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Quantum Nanoelectronics Research Center

QNERC NEWS

# Spinning electrons and trapping light

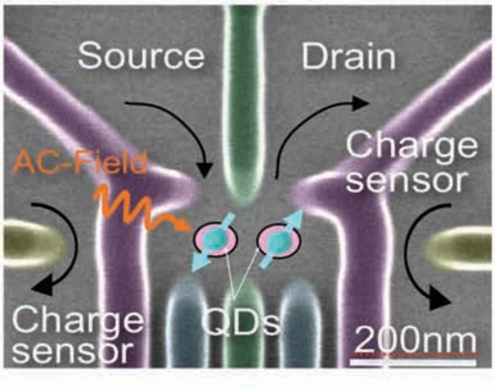
## Silicon quantum bits

Quantum computers process data by employing quantum bits—also known as qubits—instead of conventional data bits and standard transistors. A qubit can represent both a "1" and "0" at the same time, so this approach promises massive gains in computational power. But qubits are difficult to generate and manipulate.

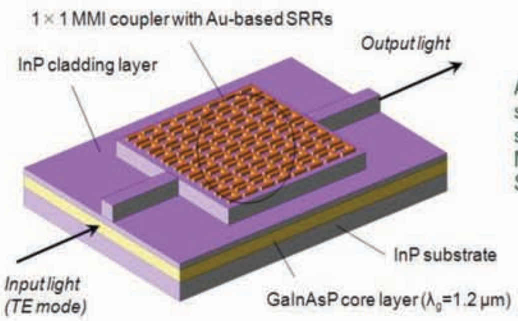
"A promising way to realize qubits is by employing the electron spin in quantum dots, which you can think of as electrons trapped in a box," says assistant professor Tetsuo Kodera of QNERC. Electron spin qubits in gallium arsenide (GaAs) devices have recently been developed in labs, though maintaining their stability can be a problem.

Consequently, Kodera is looking to exploit the properties of silicon to generate quantum dots, which should be more inherently stable, although the fabrication challenges are greater than with GaAs because they must be made much smaller to achieve the same results.

*From left:* Tomohiro Amemiya, Tetsuo Kodera




SEM image of double quantum dot (QD) structure consisting of an upper gate for inducing inversion carriers and lower gates for depletion, is proposed for fabticating quantum computation schemes using electron spins in QDs.




All-optical waveguide switching device consisting of InP-based 1×1 MMI coupler with gold SRRs.

## How to trap light

The goal of Tomohiro Amemiya, a QNERC assistant professor, is to fabricate novel optical devices so as to enhance optical communications. In addition to using well known materials such as GaAs for fabricating these devices, he is also introducing negative refractive index meta-materials, which will enable control not only of the device material's permittivity, but also its permeability.

"By controlling both the permittivity and permeability we can trap light in a device," explains Amemiya. "This would enable us to fabricate optical memory and optical memory buffers."

Currently, no hybrid optical communications devices employing meta-materials have reportedly been developed. "So the challenge is to actually fabricate such a device, which is very difficult because the structure incorporating the negative refractive index material has to be made at the nano-scale level," says Amemiya. "Yet if we are successful, it would eventually lead to much higher communications speeds."

## Masahiro Asada

*Director, QNERC; Professor, Tokyo Tech*
http://www.pe.titech.ac.jp/AsadaLab/

### Record Fundamental Frequency of Terahertz Oscillators Using Resonant Tunneling Diodes

The terahertz frequency (THz) range between light and radiowaves is in the spotlight because of important applications, such as ultrahigh-speed wireless communications, spectroscopy, and imaging. Resonant tunneling diodes (RTD) are potential candidates as compact and coherent sources of THz radiation-an essential requirement for these applications.

Masahiro Asada and coworkers at Tokyo Tech in collaboration with NTT Photonics Labs achieved an 831 GHz fundamental oscillation in RTDs at room temperature. This is the highest ever fundamental frequency of electronic single oscillators produced at room temperature, breaking the previous record of 712 GHz (also by an RTD) reported 18 years ago. Although harmonic oscillation over 1 THz has been reported previously, the fundamental oscillation is of greater importance because it is more suitable for practical applications.

The RTD device structure included an integrated micro antenna. The RTD was designed to have a low capacitance and a very-high current density for the generation of THz oscillations. Notably, the output power was more than one microwatt. Theoretical analysis showed that possibility of a fundamental oscillation of greater than 1 THz in structures where the electron transit time is suppressed. The output power of more than 100 microwatts was also expected by the slot antenna with an offset structure.

[1]Safumi Suzuki, Atsushi Teranishi, Kensuke Hinata, [1,2]Masahiro Asada, [3]Hiroki Sugiyama, and [3]Haruki Yokoyama

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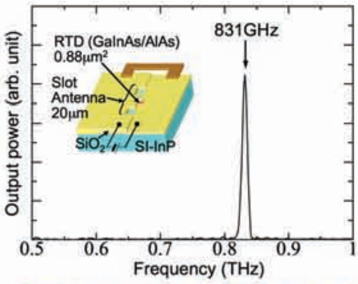
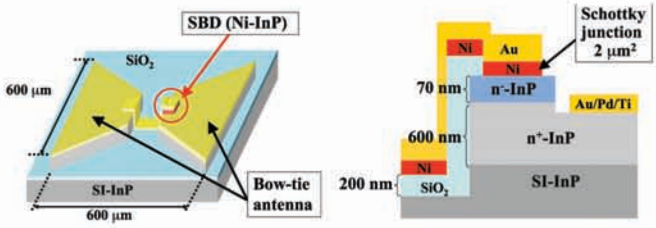
*Applied Physics Express* **2**, 054501 (2009).




Oscillation spectrum at 831 GHz of the RTD oscillator. The inset is the fabricated structure.

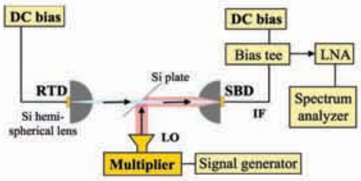



THz detector with SBD and bow-tie antenna, and the cross section of the SBD.

### Detection of Terahertz Output Power of Resonant Tunneling Diodes Using InP Schottky Barrier Diodes

Compact detectors and coherent sources are key components for practical applications of devices operating in the terahertz (THz) frequency range. InP Schottky barrier diodes (SBD) show promise as detectors because they operate with high speed and low-bias voltage at room temperature, and in addition, they can be integrated with other high-speed InP-based electron devices. THz oscillators with resonant tunneling diodes (RTDs) and detectors with SBDs—both based on InP—could form a useful combination for THz applications. However, there have been very few reports on InP SBDs so far.

Masahiro Asada and coworkers fabricated THz detectors with Ni-InP SBDs and broad-band bow-tie antennas, and demonstrated the heterodyne detection of oscillation signals from an RTD. The oscillation frequency and output power of the RTD used were 550 GHz, and <1 microwatt, respectively. A second harmonic heterodyne with a 280-GHz local oscillator was utilized for detection. The change in oscillation frequency with bias voltage was accurately measured from the signal, which was useful for precise control and stabilization of oscillation. The spectral linewidth was measured to be at most 10 MHz, and is expected to be reduced even further by using highly optimized RTD structures.




Detection of oscillation signal of RTD with SBD using harmonic heterodyne system.

[1]Ryo Yokoyama, [1]Kouichi Karashima, [1]Masato Shiraishi, [1]Safumi Suzuki, [1]Satoshi Aoki, and [1,2]Masahiro Asada

1 Interdisciplinary Graduate school of Science and Engineering, Tokyo Institute of Technology
2 Quantum Nano-Electronic Research Center, Tokyo Institute of Technology

*Proceedings of the Int. Conf. Infrared and Millimeter Waves & Terahertz Electronics*, T5E07, Busan, Sept. 2009.

## Shunri Oda

*Professor, Tokyo Tech*
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### Control of Electrostatic Coupling in a Silicon Double Quantum Dot Operating at 4.5 K

Silicon double quantum dots (DQDs) structures are of interest for spin-based quantum computers because of potentially long coherent times due to almost absence of nuclear spins in silicon.

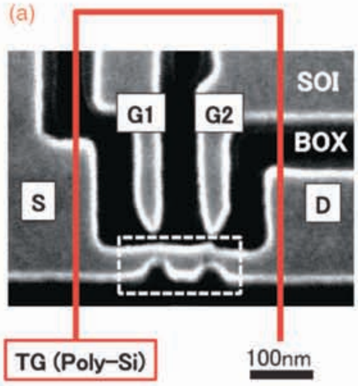
However, electron spin manipulation and detection have not been demonstrated yet in silicon systems due to the large sizes of silicon DQDs reported so far.

Now, Gento Yamahata and Shunri Oda and coworkers at Tokyo Tech and University of Southampton have fabricated a silicon DQD structure with top gate and side gates, and characterized electron transport through the silicon DQD at low temperatures.

The silicon DQD and side gates were patterned using high-resolution electron beam lithography and electron cyclotron resonance reactive ion etching, followed by the formation of a poly-silicon top gate.

The resulting small DQDs enabled the observation of clear electron transport through DQDs at 4.5 K, as well as the demonstration of successful modulation of the inter-dot electrostatic coupling by the side gates in the silicon DQDs.

The realization of small silicon DQDs with externally tunable inter-dot coupling is important for manipulation and detection of the spin states in silicon.




SEM image of the silicon double quantum dot device.

Gento Yamahata, Tetsuo Kodera, Hiroshi Mizuta, Ken Uchida, and Shunri Oda

*Applied Physics Express* **2**, 095002 (2009).

## Shigehisa Arai

*Professor, Tokyo Tech*

http://www.pe.titech.ac.jp/AraiLab/index-e.html

### Lateral current injection type laser for optical interconnection

Ultra low-power consumption light sources and low-noise photodetectors are essential to exploit the advantages of optical systems in the short-reach, and on-chip optical interconnections. High-index contrast, strong optical confinement structures — composed of a semiconductor core and polymer claddings — are of interest to achieve low threshold operation of semiconductor lasers.

Shigehisa Arai and his colleagues have been engaged in research on low threshold membrane lasers with strong optical confinement waveguides. However, an injection type membrane laser has been elusive because conventional current injection schemes are not applicable.

Here, the Arai group demonstrate lateral current injection (LCI) type lasers composed of a 400-nm-thick GaInAsP core layer including five compressively-strained quantum-wells on a semi-insulating InP substrate by OMVPE regrowth technique.

A threshold current of 49 mA, and a differential quantum efficiency of 5.5% were obtained for a stripe width of 2.0 μm and a cavity length of 805 μm. Further reduction of the threshold current as well as an increase of the differential quantum efficiency will be reported shortly.

These are important results for the realization of not only membrane semiconductor lasers but also for low-noise photodetectors for low power consumption photonic integrated circuits.

**Tadashi Okumura[1,2], Munetaka Kurokawa[1,2], Mizuki Shirao[1], Daisuke Kondo[1,2], Nobuhiko Nishiyama[1], Takeo Maruyama[3], and Shigehisa Arai[1,2]**

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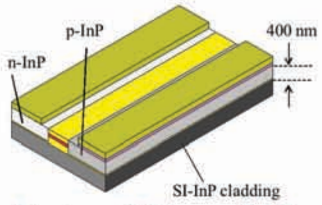
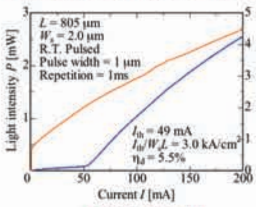
3 Graduate School of Natural Science & Technology, Kanazawa University, Kakumacho, Kanazawa-shi, Ishikawa, 920-1192, Japan

Optics Express, **17** 12564 (2009).




Structures of LCI laser on SI-InP




Lasing spectra

### Low threshold, high efficiency operation and external optical feedback tolerance of distributed-reflector lasers with wire-like active regions

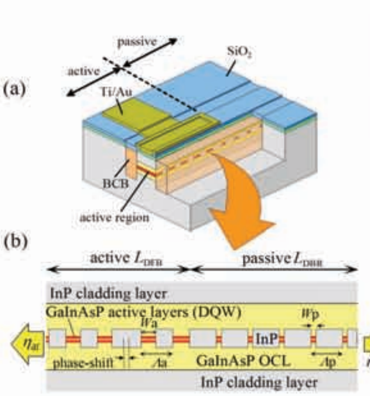
The explosive growth of data communications has led to intense demand for low power dissipation, and cost effective light sources for optical local access networks and interconnections.

A distributed reflector (DR) laser—consisting of an active distributed feedback (DFB) section and passive distributed Bragg reflector (DBR) sections-with wire-like active regions can be operated at a low-threshold current because of its small active volume and strong index-coupling grating structure.

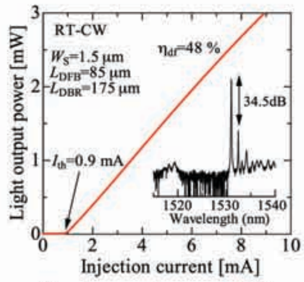
Now Shigehisa Arai and members of his group report on the low threshold and high efficiency operation of distributed reflector lasers. They achieved a threshold current as low as 0.9 mA and a high external differential quantum efficiency ηdf of 48% from the front facet by reducing the doping concentration of the waveguide layer. The injection current for 1 mW light output was only 3.6 mA—the lowest ever reported in any kind of edge-emitting-type single-mode laser.

The researchers also studied the endurance against external feedback of the DR laser, which is critical for cost-effective isolator-free modules, by measuring the relative intensity of noise. As a result, isolator-free 2.5 Gb/s 10-km transmission by directly modulated DR laser was demonstrated for an optical feedback level of -13.5 dB with a low power penalty of 2 dB.

Thus, the DR laser with wire-like active regions is promising as a low-power-consumption, low cost light source for access and metro networks.




(a)Schematic diagram of DR laser, (b)cross-sectional structure of wirelike active regiondouble quantum dot device.




.I-L characteristic of a DR laser with /16 phase shift

SeungHun Lee[1,2], Takehiko Shindo[1,2], Noriaki Tajima[1,2], Daisuke Takahashi[1,2], Nobuhiko Nishiyama[1], and Shigehisa Arai[1,2]

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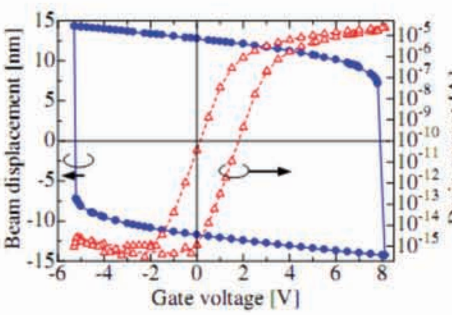
IEEE Photon. Technol. Lett. **21**, 1414 (2009).
IEEE Photon. Technol. Lett. **21**, 1529 (2009).

### A novel fast nonvolatile nanoelectromechanical memory device

Mirco/nano electromechanical systems (MEMS/NEMS) are used for fabricating sensors, resonators, display devices, and other such devices. Generally, the mechanical operation speed of MEMS/NEMS increases by decreasing their characteristic length and an oscillation frequency of over 1 GHz has already been reported for 1.1-μm-long SiC-based resonators. To apply the fast mechanical operation to electric devices, Shunri Oda's group have proposed the NEMS memory device, which is a fast and nonvolatile memory, consisting of a movable floating gate structure and a field effect transistor. However the memory properties of NEMS memory are still not fully understood.

Tasuku Nagami, a member of a team led by Shunri Oda, at Tokyo Tech conducted finite element electromechanical simulation, and demonstrated the readout and switching operation of the NEMS memory. They optimized the device structure to improve mechanical symmetry and to lower the mechanical potential barrier for the lower switching voltage.

They then analyzed the electrical properties by combining the electromechanical simulation with drift-diffusion analysis. The NEMS memory had less than 10 V of the switching voltage which is lower than that of a conventional flash memory, and about 3x10$^4$ ON/OFF current ratio.




Beam displacement, drain current –gate voltage relationships.

Tasuku Nagami, Yoshishige Tsuchiya, Shinichi Saito, Tadashi Arai, Toshikazu Shimada, Hiroshi Mizuta, and Shunri Oda.

*Japanese Journal of Applied Physics* **48**, 114502 (2009).


## Adarsh Sandhu

*Associate Professor, Tokyo Tech*

http://www.sandhulab.jp/index-e.html

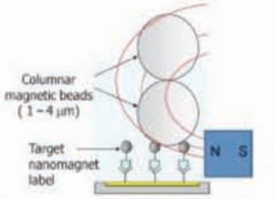

### A Novel Protocol for Detection of Nano-Magnetic Labels for Point of Care Medical Diagnostics: Magnetically Induced Manipulation of Superparamagnetic Microbeads.

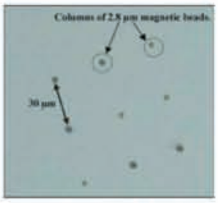
Biosensing platforms based on the detection of functionalized superparamagnetic beads acting as "magnetic-labels" are promising for rapid, high sensitivity and inexpensive point of care diagnosis of heart diseases, cancer and even testing automobile drivers for the influence of illegal drugs.

In order to improve quantification, it is essential to use nanometer-scale magnetic labels, which are comparable in size to actual biomolecules. However, detecting such labels is extremely challenging by typical magnetic sensors due to intrinsic noise. Here, Yoshitaka Morimoto and colleagues at Tokyo Tech. demonstrate a simple protocol for detecting nanometer sized magnetic labels over large surface areas.

The procedure for detecting nanometer sized magnetic-targets consists of a three step process: Immobilization of targets onto predefined spots on silicon substrates; self-assembly of large microbeads ('columnar-beads') onto the targets via dipole-dipole interaction induced by the action of an external magnetic field; and optical observation of the substrates to monitor the capture of the self-assembled 'columnar beads'.

Captured 2.8 μm diameter 'columnar-beads' by 12 immobilized 130-nm targets were easily visible under an optical microscope, although targets themselves could not be detected by magnetic sensors. Self-assembly of 'columnar-beads' could readily be extended for the detection of magnetically labeled biomolecuels.




Concept of the self-assembly of magnetic microbeads on nanometer sized target beads (LEFT), and an optical image showing the capture of 2.8 micrometer beads by 130 nm

Y. Morimoto, A. Abe, M. Hatakeyama, H. Handa, and A. Sandhu.

*IEEE Transactions on Magnetics* **45**, 2871 (2009).

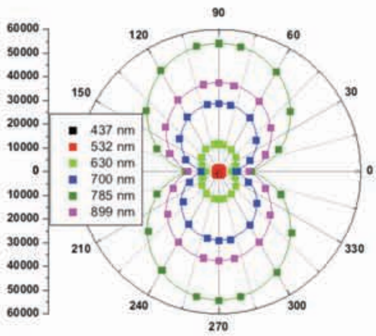
### Photonic Switch Utilizing Colloidal Magnetic Beads

Magnetic beads (MBs) dispersed in solution offer novel routes for magnetically tunable applications such as photonic crystals and liquid crystals. Magnetic interaction between MBs enables the formation of periodic or optically-anisotrophic structures. So far, the structures have been mainly manipulated by the strength of external magnetic fields, an approach whose shortcomings including slow response time, high power consumption, and high field-dependent response time.

Sang Yoon Park and other members of Adarsh Sandhu's group have investigated the structural and optical properties of MBs in a variety of magnetic fields, and developed magneto-optical devices utilizing rotational self-assembled magnetic chains.

Magnetic chains were formed when an external magnetic field was applied to a solution containing MBs. The chains were rotated by a rotating magnetic field, generated by quadro-polar electromagnets. The sample holder containing the magnetic beads was irradiated with unpolarized white light, and the transmitted light was detected by spectrometer.

The optical transmittance was found to be dependent on the length of the MB chains. The use of rotating magnetic chains enabled the optical response time to be drastically reduced compared to conventional methods.




Optical transmittance as a function of angle between light direction and magnetic field direction

Sang Yoon Park, H. Handa, and A. Sandhu.

*Journal of Applied Physics* **105**, 07516 (2009).

## Visiting Professors

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**Kunji Chen**
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