## Shunri Oda

Professor, Tokyo Tech

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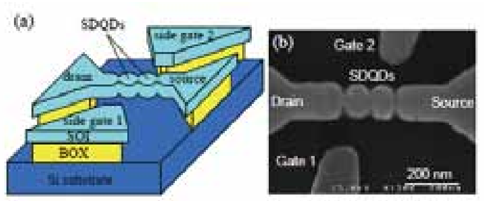
### Experimental Observation of Enhanced Electron–Phonon Interaction in Suspended Si Double Quantum Dots

Semiconductor double quantum dots (DQDs) are promising candidates for charge/spin qubits as basic information storage elements in quantum computer architectures. However, certain mechanisms may destroy the coherence in the system since the DQDs can never be isolated completely from their environment. It is expected that a system composed of DQDs embedded in a suspended nanostructure (SDQDs) can substantially reduce the decoherence in qubits. So far, there has been no investigation of electron–phonon interaction in silicon SDQDs.

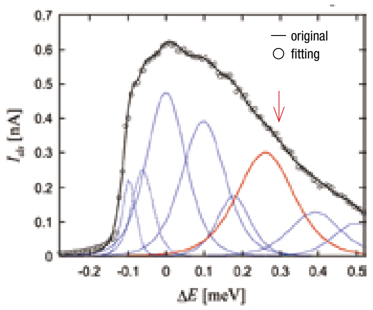
Shunri Oda and coworkers at Tokyo Tech in collaboration with Hitachi Cambridge Laboratory and Southampton University studied the electron–phonon interaction in silicon SDQDs through the observation of inelastic tunneling in the drain-to-source current.

Fig. 1 shows device structure Si based SDQDs fabricated by the combination of electron-beam lithography, oxidation, and etching. The variation of the of the source to drain current with gate voltage was measured at 120mK. Analysis of the current characteristics showed a current peak due to inelastic tunneling at 260meV as shown by the red curve in Fig. 2. Theoretical analysis in terms of phonon spectral density in SDQDs agreed with the observed band.

These results suggest the existence of distinctive phonon modes in silicon SDQDs and the possibility of tailoring the electron–phonon interaction in such structures.




1. Structure of SDQDs devices and their SEM image




2. Source-drain current versus the potential difference in SDQDs device

**Jun Ogi, Thierry Ferrus, Tetsuo Kodera, Yoshishige Tsuchiya, Ken Uchida, David A. Williams, Shunri Oda, and Hiroshi Mizuta**

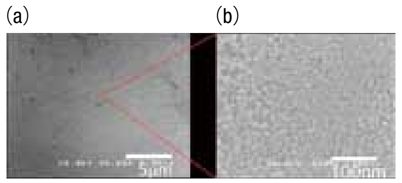
*Japanese Journal of Applied Physics*, **49**, 045203, (2010)

### Fabrication of Nanosilicon Ink and a Two-Dimensional Array of Nanocrystalline Silicon Quantum Dots

An assembly of nanoparticles using a colloidal solution is promising for the fabrication of highly integrated electron and photoelectronic devices because of low manufacturing costs, flexible substrates, and alternative methods that can overcome the limitations of top-down technology.

Shunri Oda and coworkers at Tokyo Tech successfully prepared two-dimensional arrays of nanocrystalline silicon (nc-Si) quantum dots with a uniform size of 10 nm. However, the area of two-dimensional arrays was limited because of problems associated with the dissolution in water and agglomeration of nc-Si due to the reactivity of the surface. The key issue was modification of the surfaces of nc-Si particles.

Recently, the researchers described the evaluation of surface modification states of nc-Si QDs by zeta potential and particle size distribution measurements. Optimization of the surface modification process enabled the successful realization of a well-dispersed nc-Si QD solution—'nanosilicon ink'. Furthermore, the group successfully fabricated a two-dimensional array of nc-Si QDs using the Langmuir-Blodgett film method over an entire 1 x 1 cm$^2$ silicon substrate.




SEM images of the LB film.
(a) Low magnification.
Nc-Si QDs assembled in a large area.
(b) High magnification.

**Tetsuya Ishikawa, Hiroki Nikaido, Koichi Usami, Ken Uchida, and Shunri Oda**

*Japanese Journal of Applied Physics*, **49**,125002, (2010)

### Visiting Professor

**Kaustav Banerjee**
Professor, University of California, Santa Barbara

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## UC Santa Barbara scientist Kaustav Banerjee sees opportunities for collaboration

**Kaustav Banerjee**
**Department of Electrical and Computer Engineering, University of California, Santa Barbara**

When Kaustav Banerjee received an invitation to visit Tokyo Tech from QNERC's Shunri Oda, he was excited to come. "I've long been impressed by the work of some of the faculty members at Tokyo Tech," says Banerjee. "So I was delighted when Shunri Oda invited me to spend some time with his group and with other faculty members like Ken Uchida."

After visiting a number of labs, Banerjee sees possibilities for various kinds of collaboration. He says that QNERC has a very good infrastructure along with some highly regarded staff, and looks well positioned to make advances in nanotechnology.

"I certainly see opportunities where we could work together," says Banerjee. "And not only in writing and submitting joint proposals, perhaps to both the Japanese and U.S. governments, but also in academic exchange."

One potential area of collaboration is in the field of carbon-based nano-materials. Banerjee's group in Santa Barbara is seeking to exploit the unique properties of carbon-based nanomaterials such as nano-tubes and graphene, and to identify new applications for them in electronics.

He notes that both Oda and Uchida are active in this field. Uchida, for instance, is studying the effects of strain on graphene, and he is already recognized for his research on strain in silicon.

Kaustav Banerjee of University of California, Santa Barbara.

"Now he has an excellent set-up to introduce strain into graphene and to quantify it," says Banerjee. "By employing strain, you can modulate electronic properties, which makes it a very interesting technique."

During his stay at Tokyo Tech Banerjee also met with two other researchers of graphene, Toshiaki Enoki, an experimentalist from the Chemistry Department, and Tsuneya Ando, a theoretician from the Physics Department. "I have known about their work and it was exhilarating to discuss some cutting-edge issues on graphene with them."

## New high performance electron-beam lithography system at QNERC

Recognizing the importance of nanotechnology in science and technology, the Japanese government has created the Nanotechnology Network Program to fund selected research institutes around Japan in the development of the technology. Tokyo Tech has been a recipient of such funding from the beginning, a factor that has helped furnish its Quantum Nanoelectronics Research Center with leading edge facilities and equipment.

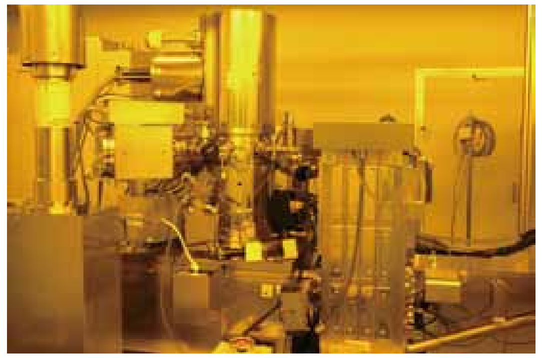
"Even experimental semiconductor facilities like ours are very expensive," says Yasuyuki Miyamoto, of the Department of Physical Electronics. "Our electron beam lithographic equipment alone costs over USD 1,500,000, while yearly running costs exceed USD 120,000. So this funding it vital for our research."

Electron beam (e-beam) lithography provides a way to overcome the limits of conventional optical lithography by enabling the creation of extremely fine patterns of resist for producing very small nanodevices such as transistors and lasers. Notably, researchers at QNERC have achieved periodic patterns of resists as small as 10 nanometers in width.

"And we've been able to transfer these patterns from the resist to metal patterns," says Miyamoto. We have also developed processes that enable us to employ the patterns to produce semiconductors with a periodicity of 25 nanometers. In Japan at least, we are leaders in this research."

In March 2010 a new e-beam system was installed to replace one of the two older machines. "The new system gives us a choice of three acceleration voltages: 25, 50 and 100 kilovolts," says Miyamoto. "Compared to the old, single 50 kilovolt system that we been replaced, we now have much more flexibility. Also, the higher acceleration voltage will enable us to produce even smaller resist patterns, eventually less than 10 nanometers, which will place us in the top international rankings of this research."

The ultimate goal, he adds, is to produce new compound semiconductors such as indium gallium arsenide capable of operating at very high frequencies that will be needed for new generations of mobile communications.



New electron beam lithography system at QNERC with a choice of 25, 50 or 100 kV acceleration voltages.

## Masahiro Asada

Director, QNERC; Professor, Tokyo Tech

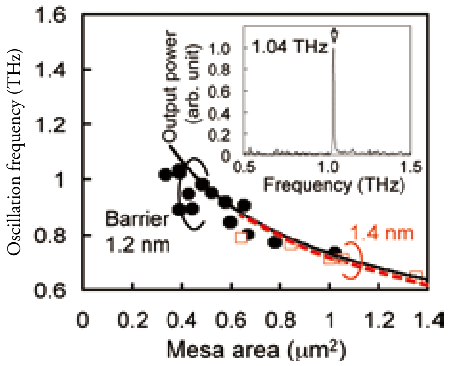
http://www.pe.titech.ac.jp/AsadaLab/

### First Fundamental Oscillation above one Terahertz in a Room-Temperature Electron Device

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. Because the source is a key component, optical and electron devices generating THz frequency are being intensively studied from both light and radiowave sides, towards the THz range.

Masahiro Asada and coworkers at Tokyo Tech in collaboration with NTT Photonics Labs describe the first observation of a room-temperature fundamental oscillation above 1 THz in an electron device. The device consists of an InGaAs/AlAs resonant tunneling diode with a micro-slot antenna. In 2010, this group also achieved a record highest 831 GHz frequency in room-temperature electron devices. However, tunneling and transit delays limited further increases of this frequency. To solve this problem, thin barriers and a graded emitter were introduced in their latest device. Notably, the thin barrier resulted in a reduction in the tunneling delay, and the graded emitter suppressed interband electron scattering, which caused the large transit delay.

The latest device oscillates at 1.04 THz with an output power of 7 microwatts. Theoretical analysis is in good agreement with the experimental results, and the researchers expect an oscillation close to 2 THz by optimizing the structure.




Variation of the oscillation frequency with the size of the resonant tunneling diode. The inset shows the frequency spectrum of the 1.04 THz oscillation.

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

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2 Quantum Nano-Electronic Research Center, Tokyo Institute of Technology
3 NTT Photonics Laboratories, NTT Corporation

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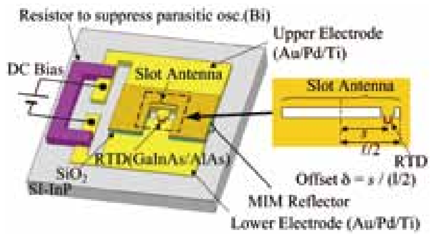
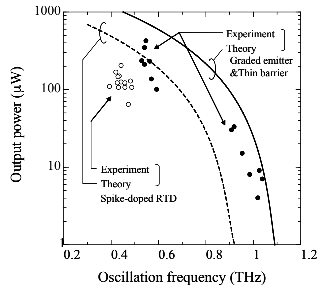
### High Power Resonant Tunneling Diode Oscillators for Terahertz Sources

The resonant tunneling diode (RTD) is considered as being an excellent candidate for compact and coherent sources in the terahertz (THz) frequency range. However, the small output power of only 1—10 microwatts limits applications. Here, Masahiro Asada and coworkers demonstrate RTD oscillators with output powers of several hundred microwatts using offset-fed slot antennas.

The oscillator was composed of a slot antenna and an RTD positioned at a pre-defined distance from the center of the slot. In this structure, the radiation conductance which determines the output power is adjustable to its maximum by changing the position of the RTD (offset). An oscillator with 100-micron-long antenna and 90% offset (45 micrometers from the center) had an output power of 200 microwatts at 443 GHz. By using further optimized antenna lengths and offsets together with RTDs having thin barriers and a graded emitter for reduced electron delay, a power of 420 microwatts at 550 GHz was obtained for a 130-micron-long antenna and an 89% offset. High output powers at even higher frequencies are possible by further reductions of delay in RTDs. Combining this structure with the array configuration is expected to yield output powers of more than 1 miliwatt.




Resonant tunneling oscillator with offset-fed slot antenna.




Variation of the output power with frequency of resonant tunneling oscillators.

Kensuke Hinata[1], Masato Shiraishi[1], Hirotaka Shibayama[1], Kaname Ishigaki[1], Safumi Suzuki[1], Masahiro Asada[1,2], Hiroki Sugiyama[3], and Haruki Yokoyama[3]

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*National Conventional Record of Japanese Society of Applied Phyics,* to be presented, March 2011

## Shigehisa Arai

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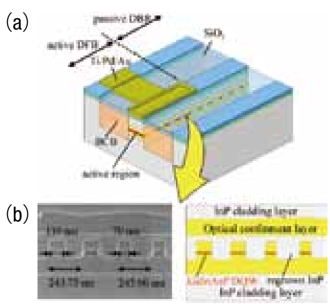
### Distributed Reflector Lasers for High-Speed Access Networks

The explosive growth of data communications has led to increasing demand for high bit-rate access networks. Furthermore, high-speed optical interconnects such as active optical cables have attracted great interest to deal with large data capacity. For such short distance applications, low-power consumption is an essential requisite for optical transmitters.

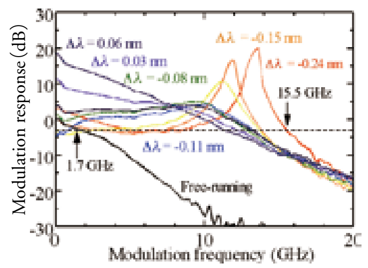
Shigehisa Arai and colleagues have been conducting research on distributed reflector (DR) lasers with wire-like active regions, which are promising candidates for low-threshold and high efficiency operation because of their small active volume and strong index-coupling grating structure.

Here, the researchers demonstrated 2.5 Gbps isolator-free operation, which will be indispensable for on-chip interconnects and for reducing the costs of transmitter modules for access networks. Notably, the critical feedback level—measured to be as high as -12.5 dB—was much higher than that of conventional single-mode lasers.
On the other hand, the modulation bandwidth enhancement by optical injection locking (OIL) was successfully demonstrated with DR lasers. The 3 dB bandwidth of 15.5 GHz was achieved with a bias current of only 5 mA.

These results will find applications for the realization of cost effective and low power consumption high bit-rate access networks.




(a) Schematic diagram and (b) cross sectional SEM image of DR laser.




Small signal modulation bandwidths under injection ratio of 13 dB.

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

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*IEEE Photonics Technology Letters*, **21**, pp. 1529–1531, (2009)
*Optics Express*, **18**, pp. 16370–16378, (2010)

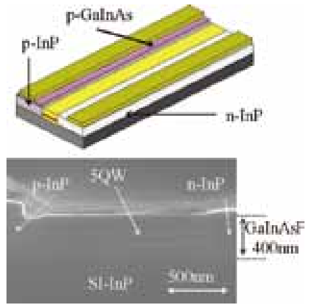
### Lateral Current Injection Type Laser and Photodiodes for Optical Interconnection

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 thin semiconductor core (membrane) and polymer claddings—are of interest to achieve low threshold operation of semiconductor lasers.

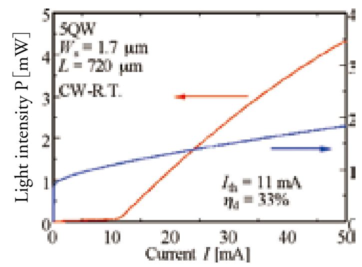
Shigehisa Arai and colleagues are engaged in research on lateral current injection (LCI) type lasers as a step towards electrically driven membrane lasers for on-chip optical interconnections. They successfully realized the room-temperature continuous-wave operation of LCI lasers fabricated on semi-insulating InP substrates. A threshold current of 11 mA (density of 900 A/cm$^2$) and an external differential quantum efficiency of 33% were attained for a device with 5 quantum-wells with a stripe width of 1.7 μm and the cavity length of 720 μm.

Photodiodes (PDs) with a lateral junction structure were also realized with responsivities of 0.9 A/W at 1500 nm and 0.27 A/W at 1550 nm. A 3-dB bandwidth of 6 GHz and 6 Gbps error-free operation under non-bias condition were achieved.

These results are important for low power consumption photonic integrated circuits based on electrically driven membrane DR lasers and PDs.




Schematic diagram and cross sectional view of LCI structure.




Lasing properties of LCI lasers on SI-InP.

Tadashi Okumura[1,2], Hitomi Ito[2], Daisuke Kondo[2], Nobuhiko Nishiyama[2], and Shigehisa Arai[1,2]

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*Japanese Journal of Applied Physics*, **50**, 020206, (2011)