that are difficult to obtain by bulk synthesis.

(1) (Sr, La)CuO_2 (T_C =40 K)

Infinite-layer compounds have the simplest structure among high- T_C superconductors (see Fig. 1(a)). However, despite this simple structure and the fact that they are the electron-doped superconductors with the highest T_C, they have been studied very little. This is because the synthesis of these compounds requires a high pressure of above 2.5 GPa. MBE enables us to synthesize this high-pressure phase via an epitaxial effect. Figure 1(b) shows the ρ-T curve of our single-crystalline (Sr, La)CuO_2 thin film grown on a special substrate ($KTaO_3$). The low resistivity and metallic behavior indicate excellent crystallinity [1].

(2)T'- (La, Ce)$_2CuO_4$ (T_C =30K)

The other kind of electron-doped superconductor is represented by (Ln,Ce)$_2CuO_4$. This structure is formed with Ln=Pr, Nd, Sm, Eu, Gd, by using the conventional solid-state reaction method. The maximum T_C (25 K) of this series is achieved with (Pr,Ce)$_2CuO_4$ and (Nd,Ce)$_2CuO_4$. Low-temperature MBE growth makes it possible to synthesize (La,Ce)$_2CuO_4$, which attains the highest T_C in this group (30 K). Moreover, we found that there is a tendency for the T_C to become higher as increasing the ionic radius of the Ln elements. This gives us a clear guiding principle in the search for new high-T_C superconductors [2].

[1] S. Karimoto et al., submitted to Appl. Phys. Lett.
[2] M. Naito and M. Hepp, Jpn. J. Appl. Phys. **39** (2000) L485.

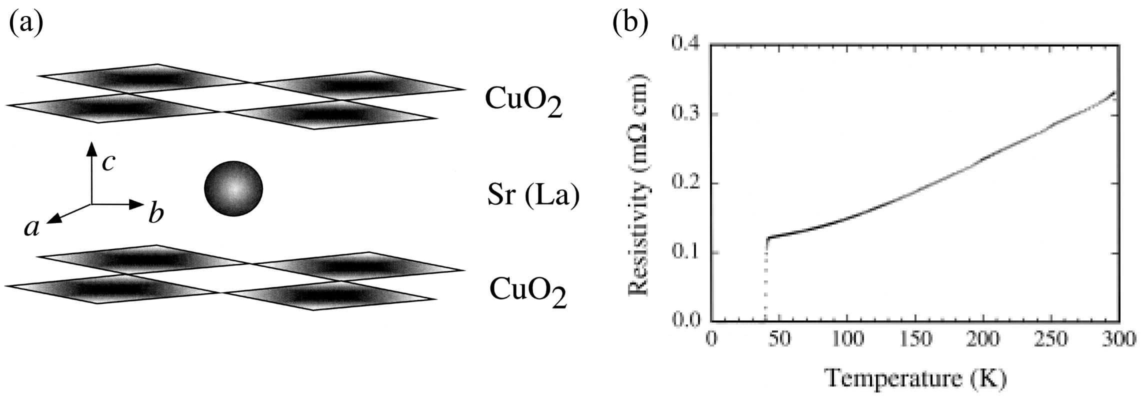


Fig. 1. (a) Crystal structure and (b) best ρ -T curve for (Sr, La) CuO_2 thin film.

Novel Material Design in Quantum Dot Superlattices

Hiroyuki Tamura and Hideaki Takayanagi
Materials Science Laboratory

If we consider a quantum dot (QD) as a building block and put it on a site of lattice, we can create an artificial crystal called quantum dot superlattice. There are several advantages of using semiconductor dots in making artificial crystals. First, the lattice structure can be widely chosen. One can fabricate a lattice structure which does not exist in nature. Second, the electron filling can be freely modified. As a consequence, various types of interesting electronic properties can be expected. We have proposed that specific types of quantum dot superlattice exhibit ferromagnetism which should be observable in experiment [1].

Recently, we have presented the theoretical design of quantum dot superlattice exhibiting ferromagnetism by using a quantum-wire network shown in Fig. 1 [2]. The electronic structure calculations based on a local spin density approximation (LSDA) show that our designed QD artificial crystal from a structure comprising the crossing 0.104-μm-wide InAs quantum wires forms an effective Kagome lattice having a flat band. Our examined QD artificial crystal has the ferromagnetic ground state when the flat band is half-filled as shown in Fig. 2, even though it contains no magnetic elements. We have also demonstrated that the ferromagnetic and paramagnetic states can be freely switched by changing the electron filling.

By extending the idea of dot superlattices, one can think of other interesting possibilities of artificial materials. In the near future, the semiconductor nano-technology may allow us to realize other interesting electronic properties, such as superconductivity, in quantum dot superlattices.

[1] H. Tamura, K. Shiraishi, and H. Takayanagi, Jpn. J. Appl. Phys. **39** (2000) L241.
[2] K. Shiraishi, H. Tamura, and H. Takayanagi, Appl. Phys. Lett. **78** (2001) 3702.

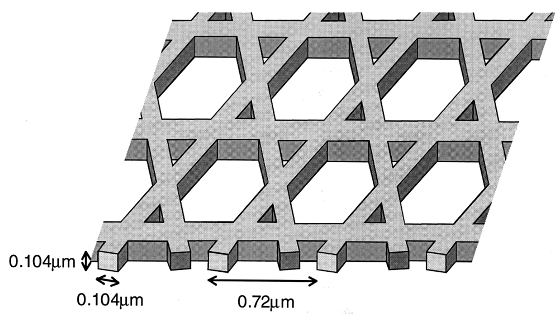


Fig. 1. The effective Kagome crystal we examined. The crossing quantum wire is InAs and the barrier region is $In_{0.72}Ga_{0.28}As$ with barrier height of 0.21eV.

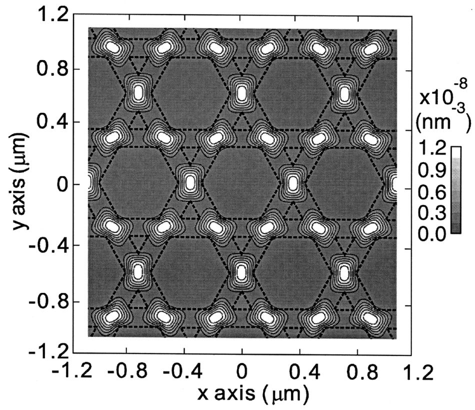


Fig. 2. A cross-sectional view of LSDA-calculated spin density of ferromagnetic states.

Successful Fabrication of 2D Photonic Crystals

Masaya Notomi, Akihiko Shinya, and Itaru Yokohama
Materials Science Laboratory

A photonic crystal is an artificial periodical structure composed of different refractive-index materials and its use is expected to lead to the development of smaller optical devices and larger scales of integration. We have been focusing on the SOI (Silicon On Insulator) structure and have been researching 2D photonic crystals in cooperation with Telecommunications Energy Laboratories.

We have fabricated vertical holes with a triangular lattice pattern in a 200 nm-thick silicon layer with a period of 400 nm. The structure of this 2D photonic crystal is characterized by silicon regions (high refractive index) and air regions (low refractive index) in the vertical holes that are periodically arranged along the horizontal plane of the silicon layer. The propagated light is vertically confined in the silicon layers because silicon has a higher refractive index than silicon oxide or air. Measurements have revealed that a clear photonic bandgap (a feature of photonic crystals that functions as an optical insulator) is formed in the optical-communications wavelength region [1]. We have also proposed a width-varied line-defect structure that is applicable to the above structure. Figure 1 shows a SEM photograph of the width-varied line-defect structure we fabricated. Measurement results, such as the transmission-spectrum (Fig. 2), show that we have achieved low-loss transmission under single-mode conditions for the first time [2].

In this research, we have demonstrated the 2D photonic crystal and line-defect structures using SOI structures. These structures are suitable as basic elements for ultra-small optical integrated circuits.

[1] I. Yokohama et al., OECC 2000 (2000) 11B2-4.
[2] M. Notomi et al., Electron. Lett,. **37** (2001) 293.

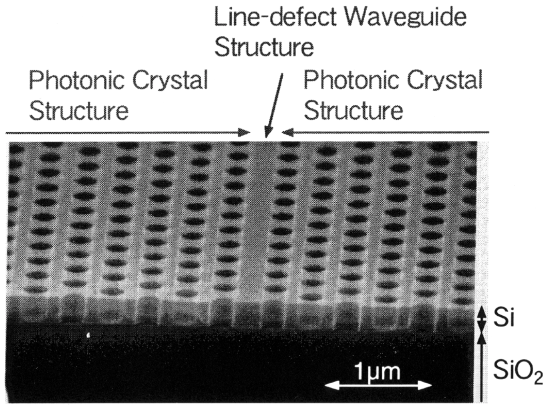


Fig. 1. SEM viewgraph of fabricated line-defect waveguide structure.

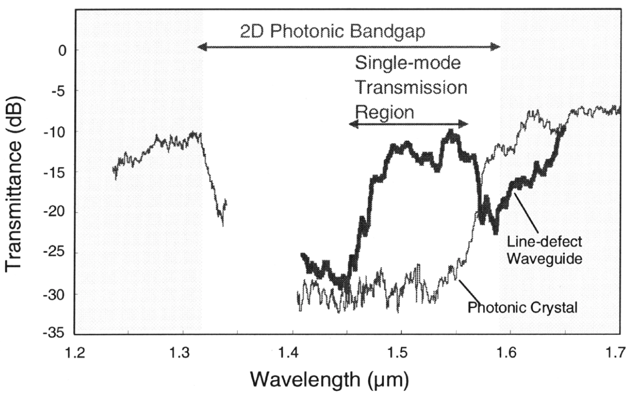


Fig. 2. Tranmission spectra.

Overview of Quantum Physics and Electronics Research

Takaaki Mukai
Physical Science Laboratory

Our research in the fields of quantum physics and electronics, which is based on semiconductor nano-structures fabricated by high-quality semiconductor crystal growth and advanced device fabrication techniques, focuses on quantum electronic state control, carrier interactions and wide-bandgap semiconductor physics. Our aim is the development of innovative semiconductor devices. The Quantum Solid State Physics Research Group and the Wide-Bandgap Semiconductor Research Group are working in the following areas.

Quantum Solid State Physics Research Group

(1) Carrier interactions in low-dimensional semiconductor heterostructures (two dimensional carrier transport and correlation effects in high-mobility semiconductors, carrier interactions in bilayer (electron-electron and electron-hole) systems, and interactions between nuclear-spin and conduction electrons in semiconductors).

(2) Quantum electronic state control in quantum dot systems (electronic properties of vertical and lateral semiconductor quantum dots (artificial atoms and molecules), spin control in quantum dots, carrier dynamics of quantum dots, and fundamental properties of solid-state quantum computers using artificial molecules).

(3) Semiconductor nano-mechanical systems (fabrication of nano-mechanical structures and their characterization) and nano-probing (direct nano-scale imaging of electronic states by low-temperature scanning-tunneling-microscopy (STM) technique).

Wide-Bandgap Semiconductor Research Group

(1) High-quality GaN crystal growth (mechanism of GaN and facet-controlled crystal growth by MOCVD, high-concentration p-type doping, and device processing technology).

(2) GaN semiconductor device physics (electronic and optical properties of GaN quantum well structures, electronic devices suitable for high-temperature operation, and short-wavelength light emitting devices).

(3) Electron field emission in AlN cold cathode materials (field emission characteristics, such as threshold field and available emission current, as a function of Si-dopant density).

Major results obtained this fiscal year 2000 are reported in the following pages. We experimentally investigated Kondo effect caused by spin correlated transport in well-defined semiconductor quantum dots. We successfully demonstrated the unitary limit Kondo effect, i.e., theoretical maximum in conductance. We also discovered novel aspect in Kondo effect that appears when even number of electrons are involved. These results promise controllable electron-spin correlation in quantum dots, leading to future "quantum correlated electronics".

We have successfully imaged electron waves (Friedel oscillations) in real space by applying low-temperature STM technique. Different from localized electron waves at surface boundaries so far observed, our direct observations were carried out for conducting electrons in two-dimensional electron gas accumulated in near-surface region of InAs. We believe that this technique will be indispensable for fully understanding ultimately small devices.

Besides conventional electronic and photonic device applications of nitride-based semiconductors, we demonstrated novel property favored in wide bandgap materials, i.e., highly efficient electron-field-emission in heavily Si-doped AlN. Available emission current density obtained in our AlN has already exceeded the maximum value realized so far in diamond, which is exciting enough for future applications to field-emission display and so on.

Novel Kondo Effect in Quantum Dots

Toshimasa Fujisawa and Satoshi Sasaki
Physical Science Laboratory

Quantum dots, in which electrons are confined by semiconductor nano-structures, show the quantum mechanical duality (particle- and wave-nature) for the electrons; the number of the electrons in the quantum dot is precisely controllable and discrete energy states are formed as a result of electron-wave interference. Moreover, many electron-spin related phenomena have been investigated in quantum dots. Since the electronic states in quantum dot resemble natural atoms, quantum dots are often called artificial atoms. The properties of quantum dots that can control a single electron-spin are promising for an application to the element (quantum bit) that realizes quantum information processing, such as quantum computers. In order to explore the possibility of quantum gates that correlate quantum bits, Kondo effects in quantum dots are attractive for their spin correlated transport.

The Kondo effect in quantum dot is a quantum mechanical co-tunneling process caused by the electron-spin interaction between electrons in the quantum dot and electrons in the lead. Even when the electron transport is restricted by Coulomb blockade effect, an electron can flow through the dot by making spin correlated singlet state if the dot has an electron-spin. The Kondo effect normally appears when the dot has odd number of electrons (total spin 1/2), but is absent when the dot has even number of electrons (total spin 0). The conductance through the dot is enhanced by the Kondo effect as opposed to classical Coulomb blockade effect, and at a low temperature the conductance is expected to reach $2e^2/h$, which is called unitary limit (see Fig. 1(a)). We successfully achieved the unitary limit Kondo effect and confirmed the coherent electron transport for the Kondo effect from electron interference experiments [1]. Furthermore, application of magnetic field allows us to tune the dot to the specific spin degenerated state. Even if the number of electrons is even (N = 6 for Fig 1(b)), energy degeneracy between spin singlet state and triplet state makes the spin correlation more possible, and thus remarkable novel Kondo effect shows up [2]. The series of experiments indicate that the electron-spin correlation can be well controlled in a quantum dot.

This work is collaborated with Prof. L. P. Kouwenhoven at TUDelft, Prof. S. Tarucha at University of Tokyo (also at ERATO and NTT) and co-workers.

[1] W. G. van der Wiel et al., Science **289** (2000) 2105.
[2] S. Sasaki et al., Nature **405** (2000) 764 .

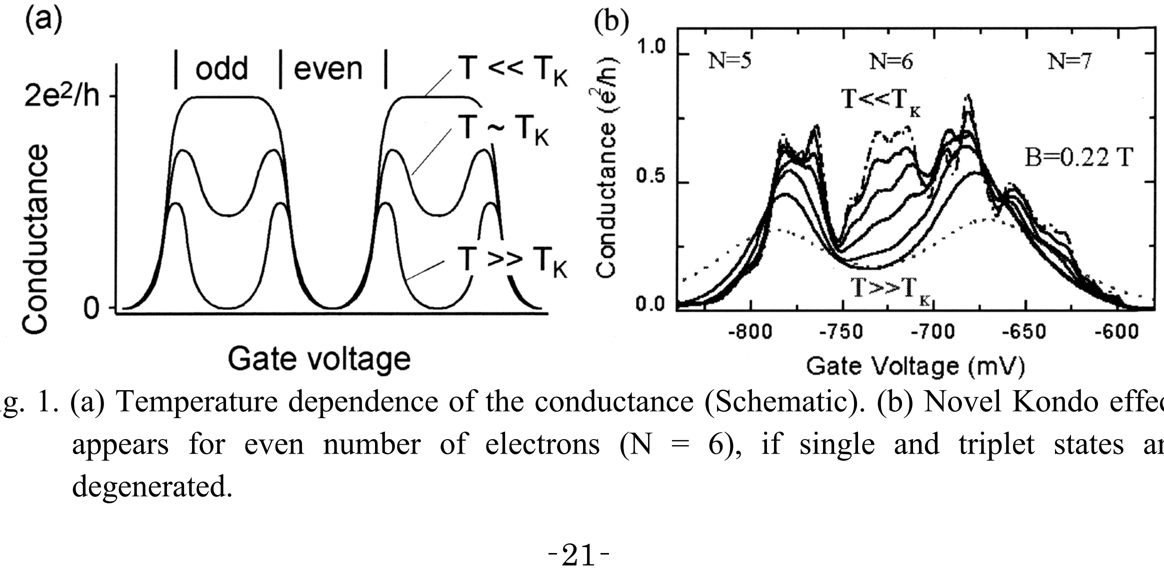


Fig. 1. (a) Temperature dependence of the conductance (Schematic). (b) Novel Kondo effect appears for even number of electrons (N = 6), if single and triplet states are degenerated.

Friedel Oscillations in 2D Electron Gas Systems at Semiconductor Surfaces

Kiyoshi Kanisawa, Hiroshi Yamaguchi, and Yoshiro Hirayama
Physical Science Laboratory

The operational principle of the semiconductor electronic devices fabricated so far is based on the control of the number of electrons passing through the active part of devices. This principle utilizes the feature of electrons as *material particles*, which had been the excellent description in the classical theory of physics. The recent progress in the semiconductor processing techniques allows the accurate manufacturing of ultimately small devices whose size is in the range of tens of nanometers. In these devices, we need to take into account the other feature of electrons, which is that they act as *matter waves*. This feature is one of the most significant conclusions drawn from the principle of quantum mechanics. Recently, there have been many device proposals based on novel operational concepts arising from this quantum mechanical feature. To understand the transport phenomena in these kinds of devices in detail, the behavior of electrons as *matter waves* should be directly observed. From this point of view, we have successfully imaged electron waves in real space by applying low-temperature scanning tunneling microscopy (STM) and our unique crystal growth technique that enables the preparation of an electrically conductive and extremely flat surface of InAs [1,2].

Figure 1 shows local density of states (LDOS) images at a defect scatterer on the InAs surfaces with different electron energies. Wave patterns made up of concentric circles are clearly imaged in the vicinity of the isolated defect. From the nature of oscillation damping, we can conclude that this is the so-called Friedel oscillation due to electrons being laterally scattered by the defect. By observing the bias voltage dependence, the effective mass was estimated to be 0.043 m_0, which is in good agreement with previous reports. Our detailed analysis indicates that the observed oscillations are caused by the scattering of the two-dimensional electron gas accumulated in the near-surface region of the InAs surfaces.

[1] H. Yamaguchi et al., Jpn. J. Appl. Phys. **38** (1999) 635.
[2] K. Kanisawa et al., Phys. Rev. Lett. **86** (2001) 3384.

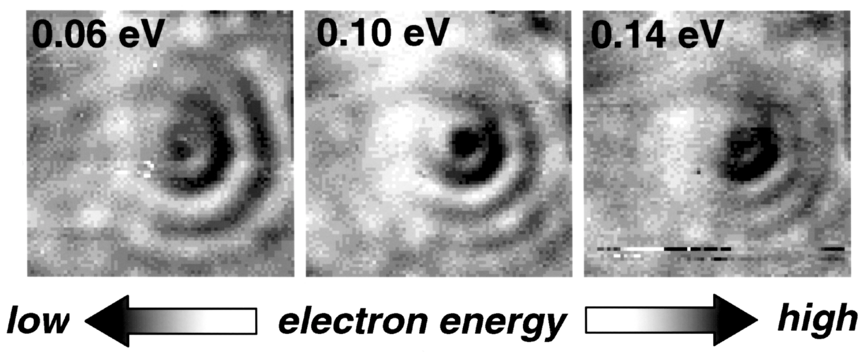


Fig. 1. LDOS images in the vicinity of a point scatterer on epitaxially grown InAs (111)A surfaces.

Large Electron-Field-Emission from Aluminum Nitride

Makoto Kasu and Naoki Kobayashi
Physical Science Laboratory

Aluminum nitride (AlN) has negative electron affinity. Therefore, it is very promising for field emission. Field emission is mainly of interest in its application to field-emission displays, thin flat-panel displays suitable for moving-pictures, and to micro vacuum tubes made of semiconductor microstructures suitable for high-frequency amplifiers. However, the AlN crystal quality reported so far has not been good enough for field emission, and, because the reported AlN was undoped and its free-electron density was low, the reported current density of the field emissions was much lower than that of diamond.

We chose a silicon-carbide (SiC) substrate which has the same lattice constant in plane and the same thermal expansion coefficient as those of AlN. We then grew AlN crystal at 1100°C by MOVPE and this produced AlN crystal of high quality. The full-width at half maximum of the (0002) x-ray rocking curve was less than 100 sec. The value is the narrowest ever, showing that we have grown the best quality AlN. We found that, as the Si dopant density in AlN is increased, the electric field necessary for field emission is decreased as shown in Fig. 1 [1]. The mechanism is shown in Fig. 2. The doped Si supplies the electrons necessary for field emission, and the Si atoms form the impurity level. The electrons are supplied through the impurity band to the surface. Further, we found that ridge structures whose top width is of the nanometer order are formed spontaneously by heavy Si doping (see inside-cover) [2]. The ridge-structure formation lowers the energy barrier necessary for field emission by about 2 eV. As a result, using heavily Si-doped AlN, we have obtained a field-emission current density of 66 mA/cm^2, twice that for diamond. In a basic structure for a field emission display, we observed red, green, and blue light from phosphors excited by field-emitted electrons (see inside-cover). Its luminance was 1200 cd/m^2, which is intense enough for a practical display.

[1] M. Kasu and N. Kobayashi, Appl. Phys. Lett. **76** (2000) 2910.
[2] M. Kasu and N. Kobayashi, Appl. Phys. Lett. **78** (2001) 1835.

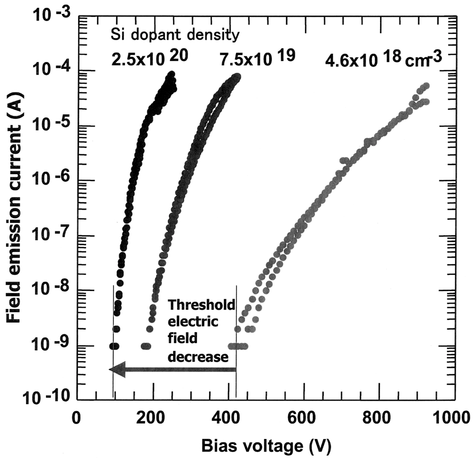


Fig. 1. Si-density dependence of field emission characteristics.

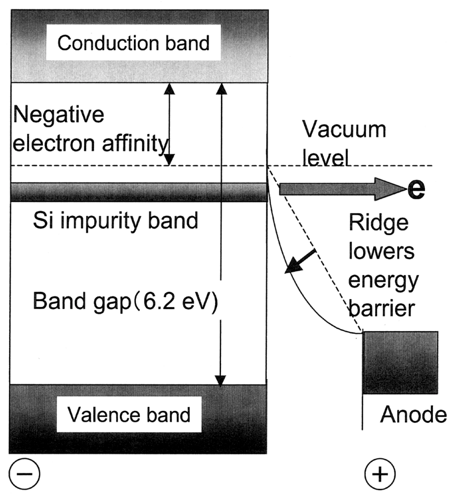


Fig. 2. Mechanism of large field emission.

Overview of Quantum Optics and Optical Materials Research

Takaaki Mukai
Physical Science Laboratory

In the fields of quantum optics and optical materials we pursue our studies for the development of core-technologies that will innovate optical communications and optical signal processing as well as for the scientific progress of the field. Optical State Control Research Group, Ultrafast Optical Physics Research Group and Optical Device Physics Research Group are engaged in the subjects listed below.

Quantum State Control Research Group
(1) Quantum communication and information processing (proposal and verification of a new quantum cryptography, studies on quantum protocols, quantum entanglement, and quantum computing).
(2) Atom optics (experimental and theoretical studies on Bose-Einstein condensation of alkali atoms, and control of new quantum states by laser lights).

Ultrafast Optical Physics Research Group
(1) High-irradiance soft X-ray generation from femtosecond laser-produced plasma and its application to materials science (demonstration of high-irradiance soft X-ray pulse generation and table-top soft X-ray laser, clarification of soft X-ray generation mechanism, and demonstration of time-resolved soft X-ray spectroscopy).
(2) Ultrafast laser pulse induced terahertz radiation and its application.

Optical Device Physics Research Group
(1) Coherent control of excitonic and spin states in quantum dots (optical Rabi oscillations in a zero-dimentional exciton, experimental study of excitonic properties of quantum dots, spin-polarized electron transport in quantum wires).
(2) Optical properties in nitride-semiconductors and their device applications (optical properties of nitride quantum wells, including excitonic and piezo-electric effects, and nitride photo-conductive detector).
(3) Nano-scale fabrication process for photonic crystal materials (dry etching process for damage-free surfaces of GaAs and GaN, and design and fabrication of photonic crystal structures).

Major results obtained this fiscal year 2000 are reported in the following pages. We investigated strong gain saturation behavior in fiber optical parametric amplification and demonstrated its application to noise suppression and optical limiter operations. Parametric process in optical fiber is promising for the generation of quantum entangled photon twins for quantum communications.

Nanostructure-array targets were employed to create larger-volume plasm with high-local-density, compared with those from flat target, in X-ray generation from femtosecond-laser-produced plasma, resulting in large soft x-ray conversion efficiency as well as suppression of broadening of generated x-ray pulse duration.

We demonstrated long-lived exciton coherence more than 40 ps in a single isolated InGaAs quantum dot. Favored by this long-lived coherence, we clearly observed exciton Rabi oscillation, i.e., coherent population flopping induced by the strong coupling light resonant to excitonic discrete level. This promises the coherent control of the quantum states in semiconductor quantum dots applicable to quantum computation.

Optical Parametric Amplification in Fiber

Kyo Inoue and Takaaki Mukai
Physical Science Laboratory

Quantum correlated two photons (entangled photon-pair) have the unique feature that the photon states are undetermined before measurements while the state of one photon is uniquely determined when the other photon state is measured. Utilizing entangled photon-pairs, novel communications based on quantum nature of photons (e.g., quantum cryptography) is possible. For generating entangled photon-pairs, parametric down conversion via the second-order optical nonlinearity has been widely used. However, this scheme has disadvantages for fiber communication systems, such that (1) available wavelengths are limited to short wavelength bands (< 1 μm), and (2) coupling efficiency to fiber is quite low because bulk materials are used.

We study optical parametric amplification process in optical fibers, aiming at generating entangled photon-pair suitable for fiber communications. When pump light is input into a fiber, signal and idler lights are generated in the either wavelength side of the pump via four-photon mixing process (Fig. 1) [1]. These photons are quantum correlated. They are generated at wavelengths suitable for fiber communications (1.5-μm band), and they can be directly coupled to fiber transmission lines without any coupling loss.

We are investigating a fiber optical parametric amplifier where signal light is injected into the fiber together with pump light. What we have done are, (1) experimental demonstration and theoretical calculations of unique saturation characteristics (Fig. 2), different from conventional optical amplifiers, that the signal output power increases, reaches a peak value, and then decreases, as the input signal power increases [1], (2) demonstration of noise suppression effect and low noise property operated in the output peak region (indicated by the arrow in Fig. 2), (3) observation and clarification of mechanism of spectral hole burning, (4) demonstration of optical limiter operations [2,3]. These works indicate that fiber parametric amplifier is applicable to ultra-fast optical functional devices accompanied with significant signal gain. Based on the above results, we will aim at generating entangled photon-pair in the communication wavelength band.

[1] K. Inoue and T. Mukai, Opt. Lett. **26** (2001) 10.
[2] K. Inoue, Electron. Lett. **36** (2000) 1016.
[3] K. Inoue, IEEE Photon. Technol. Lett. **13** (2001) 338.

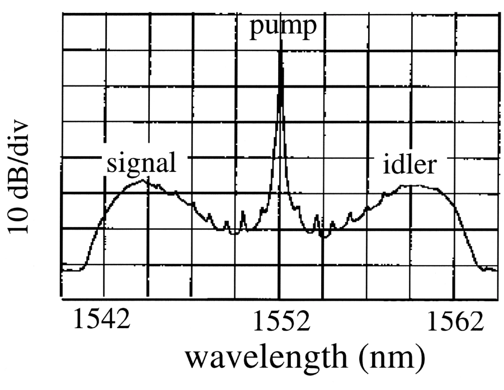


Fig. 1. Fiber output spectrum (only pump light is injected).

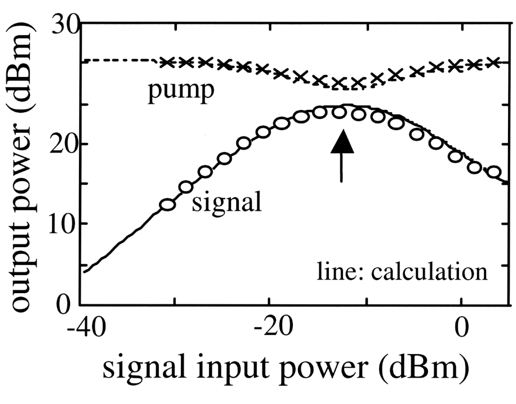


Fig. 2. Output characteristics of parametric amplifier.

Efficient X-ray Generation from Femtosecond-Laser-Produced Plasma on Nanostructure-Array Targets

Tadashi Nishikawa and Hidetoshi Nakano
Physical Science Laboratory

X-ray generation from femtosecond-laser-produced plasma is an attractive way to obtain short pulse x-rays. However, due to the formation of solid density plasma at a target surface, the interaction depth of the femtosecond laser pulses is restricted to skin depth, i.e., around 50 nm, and thus the conversion efficiency is limited. In order to improve the conversion efficiency, a double-laser-pulse excitation technique is commonly used. After the expansion of the preformed plasma created by the first laser pulse, the expanded low-density plasma is heated effectively by the intense second laser pulse, and large x-ray conversion efficiency is obtained. But with this technique, the generated x-ray pulse duration is broadened from 5 ps (single pulse excitation) to around 100 ps due to the slow cooling rate of low-density plasma. To overcome these problems, we utilized nanostructure-array targets to extend the interaction depth of the laser pulse to around 20 μm. Large-volume plasma with high-local-density is created on these targets by a single laser pulse excitation, and large soft x-ray conversion efficiency enhancement can be achieved while keeping the short x-ray pulse duration.

Two types of nanostructure-arry targets were used in our experiment. One is a nanohole-array structure [1]. This structure was made by utilizing the anodic oxidation of an aluminum plate. By a self-ordering process, an anodic-alumina layer that has central, cylindrical, and uniformly sized pores that run perpendicular to the surface is formed on the aluminum plate. The pore diameter is around 90 nm and the distance between the adjacent pores is 100 nm. The other structure is a nanocylinder-array structure [2]. After filling up the alumina nanoholes with Au by electrodeposition, the alumina part was removed (Fig. 1). The cylinder diameter is 80 nm and the cylinder heights are 9 and 18 μm.

These targets were irradiated with 100 fs laser pulses at the peak intensity of 1.5×10^{16} W/cm^2, and generated soft x-ray fluence spectrum was measured (Fig. 2). Around a 50-10 fold soft x-ray fluence enhancement compared with a conventional plane surface target was achieved at 5-25 nm wavelengths. X-ray pulse duration on both nanostructure-array targets was 17 ps, which is shorter than that obtained by the double-laser-pulse excitation technique on a plane surface target or by synchrotron radiation. The x-ray pulse peak intensity on the nanostructure-array targets was 5-7 times higher than that on a plane surface target.

[1] T. Nishikawa et al., Appl. Phys. Lett. **75** (1999) 4079.
[2] T. Nishikawa et al., International Conference on X-ray Lasers 2000.

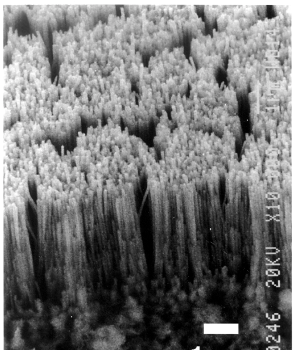


Fig. 1. SEM image of a Au nanocylinder -array target's side view.

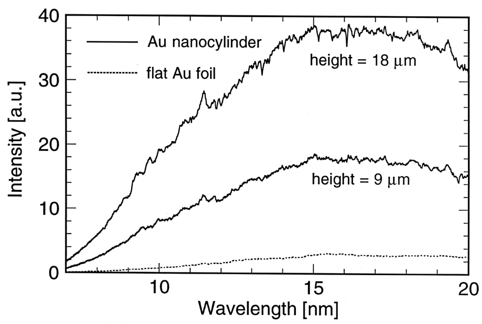


Fig. 2. Soft x-ray spectral fluence from a Au nanocylinder-array target (solid line) and from a gold foil target (dotted line).

Exciton Rabi Oscillation in Single Quantum Dot

Hidehiko Kamada and Hideki Gotoh
Physical Science Laboratory

Optical Rabi oscillation is the most fundamental examples of coherent nonlinear light-matter interactions. It is the essential physics that coherent optical control of the quantum states relies on. Excitons in semiconductor quantum dots (QD's) are above all promising elements for such coherent manipulation because of long-lived coherence favored by discrete energy level structure. We observed the exciton Rabi oscillation in QDs.

In a single isolated InGaAs dot, an excited state resonance was chosen as upper level of relevance. Upon resonant excitation, the exciton emission was found to split into doublet for increasing excitation density [1]. This splitting increased proportional to the electric field as expected for Rabi splitting (Fig. 1 left). To observe the oscillation in time-domain, a single-dot exciton dipole interferometry was then conducted. Under low excitation, the coherent dipole oscillation induced by the first pulse persists as long as 40 ps: Correspondingly the dipole interference fringe decay with this time constant was observed (Figs. 1(a) and 1(b)). This demonstrates a long-lived exciton coherence. As the excitation increased more than one order of magnitude, the radiation induced not only the dipole oscillation but also the population oscillation, leading to a mixing of the Rabi frequency into the dipole interference fringe (Fig. 1(d)) as well as another oscillatory behavior with a period of 10-20 ps in the fringe envelope (Fig. 1(c)). The frequency of this slowly varying oscillation was found to increase proportional to pulse area, manifesting the relevance of the Rabi oscillation [2]. Observation of the coherent population flopping promises the coherent control of the quantum states in semiconductor QDs.

[1] H. Kamada et al., ICPS25, Osaka, (2000) H169.
[2] H. Kamada et al., CLEO Pacific Rim 2001, Chiba, (2001) ThG4-3.

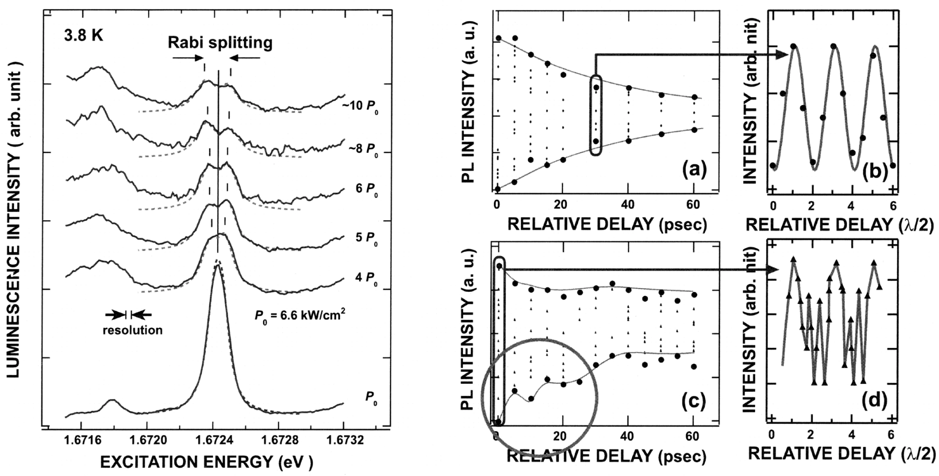


Fig. 1. Energy splitting of exciton PL for increasing excitation density (left). Exciton interference as functions of pulse-pair interval (right): (a) fringe envelopes for a power density $P1$ (0.067 μJ/cm^2 /pulse) and (b) decomposed fring near 30 ps, (c) envelopes for 12 $P1$ (0.8 μJ/cm^2 /pulse) and (d) fringe near 0 ps.

Ⅱ. Data

International Symposium on Carrier Interactions in Mesoscopic Systems

The symposium was held on February 13th and 14th, 2001, at the NTT Atsugi R&D Center and was organized by New Energy and Industrial Technology Development Organization (NEDO), Core Research for Evolutional Science and Technology - Japan Science and Technology Corporation (CREST-JST), and NTT Basic Research Laboratories.

Carrier interactions in layer and nano structures have attracted much interest because they will be important to realize novel systems, possibly leading to quantum computing and carrier superfluidity. In this symposium, we tried to cover many areas from science and technology using the single key-word of *carrier interactions* for classification rather than the more conventional terms, semiconductor, superconductor and device physics. NTT Basic Research Laboratories have led this field, and the aim of the symposium was to gather together leading scientists to discuss the most recent topics.

Oral sessions consisted of 19 presentations by invited speakers and the main members of the NEDO and CREST collaborating research teams. The plenary presentation for carrier interactions in layer and nano semiconductor systems was given by Prof. K. von Klitzing (Max-Planck-Institut), who discovered the quantized Hall effect and won a Nobel Prize in Physics in 1985. This was followed by theoretical and experimental reports on electron bilayer systems, electron-hole proximity systems, carrier interactions in layer structures, electron spin, and nuclear spin. In particular, electron bilayer systems were highlighted as ideal systems for the study of carrier interactions. Furthermore, recent topics related to spin blockade and the Kondo effect were discussed as examples of carrier interaction effects in quantum dots. Process and growth technologies toward the fabrication of structures suitable for carrier interaction studies and nanoprobe measurements were also presented. Finally, we discussed approaches towards the realization of solid-state quantum computing, which is perhaps the most exciting target for applying carrier interaction effects. Poster sessions consisted of 46 contributed presentations. They covered the fabrication of nano structures, quantum Hall effects, carrier interactions in bilayer systems, Kondo effect in quantum dots, control of electron spin in semiconductors, and proposals for solid-state quantum computation. The number of participants was 142 (97 from outside of NTT). Participants were strongly impressed by the high quality of the symposium.

Plenary presentation by Prof. Klaus von Klitzing (center), welcome address by Dr. Sunao Ishihara, director of NTT Basic Research Laboratories (left), and oral session at the symposium (right).

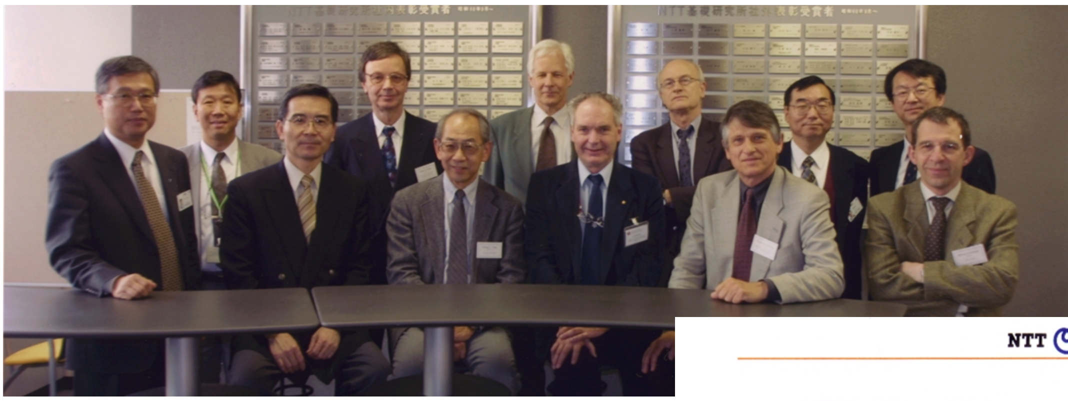
Advisory Board

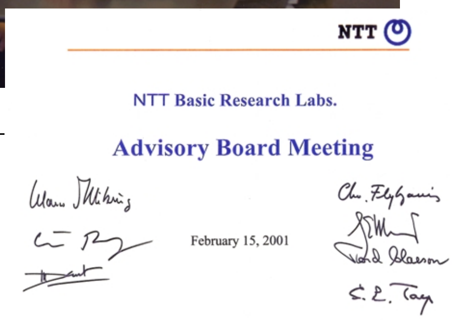
The Advisory Board, an external evaluation committee for NTT Basic Research Laboratories (BRL), convened for the first time for two days, February 15 and 16, 2001. The Advisory Board seeks to (1) evaluate research plans and achievements objectively and in a timely manner, (2) dispatch information effectively to the world through board members, and (3) reinforce systematic research cooperation with the board-member organizations.

On the first day, executive managers and group leaders outlined the research activities of BRL to give board member a grasp of the progress of BRL’s research and its research strategy. After that, board members were given a guided tour of the facilities. On the second day, they held discussions on the basis of the information obtained on the first day in a closed session. Then, the advisory board committee reported on the management of BRL.

The board evaluated us very well, commenting that the research level is generally high, the research environment exceeds international standards, and equipment is maintained well. However, they pointed out that certain research fields are getting weak due to the departure of senior researchers. Regarding management, we received many unsparing but constructive suggestions. Among them, technical engineers are required because of technical succession, continuous reservation of young talent is important, and laboratories should be activated more through more internal competition and cooperation between groups.

Because this was our first experience with an external evaluation, we spent much time for preparation. Meanwhile, this was a very precious opportunity: we received an objective evaluation of our research level and many suggestions, which may serve as indicators of future directions. About the Advisory Board itself, although board members were favorably impressed, they commented that the contents should not be selected beforehand and all actual conditions should be shown. For this purpose, the program is too short. Furthermore, they commented that the evaluation be done every year. We decided that next board committee will convene in a year and half. This interval is shorter than we had planed.





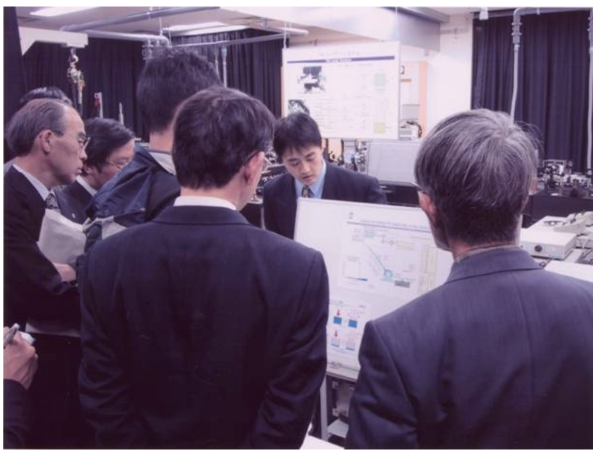
Board Members	Affiliation	Field
Prof. Claeson	Chalmers UT	Superconductor devices
Prof. Devoret	CEA Saclay	Mesoscopic physics
Prof. Flytzanis	Ecole Normal	Non-linear optics
Prof. Mooij	Delft UT	Quantum computer
Prof. Ploog	P.D. Inst.	Nanostructures
Prof. Tang	Cornell U	Quantum optics
Prof. von Klitzing	MPI	Quantum physics

Science Plaza 2001

"Science Plaza 2001", the annual open house event of NTT Basic Research Laboratories, was held from February 13-14, 2001, at the NTT Atsugi R&D Center. The International Symposium on Carrier Interactions in Mesoscopic Systems (CIM2001) was held concurrently. Participants of "Science Plaza 2001" were allowed to attend the CIM opening remark by Dr. Sunao Ishihara, Director of NTT Basic Research Laboratories, and the CIM plenary talk by Dr. K. von Klitzing, Physics Nobel Laureate.

In "Science Plaza 2001", the activities of NTT Basic Research Laboratories were demonstrated via presentations in a "Poster Session", "Laboratory Tour", and "Video Theater". The "Poster Session" featured 41 presentations on the topics of materials and physics, and the actual researchers directly explained and discussed these topics with the participants. The "Laboratory Tour" featured extremely low temperature technology, the creation of X-ray lasers, the synthesis of high-Tc materials by molecular beam epitaxy, a clean room tour and a peta-media tour, and we showed our research equipment and facilities to the participants. The "Video Theater" featured "Mesoscopic Superconductors—A Perspective from an International Symposium" and "Novel Trend — Mysteries of Quantum Theory Clarified by Experiments", and we demonstrated some of our research activities with pictures.

We had about 200 participants at "Science Plaza 2001" even though the NTT Atsugi R&D Center is located about 2 hours far from the center of Tokyo. In addition, some participants came from cities more than 300 km away (Sapporo, Sendai, Nagoya, Kyoto, Osaka, and Kohchi) by plane, train, and/or bus. Many of the CIM participants also attended "Science Plaza 2001". Since so many people requested to join the "Laboratory Tour", we prepared additional tours. The participants gave us many hints and insights for future research and many words of encouragement for uninterrupted basic and fundamental research in materials and physics. We would like to again thank all participants of "Science Plaza 2001".



List of Award Winners (Fiscal 2000)

The 8th Japan Society of Applied Physics Young Scientist Award for the Presentation of an Excellent Paper	K. Kumakura	"High Hole Concentration Realized by Mg-doped InGaN and InGaN/GaN Superlattices"	Sept. 3, 2000
JJAP Paper Award, the 22nd Paper Award of the Japan Society of Applied Physics	H. Kageshima K. Shiraishi M. Uematsu	"Universal Theory of Si Oxidation Rate and Importance of Interfacial Si Emission"	Sept. 4, 2000
Electronics Letter Paper Award (The Institute of Electronics, Information and Communication Engineers)	O. Hanaizumi* Y. Sakurai* Y. Aizawa* S. Kawakami* E. Kuramochi S. Oku *Tohoku Univ.	"Embedding of III V Compound Semiconductors into 3D Photonic Crystals"	Oct. 2, 2000
Matsuo Science Prize (Matsuo Foundation)	Y. Yamamoto	"Fundamental Research on Optical and Quantum Physics"	Oct. 18, 2000
ISPA AWARD (Internet International Symposium on Silicon-Containing Polymers and Applications)	H. Nakashima	"Switchable Induced Circular Dichroism of Chiral Aggregates of Poly(alkylalkoxyphenylsilane) Bearing Remote Chiral Groups"	Feb. 23, 2001
Poster Award (First International Conference on Molecular Electronics and Bioelectronics)	K. Furukawa	"End-Grafted Polysilane —Approach for Single Polymer Science and Electronics"	Mar. 7, 2001

List of In-House Award Winners (Fiscal 2000)

NTT R&D Award	H. Hibino Y. Ono Y. Homma Y. Takahashi A. Fujiwara	"Integration of Atomically Controlled Nanostructures and Single Electron Functionality"	Dec. 19, 2000
Award for Achievements by Director of Basic Research Laboratories	T. Kawamura Y. Watanabe Y. Utsumi K. Uwai	"Surface Reconstructions of Semiconductor Materials in Gas-Phase Growth by Using Grazing Incidence X-ray Diffraction"	Mar. 26, 2001
Award for Achievements by Director of Basic Research Laboratories	H. Shibata	"Observation of Josephson Plasma in High-Tc Superconductors"	Mar. 26, 2001
Award for Achievements by Director of Basic Research Laboratories	K. Kanisawa H. Yamaguchi Y. Hirayama	"Direct Imaging of Low-Dimensional Electron Waves in Semiconductors"	Mar. 26, 2001
Award for Achievements by Director of Basic Research Laboratories	M. Kasu N. Kobayashi	"Large Electron Field Emission from Aluminum Nitrides"	Mar. 26, 2001
Award for Excellent Papers by Director of Basic Research Laboratories	S. Sasaki	"Kondo Effect in an Integer-Spin Quantum Dot" Nature **405** (2000) 764.	Mar. 26, 2001
Award for Excellent Papers by Director of Basic Research Laboratories	H. Tamura	"Ferromagnetism in Semiconductor Dot Array" Jpn. J. Appl. Phys. **39** (2000) L241.	Mar. 26, 2001

List of Visitors' Talks (Fiscal 2000)

I. Device Physics

Date	Speaker	Affiliation "Topic"
April 13	Prof. Seiji Takeda	Osaka University "Novel fabrication process of Si nano structure and oxidation"
May 10	Dr. Neil Zimmerman	National Institute of Standards and Technology, USA "Long-term charge offset and glassy dynamics in SET transistors"
May 18	Prof. Ernst Bauer	Arizona State University, USA "SPELEEM"
June 29	Dr. Stefan Heun	Sincrotrone Trieste ELETTRA, Italy "Nanospectroscopy on InAs nanocrystals"
July 13	Dr. Matthew P. Halsall	University of Manchester, UK "Si-Ge self assembled quantum dots"
Aug. 25	Prof. Pulickel M. Ajayan	Rensselaer Polytechnic Institute, USA "Growth and structure of carbon nanotubes"
Sept. 18	Dr. C. N. McKinty	University of Surrey, Guildford, UK "Investigating the use of sputtered β-$FeSi_2$ for solar cell applications"
Nov. 1	Prof. Robert L. White	Stanford University, USA "A review of the research at the Stanford Center for Research on information storage materials"
Jan. 17	Prof. Otto Zhou	University of North Carolina, USA "Growth and application of carbon nanotube"
Jan. 19	Dr. Stefano Fontana	Sincrotrone Trieste ELETTRA, Italy "The spectromicroscope of Elettra"
Jan. 19	Dr. Toshihisa Tomie	Electrotechnical Laboratory "Photoelectron micro-spectroscopy with a laser-plasma X-ray source"
Jan. 24	Dr. Dean Collins	The Advanced Research and Development Activity, USA "Details of ARDA's program in quantum information science"
Jan. 24	Dr. Keith Schwab	The Laboratory for Physical Science, USA "Quantum computing research at the laboratory for physical sciences"
Jan. 31	Prof. Stoyan S. Stoyanov	Institute of Physical Chemistry, Bulgarian Academy of Sciences, Bulgaria "A shape of the steps at the surface of Si crystal with SiO_2 inclusions"

March 5	Prof. Takashi Morie	Hiroshima University "Image-recognition integrated circuit systems based on brain-like processing"
March 27	Prof. K. P. Jain	Indian Institute of Technology, Delhi, India "Raman and photoluminescence spectroscopy of silicon nanostructures"

II. Materials Science

Date	Speaker	Affiliation "Topic"
April 5	Prof. Yasuhiko Arakawa	The University of Tokyo "Semiconductor nano-structures: from 'crystal growth', 'optical properties', to 'quantum devices'"
April 24	Prof. Koichi Kusakabe	Niigata University "Strong correlation effects based on anomalous density of states"
May 19	Mr. Kensuke Honda	The University of Tokyo "Surface-controlled diamond electrodes and their applications"
June 29	Prof. Yang Yang	University of California, Los Angels, USA "Polymer morphology formation and influence to polymer-based LED device performance"
July 21	Dr. Jonathan Selinger	Naval Research Laboratory, USA "Theory of chiral order in polymers and lipid microstructures"
July 27	Dr. Rajeshwar P. Sharma	University of Maryland, USA "Ion channeling studies in high-Tc cuprates and CMR manganites - Direct experimental evidence of electronic phase seperation"
Aug. 17	Prof. Yehoshua Levinson	Weizmann Institute, Israel "Dephasing in quantum dots due to capacitive coupling with point contacts"
Aug. 29	Prof. Yasutomo J. Uemura	Columbia University, USA "Condensation and phase separation of high-Tc superconductors inferred from the superfluid density"
Sept. 4	Prof. Yoseph Imry	Weizmann Institute, Israel "The observability of quantum- and shot-noise and low-temperature 'decoherence'"
Sept. 8	Dr. Mark Johnson	Naval Research Laboratory, USA "Spin injection and detection in a ferromagnetic metal / 2DEG structure"
Sept. 11	Dr. Andrei Filip	University of Groningen, The Netherlands "Direct experimental comparison between the electrical spin injection in a semiconductor and in a metal"

Oct. 6	Dr. Toru Matsuyama & Dr. Andreas Richter	Hamburg University, Germany "Spin-orbit interaction in InAs 2DEG and spin-injection experiment"
Oct. 19	Dr. Lambert Alff	University of Cologne, Germany "Pairing symmetry and pseudogap in hole-doped and electron-doped high-Tc cuprates"
Nov. 24	Prof. Shigemasa Suga	Osaka University "High-energy & high-resolution photoemission spectroscopy of strongly correlated electron systems -separation of bulk and surface electronic structures"
Dec. 5	Dr. Han Chunxi	Keio University "Systematic injection of kainic acid stimulates expression of NCAM-H in reactive astrocyte of rat hippocampus"
Dec. 25	Prof. P. Ganguly	National Chemical Laboratory, India "Resistivity and metal-insulator transition: The interpretation of resistivity values in complex oxides"
Jan. 18	Prof. Emilio E. Mendez	State University of New York at Stony Brook, USA "The uniqueness of the InAs-GaSb heterojunction, and its practical consequences"
Jan. 18	Dr. Gerald Bastard	Laboratoire de Physique, Ecole Normale Superieure, France "Polaron levels and energy relaxation in InAs quantum dots"
Jan. 19	Dr. Takeshi Nakanishi	Delft University of Technology, The Netherlands "Electrical transport in carbon nanotubes"
March 8	Prof. Christian Schoenenberger	University of Basel, Switzerland "Electrical and mechanical properties of carbon nanotubes"
March 15	Prof. Kei Murakoshi	Osaka University "Characteristics of photo-induced metal nano-structure and their functionalities"
March 16	Prof. Wei Yao Liang	Cavendish Laboratory, University of Cambridge, UK "The fascination of high Tc superconductivity"
March 22	Dr. Makoto Osanai	Tokyo Medical and Dental University "Ca ion and synapse transmission"

III. Quantum Electron Physics

Date	Speaker	Affiliation "Topic"
June 13	Mr. Stuart Midgley	The University of Western Australia, Australia "Quantum waveguide theory"
July 24	Prof. Leo Kouwenhoven	Delft University of Technology, The Netherlands "The Kondo effect in quantum dots"

Aug. 18	Prof. Yoon-Ha Jeong	Pohang University of Science and Technology (POSTECH), Korea "Design considerations for SET integrated circuits: power and manufacturability"
Aug. 28	Prof. Ramasamy Dhanasekaran	Anna University, Chennai, India "Thermodynamics and nucleation Studies of AlGaN/GaN, InGaN/GaN and AlInN/GaN heterosturctures"
Sept. 1	Prof. Klaus H. Ploog	Paul-Drude-Institute, Germany "Heteroepitaxy of highly mismatched systems and role of coincidence lattice"
Sept. 8	Mr. Maarten R. Wegewijs	Delft University of Technology, The Netherlands "Coherent transport of strongly correlated electrons through three coherently coupled quantum dots"
Sept. 8	Dr. Martin N. Wybourne	Dartmouth College, USA "Single electron transport in metal nanoparticle decorated biopolymers"
Sept. 14	Prof. Uri Sivan	Technion-Israel Institute of Technology, Haifa, Israel "Self assembly of nanometer scale electronics by biotechnology"
Oct. 10	Prof. Alexander Khaetskii	Institute of Microelectronics Technology, Russian Academy of Sciences, Russia "Spin relaxation in semiconductor quantum dot"
Oct. 10	Prof. Yshai Avishai	Ben Gurion University, Israel "Kondo tunneling through real and artificial molecules"
Oct. 11	Prof. Gerhard Abstreiter	Technical University of Munich, Germany "Superlattice and quantum wire transistors fabricated by cleaved edge overgrowth"
Nov. 1	Prof. Gerrit E. W. Bauer	Delft University of Technology, The Netherlands "Semiclassical theory of mesoscopic magneto-electronics"
Nov. 7	Dr. Haiyan An	Hokkaido University "Spatial positioning control and optical properties of self-assembled InAs quantum dots on GaAs pyramids"

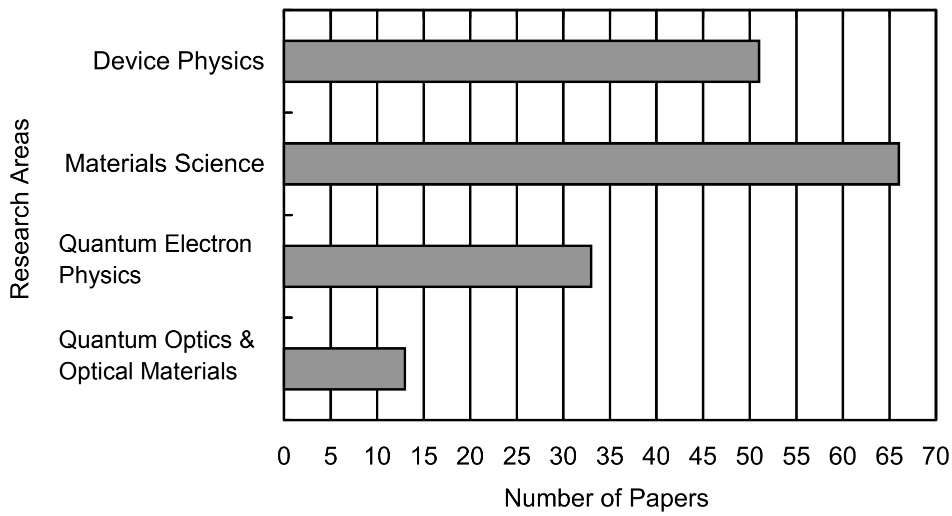
IV. Quantum Optics & Optical Materials

Date	Speaker	Affiliation "Topic"
July 14	Dr. Peter Kuerz	Carl Zeiss, Germany "Optics for extreme ultraviolet lithography"
July 28	Prof. Shun-Lien Chuang	University of Illinois at Urbana-Champaign, USA "Strained quantum-well lasers: from static to high-speed modulation properties with injection locking"

Oct. 4	Prof. Gareth Parry	Imperial College, UK "Semiconductor optical micro-cavities for LEDs, lasers, modulators and detectors"
Oct. 10	Dr. Tao Hong	Science University of Tokyo in Yamaguchi "Sound dark solitons in Bose-Einstein condensates"
Dec. 21	Dr. H. T. Grahn	Paul-Drude-Insitut, Germany "Spontaneous current oscillations and chaos in weakly coupled superlattices"
Feb. 23	Prof. Zhigang Zhang	Tianjin University, China "Pulse stretcher phase calculation and its application in chirped pulse amplifications"

Research Papers Published in International Journals (Fiscal 2000)

The number of research papers published in the international journals (English) in fiscal 2000 amounted to 163 in Basic Research Laboratories as a whole. The number of papers according to their research area is as follows.



The major journals and the number of published papers are shown below.

General Science Journals

Name	(IF99)*	Number
Nature	(29.491)	3
Science	(24.595)	1

Specialized Journals

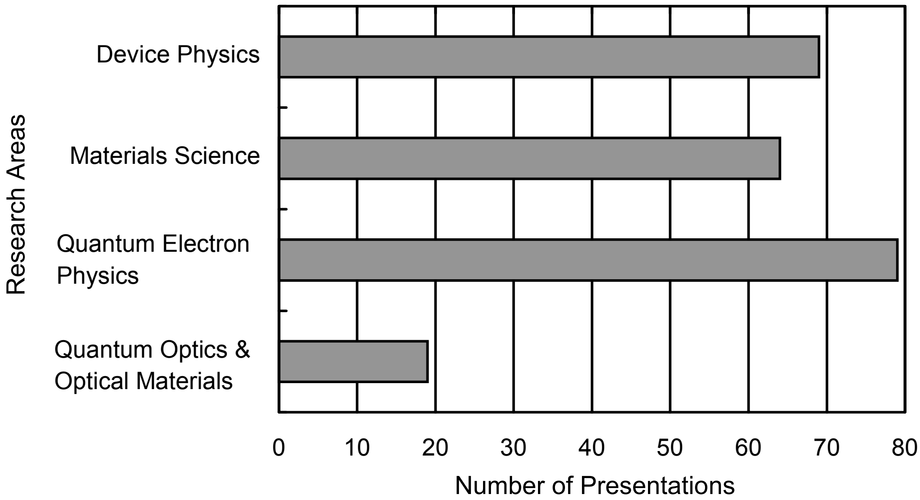
Name	(IF99)*	Number
Japanese Journal of Applied Physics	(1.411)	31
Physical Review B	(3.008)	18
Applied Physics Letters	(4.184)	15
Physical Review Letters	(6.095)	7
Journal of Applied Physics	(2.275)	5
Journal of the Physical Society of Japan	(2.083)	4
Journal of American Chemical Society	(5.537)	3
Physical Review A	(2.639)	3
Macromolecules	(3.534)	2
IEEE Electron Device Letters	(3.018)	2
Advanced Materials	(5.415)	1
Analytical Chemistry	(4.555)	1
Optics Letters	(3.537)	1

* IF99 : Impact factor 1999 (Journal Citation Reports, 1999)

The average impact factor for individual research papers from all NTT Basic Research Laboratories is 2.96.

Presentations at International Conferences (Fiscal 2000)

The number of the presentations at the international conferences in fiscal 2000 amounted to 231 in Basic Research Laboratories as a whole. The number of presentations according to their research areas is as follows.



The major international conferences and the number of presentations are shown below.

Name	Number
International Symposium on Carrier Interaction in Mesoscopic Systems 2001	22
25th International Conference on the Physics of Semiconductor	19
2000 Fall Meeting of Materials Research Society	9
2001 Spring Meeting of American Physical Society	9
2000 International Workshop on Nitride Semiconductors	8
The 2000 International Chemical Congress of Pacific Basin Societies	6
14th International Conference on High Magnetic Fields in Semiconductors	5
47th International Symposium of the American Vacuum Society	5
4th International Workshop on Quantum Functional Devices	4
10th International Conference of Metal Organic Vapor Phase Epitaxy	4
The 7th International Workshop on Femtosecond Technology	4
13th International Conference on Crystal Growth	3
12th International Symposium on Chirality 2000	3
2000 International Electron Device Meeting	2

List of Invited Talks at International Conferences (Fiscal 2000)

I. Device Physics

(1) H. Hibino and T. Ogino, "Si twinning superlattice: Growth of new single crystal Si", US-Japan seminar on Mesoscopic Phenomena on Surfaces, Park City, USA (April, 2000).

(2) Y. Takahashi, A. Fujiwara, Y. Ono, and K. Murase, "Silicon single-electron devices and their applications", The 30th IEEE International Symposium on Multiple-Valued Logic (ISMVL), Portland, USA (May, 2000).

(3) T. Ogino, Y. Homma, Y. Kobayashi, H. Hibino, P. Kuniyil, K. Sumitomo, H. Omi, D. Bottomley, and Zhaohui Zhang, "Control of atomic structures on Si surfaces for wafer-scale nanointegration", International Symposium on Advanced Science and Technology of Si Materials, Kona, USA (November, 2000).

(4) T. Ogino, Y. Homma, Y. Kobayashi, H. Hibino, P. Kuniyil, K. Sumitomo, H. Omi, D. Bottomley, and Zhaohui Zhang, "Control of Si surface for quantum-dot network devices", 4th International Workshop on Quantum Functional Devices (QFD2000), Kanazawa, Japan (November, 2000).

(5) T. Ogino, Y. Homma, Y. Kobayashi, H. Hibino, P. Kuniyil, K. Sumitomo, H. Omi, and Zhaohui Zhang, "Bottom-up approach for nanointegration", Nanoarchitectonics Using Suprainteraction (NASI1), Tsukuba, Japan (November, 2000).

(6) Y. Watanabe, S. Suzuki, F. Maeda, and T. Kiyokura, "Synchrotoron radiation photoelectron spectroscopy of nanostructures", 1st. International Workshop on Nano-scale Spectroscopy, Trieste, Italy (December, 2000).

(7) T. Ito, K. Shiraishi, and A. Taguchi, "Quantum mechanical approach for understanding the growth process of semiconductors", The 2000 International Chemical Congress of Pacific Basin Societies (Pacifichem2000), Honolulu, USA (December, 2000).

(8) Y. Takahashi, Y. Ono, A. Fujiwara, and K. Murase, "Advanced technologies for Si-based single-electron tunneling devices", International Symposium on Formation, Physics and Device Application of Quantum Dot Structures (QDS2000), Sapporo, Japan (September, 2000).

(9) K. Shiraishi, H. Kageshima, and S. Uematsu, "Microscopic mechanism of Si oxidation", 25th International Conference on the Physics of Semiconductors, Osaka, Japan (September, 2000).

(10) Y. Homma, "Surface imaging by ultrahigh vacuum scanning electron microscopy", 2nd LEEM/PEEM Workshop, Paris, France (September, 2000).

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