TOKYO INSTITUTE OF TECHNOLOGY

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QNERC
Quantum Nanoelectronics Research Center

QNERC NEWS

A Word from the Director

Research at QNERC continues to yield new insight into nanoscale phenomena and to spawn practical, valuable applications for nanotechnology. Our research centers on optics and electronics. Our researchers have been notably successful in translating advances in theoretical physics into the real-world fabrication of working devices. We leverage our core strengths in optics and electronics through joint research with colleagues in other disciplines, including even medical science.

The research findings summarized on the following pages offer representative glimpses of the work under way at QNERC. All of those findings underline two definitive and hugely exciting truths of nanotechnology: (1) that matter and energy in the nano realm interact in ways utterly different from anything observed at larger dimensions and (2) that nanoscale phenomena can render service in diverse applications that will drive advances in science and industry and, thereby, in the quality of life.

Tokyo Tech has equipped QNERC with world-class facilities to make internationally significant contributions to advances in nanotechnology. Our researchers have made the most of our resources in important projects that have earned support from sources in government and in industry.

QNERC is a small—just six research groups—institute that handles several large and scientifically important projects. It has been extremely productive in regard to scientific and technological return on investment. I look forward to maintaining that high productivity while expanding QNERC gradually by adding research teams.

Masahiro Asada
Director, QNERC
www.pe.titech.ac.jp/AsadaLab

QNERC director Masahiro Asada, whose research specialty is terahertz devices and ultrahigh-frequency electronics, stands outside the laboratory building that houses the institute.

The Tokyo Institute of Technology (Tokyo Tech), Japan's foremost university devoted to technological disciplines, established QNERC in April 2004. QNERC inherited the R&D portfolio of its predecessor, Tokyo Tech's Research Center for Quantum Effect Electronics. It translates advances in nanoscience into practical suggestions for industrial applications.

Finding real-world solutions

GaInAsP/InP Membrane Buried Heterostructure Distributed Feedback Lasers for Optical-Interconnecting Applications

Shigehisa Arai and his colleagues demonstrate two membrane distributed feedback (DFB) lasers that are promising as low-power light sources for on-chip and chip-to-chip optical interconnection. One is on a silicon-on-insulator (SOI) substrate fitted with a silicon waveguide structure for integration with silicon electrical and optical devices. The other is an air-bridge structure for robust fabrication without using wafer bonding.

The laser bonded to an SOI substrate oscillated under optically pumped continuous-wave conditions. A threshold pump power (P_{th}) of 11.3 mW arose at 15°C for a cavity length of 140 µm and for a waveguide length of 500 µm. Although the threshold was higher than with previously reported membrane DFB lasers, continuous-wave operation occurred at temperatures up to 85°C.

Arai and his colleagues fabricated the air-bridge membrane DFB laser with selective chemical wet etching. The air-bridge membrane width (W_b) was 20 µm. Stable single-mode operation (SMSR > 30 dB) occurred at temperatures up to 60°C. The thermal resistance (R_{th}) improved from 23 K/mW to 11 K/mW—one-half the level previously reported with benzocyclobutene-bonded membrane DFB lasers.

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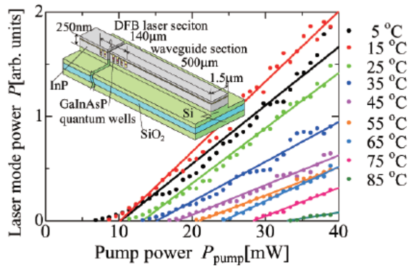
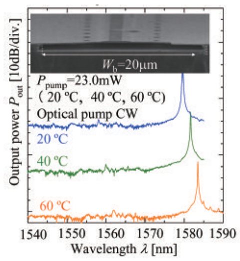
Japanese Journal of Applied Physics **46**, pp. L1158–L1160 and L1206–L1208 (2006).



The lasing characteristics of a membrane DFB laser integrated with a silicon-on-insulator waveguide.



The lasing spectra of an air-bridge membrane DFB laser.

Dr. Shigehisa Arai
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Dr. Adarsh Sandhu
Associate Professor, Tokyo Tech
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Integration of Functional Devices with Low Threshold GaInAsP/InP Distributed Reflector Lasers through a Deeply Etched Narrow Isolation Groove

Monolithically integrated distributed reflector (DR) lasers with wire-like active regions have attracted a great deal of attention in high-speed optical communication systems. Although their ultralow power consumption and simplicity of integration had been demonstrated, integration with other active devices had remained unestablished.

Shigehisa Arai and colleagues report deeply etched narrow-groove isolation and its application; that is, a DR laser integrated with a front-power monitor. The resultant laser is promising as a high-performance integrated light source for high-speed optical data communications.

A deep isolation groove of 3.8 µm occasioned high electrical isolation resistance of greater than 60 MΩ, and the optical coupling between the power monitor and the DR laser was 95%. Enabling the high coupling efficiency was the 500 nm width of the groove in BCB polymer, which corresponds to a half-wavelength. The integrated device had a moderately low threshold current (I_{th}) of 2.5 mA, and it exhibited the property of linear power monitoring. Shigehisa Arai and colleagues also report sub-mA I_{th} with DR lasers, one of which operated at an I_{th} of 0.8 mA.

Saeed Mahmud Ullah[1], Ryo Suemitsu[1], Seung Hun Lee[1], Masato Otake[1], Nobuhiko Nishiyama[2], and Shigehisa Arai[1,3]

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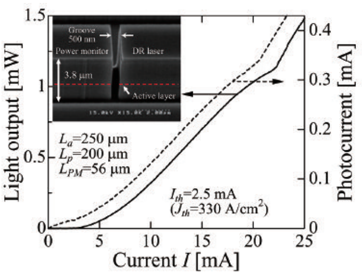
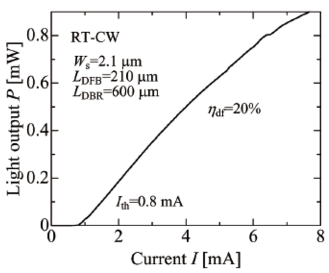
Japanese Journal of Applied Physics **46**, pp. L954–L956 and L1068–L1070 (2007).



The *I-L* and photocurrent characteristics of the integrated device.



The *I-L* characteristics of the low-threshold DR laser.

Monitoring DNA Hybridization by Quantifying Nitrogen Content with X-ray Photoelectron Spectroscopy

Biosensors are invaluable in medical diagnosis, as in the disposable biosensors used widely by diabetics to check the glucose levels in their blood. They are also useful in monitoring indicators of environmental quality, such as water purity.

Most biosensors work by detecting fluorescent or magnetic labels attached to targets. Monitoring labels, however, is a time-consuming and costly means of analyzing biomolecular reactions.

Adarsh Sandhu's research group has demonstrated a means of using X-ray photoelectron spectroscopy to quantify DNA hybridization without relying on labels. The group monitored the ratio of nitrogen to sulfur signals from thiol-modified oligonucleotides where sequences of HS-dT20, HS-dA20, HS-dT10C10, and HS-dG10A10 served as probes for the immobilization and hybridization procedures. Immobilizing streptavidin-coated magnetic beads confirmed the hybridization and thus verified the surface immobilization of the thiolated samples.

The group conducted all of the measurements with a monochromatic Al K-alpha X-ray source that had an incident area of 400 micrometers and an incidence angle of 53°. In confirming the hybridization, the range of statistical error was less than 20%.

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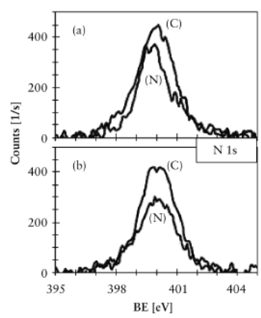
Japanese Journal of Applied Physics **46**, no. 2, pp. L49–L52 (2007).



Hybridization results showing the high resolution spectra of the N 1s signal for complementary (C) and noncomplementary (N) samples: (a) surface, after immobilization of the thiolated probe molecules; (b) solution, before the surface immobilization.

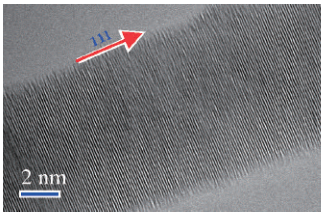
A Low-Temperature Growth Method for Small- and Uniform-Diameter Silicon Nanowires

Silicon nanowires are promising materials for future nanoelectronic and photonic devices. They could also become crucial components in chemical and biomedical sensors. Those potential applications have stimulated work on growth technologies for the controlled synthesis of silicon nanowires.

An obstacle in the vapor-liquid-solid growth of silicon nanowires of controlled diameters has been the aggregation of gold catalyst at high temperatures. A research group under the supervision of Shunri Oda reports developing a low-temperature growth method for small- and uniform-diameter silicon nanowires that overcomes the problem of gold aggregation. The resultant nanowires are defect free and are promising materials for applications in electronic and optoelectronic devices.

The group found that a low growth temperature of 350°C is crucial for preserving the size distribution of closely-packed gold droplets (8±5 nm) during the vapor-liquid-solid nucleation of silicon nanowires of small (12 nm) and uniform (±5 nm) diameters. It achieved silicon-nanowire growth at such a low temperature for the first time through the low-temperature decomposition of Si_2H_6 in a low-pressure chemical vapor deposition system.

Suppressing gold aggregation permits high-density silicon nanowire growth at controlled diameters. The small-diameter silicon nanowires, grown predominantly in (111) direction, are defect free and have single-crystal cores. Large-diameter silicon nanowires, on the other hand, are prone to a high density of defects.



A transmission electron microscopic image of a single-crystal silicon nanowire grown in (111) direction of 8 nm diameter.

Saeed Akhtar[1], Koichi Usami[1], Yoshishige Tsuchiya[1,2], Hiroshi Mizuta[2,3], and Shunri Oda[1,2]

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Applied Physics Express **1**, p. 014003 (2008)

Dr. Shunri Oda
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Variable-Temperature Scanning Hall Probe Microscopy of Ferromagnetic Garnet Thin Films

The scanning Hall probe microscope permits highly sensitive, noninvasive, and quantitative mapping of localized stray fields at the surfaces of ferromagnetic materials. Adarsh Sandhu is a pioneer in the development of the variable-temperature scanning Hall probe microscope, which permits magnetic imaging at nanometer-scale spatial resolution over areas of hundreds of square micrometers.

A good grasp of the effect of external fields and temperature on the properties of domain structures in garnets is crucial in the opto-electronics industry. Optical isolators of single-crystal ferromagnetic garnets prevent reflected light from damaging the laser sources in scanning Hall probe microscopes. The light can pass through the garnets in only one direction because of the Faraday effect.

Sandhu's group describes variable-temperature scanning Hall probe microscopy for imaging the surfaces of bismuth-substituted iron garnets $(BiTbHo)_3Fe5O_{12}$ of 50 micrometer thickness at temperatures between 77°K and 300°K. The group fabricated micro-Hall probes (1.5 μm²) photolithographically from 2DEG InGaAs/AlGaAs heterostructures that had an electron density of 2.2×10^{12} cm^{-2} and an electron mobility of 20,000 cm²/Vs. Its findings were highly consistent with the compensation temperature for the material employed. The width of the magnetic domains increased from approximately 7 μm at 300°K to 22 μm at 77°K.

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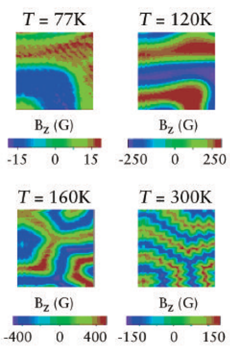
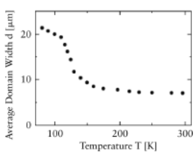
Journal of Magnetism and Magnetic Materials **310**, pp. 2693–2695 (2007).



Visualization of magnetic domains at the surface of iron-garnet film.



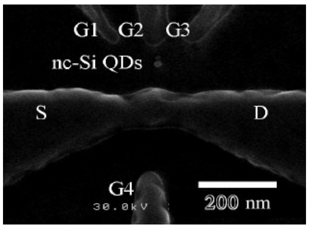
Temperature dependence of magnetic domains at the surface of iron garnets.

The Integration of Tunnel-Coupled Double Nanocrystalline Quantum Dots with a Multiple-Gate Single-Electron Transistor

Researchers have reported charge quantum bits (qubits) composed of 100 nm-diameter double quantum dots (DQDs) of a long decoherence time of around 200 ns. In addition, researchers have measured qubits with silicon single-electron transistors (SETs), which have ultrahigh charge sensitivity. Scaling down the dimensions of the silicon DQDs further would presumably increase the two-level splitting and multiply the fundamental qubit frequency accordingly

Yoshiyuki Kawata and his colleagues have for the first time integrated nanocrystalline silicon DQDs into a silicon SET. They fabricated the silicon SET with electron-beam lithography. The capacitance values for the fabricated SET agreed well with the results of three-dimensional capacitance simulations. That confirmed that the silicon SETs were defined by geometrical structure, not by dopant-induced tunnel barriers.

The group then deposited 10 nm–diameter nanocrystalline dots on a prepared resist pattern. It integrated the dots into the SET by removing unwanted dots by the lift-off process. The group employed single-electron circuit simulation, using the results obtained with the three-dimensional capacitance simulations, to analyze the effect of qubit charge polarization on the SET current.



A scanning electron micrograph of a SET into which nanocrystalline quantum dots have been integrated.

Yoshiyuki Kawata, Mohammed A. H. Khalafalla, Kouichi Usami, Yoshishige Tsuchiya, Hiroshi Mizuta, and Shunri Oda

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Japanese Journal of Applied Physics **46**, p. 4386 (2007).

Finding real-world solutions

A Novel Method for Growing High-Quality CIGS Film

$Cu(InGa)Se_2$ (CIGS) is a material used in solar cells to convert solar energy directly into electricity. A thin CIGS layer absorbs radiation from the sun, and it creates electron-hole pairs, resulting in the electron current.

A group led by Akira Yamada reports having invented a novel method for growing high-quality CIGS film, which is promising in regard to raising energy-conversion efficiency in solar cells. In the conventional evaporation method, the metal precursors impinge on the substrate surface with thermal energy. Yamada's group proposes an active-source method. Its method uses cracked selenium and ionized gallium, and those externally excited precursors migrate and diffuse easily on the growing surface, resulting in the enhancement of film quality unaccompanied by substrate heating.

The resultant CIGS film exhibits a large grain size suggestive of high quality. In addition, the method is a modified version of the conventional evaporation method and is suitable for mass production.

Akira Yamada[1], Fanying Meng[1], Yoshiyuki Chiba[2], Masahiro Kawamura[2], and Makoto Konagai[2]

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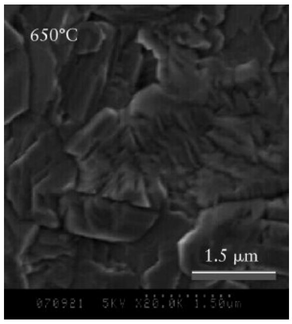
Materials Research Society Spring Meeting (April 9–13, San Francisco), Symposium Proceedings **1012**, p. 57 (2007).



A surface scanning electronic microscopic image of CIGS film grown with cracked selenium.

Dr. Akira Yamada
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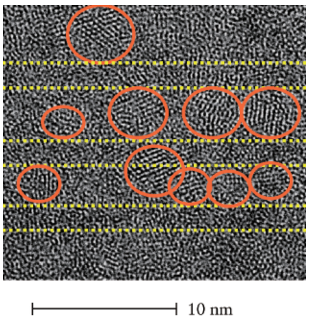
Photoluminescence from Silicon Quantum Dots in a Silicon Quantum Dot/Amorphous SiC Superlattice

Silicon quantum dot superlattices are a new absorber material for silicon-based solar cells. Shipments of solar cells exceeded 2.5 GW worldwide in 2006. Solar cells of single-crystal silicon and of cast silicon accounted, however, for more than 90% of production. Raising solar cell efficiency and achieving the absorption of the full solar spectrum will depend on progress in controlling the band gap energy, and that is therefore an exciting challenge for researchers.

A group led by Akira Yamada reports having developed size-controlled silicon quantum dot superlattices. The structure is applicable to the absorber layer of thin-film silicon solar cells, and its band gap is controllable by changing the dot size.

To fabricate the superlattices, the group deposited stoichiometric hydrogenaged a-SiC/silicon-rich a-SiC multilayers onto a quartz substrate with plasma chemical vapor deposition. It then annealed the multilayers at a temperature of around 900°C. The size of the quantum dots is controllable by adjusting the thickness of the layers. Transmission electron microscopic observation confirmed the formation of the silicon quantum dots, and reducing the dot size produced an observable blue shift of the photoluminescence peak.

This process is a simple and easy means of enhancing large modules. The group's next target is to demonstrate the applicability of the superlattices in improving solar cell performance and to fabricate tandem solar cells based on the superlattice material.



A cross-sectional transmission electron microscopic image of size-controlled silicon quantum dot superlattices.

Yasuyoshi Kurokawa[1], Shigeki Tomita[1], Shinsuke Miyajima[1], Akira Yamada[2], and Makoto Konagai[1]

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Japanese Journal of Applied Physics **46**, no. 35, p. L833 (2007).

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