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QNERC
Quantum Nanoelectronics Research Center

QNERC NEWS

Hands-on Nanotech

Zinc oxide is a common choice for gas nanosensors," observes Tokyo Tech doctoral student Abdeldjelil Habib Zahmani. "But most of those sensors are for detecting only one kind of gas. My goal is to create a zinc oxide nanosensor that will detect multiple gases. The state-of-the-art facilities here at QNERC provide an ideal research platform for tackling that goal, and I'm making steady progress."

Habib Zahmani belongs to one of the four research groups at QNERC. Joining him in discussing their work are fellow doctoral students in the three other research groups at the center. The four students are engaged in widely divergent fields of study. Yet all four are coming to grips with distinctly nanoscale phenomena. And each is benefiting hugely from QNERC's unique portfolio of capabilities in nanotechnology and nanoscience.

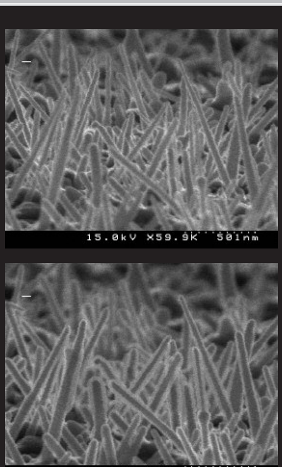
Dots, diodes, and distributed feedback

"I'm working on silicon nanodevices," explains Gento Yamahata, "in connection with quantum computing. My adviser is a leader in research on quantum dots, and I'm exploring practical means of using superposition, entanglement, and other quantum phenomena in computing applications."

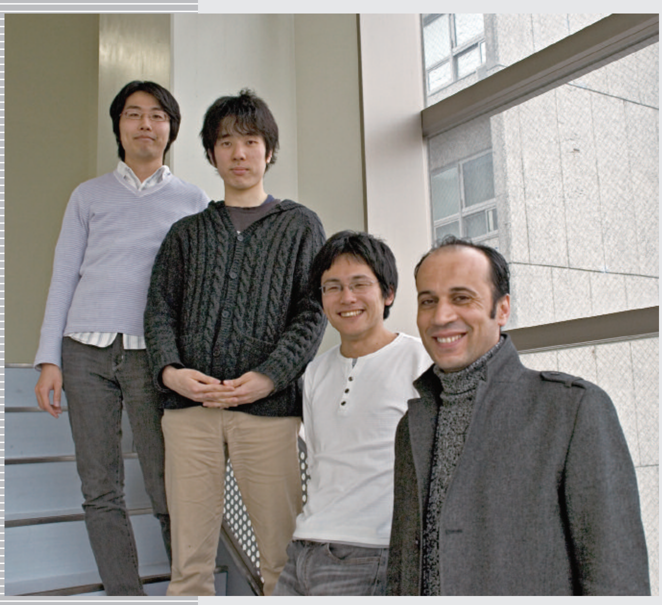
"My interest," says Safumi Suzuki, "is terahertz electronics. This has been the perfect place to study the oscillation of resonant tunneling diodes in the subterahertz and terahertz ranges."

"Our laboratory inherits the Tokyo Tech tradition of pioneering advances in optical communications," comments Tadashi Okumura. "My work here has included studying optical-interconnecting applications for membrane distributed feedback lasers."

"I needed expensive equipment to grow zinc oxide film," recalls Habib Zahmani, "and my professor secured exactly the hardware I needed." Nodding in agreement are his fellow students Okumura, Suzuki, and Yamahata. QNERC furnishes its members with the equipment required for nanoscale research and surrounds them with minds that are probing the frontiers of nanoelectronics.



Habib Zahmani grew these zinc oxide nanostructures in his laboratory at QNERC. He hopes to develop nanosensors based on zinc oxide that will detect multiple kinds of gases.



From left: Safumi Suzuki, Gento Yamahata, Tadashi Okumura, and Abdeldjelil Habib Zahmani.

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

Resonant Tunneling Diodes for Subterahertz and Terahertz Oscillators

The terahertz frequency range between light and radio waves is receiving a great deal of attention on account of its applications in ultrahigh-speed wireless communications, spectroscopy, and imaging. Compact and coherent terahertz sources are essential to these applications, but no satisfactory semiconductor terahertz source is available that operates at room temperature. An intense search is under way worldwide for room-temperature optical or electron sources.

A team led by Masahiro Asada has achieved oscillation rates of higher than 1 THz with an electron device at room temperature. The device is a resonant tunneling diode (RTD) of high current density integrated with a micro antenna, and it has generated third-harmonic oscillation of 1.02 THz. Its output power is small, less than 1 μW, but the experimental results confirm the theoretical possibility of achieving, with improved structures, oscillation in excess of 2 THz and output power of 60 μW at 1 THz. Preliminary experiments with the device have also established the feasibility of power combining in array configurations and of frequency control with bias voltage.

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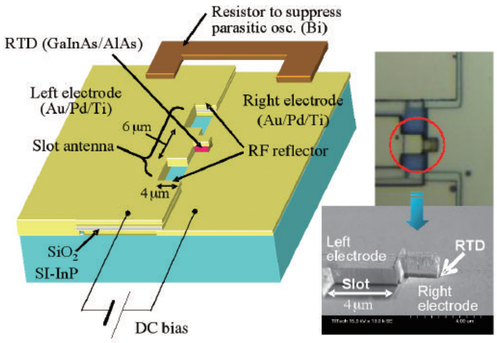
Japanese Journal of Applied Physics **47**, pp. 4375–4384 (2008)



Terahertz oscillator with resonant tunneling diode and micro s lot antenna.

Dr. Masahiro Asada

Director, QNERC; Professor, Tokyo Tech

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Dr. Shunri Oda

Professor, Tokyo Tech

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Coherent Power Combination in Multielement Subterahertz Resonant Tunneling Diode Oscillators

Masahiro Asada and his colleagues have achieved 1 THz harmonic oscillation with RTDs, but the output power was small. A team led by Safumi Suzuki and Asada fabricated multielement oscillator arrays of RTDs in the subterahertz range and observed coherent power combination in which the total output power exceeded the sum of the powers of the array elements. The devices consisted of RTDs coupled with slot antennas through metal-insulator-metal circuits.

Inducing mutual injection locking between the elements caused all the elements to oscillate at the same frequency and resulted in coherent power combining. A three-element array yielded a single spectrum and a combined output power of 13 μW, though the output power of each element was between 2 μW and 3 μW. That result suggests that improved elements could generate output power of more than 1 mW at 1 THz.

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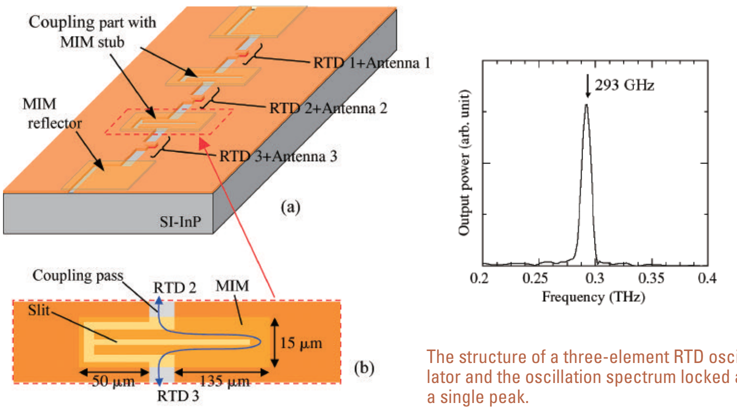
Applied Physics Express **1**, p. 093001 (2008)



The structure of a three-element RTD oscillator and the oscillation spectrum locked at a single peak.

Silicon-on-Insulator-Based Radio-Frequency Single-Electron Transistors That Operate at Temperatures above 4.2 K

Radio-frequency single-electron transistors (RF-SETs) offer high sensitivity and broad bandwidth and are therefore a promising candidate for charge quantum bit (qubit) readout, sensitive charge meters, and current standards. RF-SETs fabricated in Al/AlOx/Al tunnel junctions, GaAs quantum dots, semiconducting nanowires, carbon nanotubes, and two-dimensional electron gas (2-DEG) in intrinsic silicon operate only at temperatures up to 4.2 K.

Manoharan Muruganathan, a member of a team led by Shunri Oda, has fabricated a silicon-on-insulator (SOI)–based RF-SET that operates at temperatures of up to 12.5 K. That high-temperature performance resulted from optimizing the geometrically defined SOI-based single-dot SET structure to achieve a SET resistance of only 500 kΩ. It suggests that reducing the dot size could result in RF-SETs operable at noncryogenic temperatures. Such RF-SETs would be invaluable as silicon detectors and pixel detectors.

Manoharan Muruganathan,[1] Yoshishige Tsuchiya,[1,2,4] Shunri Oda,[1,4] and Hiroshi Mizuta[2,3,4]

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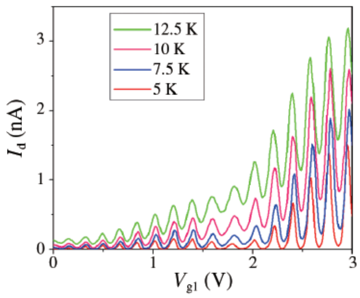
Nano Letters **8**, pp. 4648–4652 (2008)



Temperature dependence of the SET drain current as a function of gate voltage.

Low Power Consumption GaInAsP/InP Distributed Reflector Lasers for Optical Interconnections

The low power consumption of distributed reflector (DR) lasers that have wirelike active regions makes those lasers appealing light sources for high-speed optical interconnections. Researchers had verified the submilliampere threshold current (I_{th}) operations of those lasers, but the lasers' dynamic characteristics and high output power operation had been unconfirmed. Shigehisa Arai and his colleagues have verified the operation of directly modulated DR lasers at up to 10 Gb/s. In addition, they have improved the power efficiency of DR lasers, achieving, for example, external differential quantum efficiency (η_{df}) of 48% from a single facet and an I_{th} of 0.9 mA.

Reducing the surface area of the electrode reduced the parasitic capacitance in high-speed direct modulation. That allowed for achieving a data transmission rate of 5 Gb/s 10 km at a broad range of ambient temperatures. Error-free transmission took place at 10 Gbit/s under back-to-back conditions. Optimizing the doping concentration of the waveguide layer allowed for achieving a η_{df} of 48% while maintaining the I_{th} at 0.9 mA.

Seung Hun Lee,[1] Saeed Mahmud Ullah,[1] Takahiko Shindo,[1] Kyle Spencer Davis,[1] Nobuhiko Nishiyama,[2] and Shigehisa Arai[1, 2]

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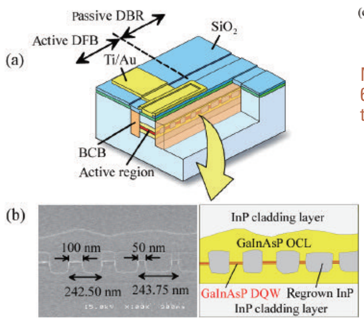
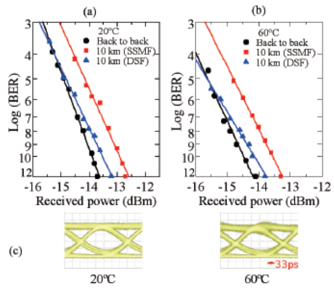
Proceedings of IEEE 20th IPRM (2008)



A schematic diagram of a DR laser (a) and a cross-sectional scanning electron micrograph of wirelike active regions (b).



Measured BER at 5 Gb/s at 20°C (a) and at 60°C (b) and eye diagrams at 5 Gb/s at those temperatures (c).

Dr. Shigehisa Arai

Professor, Tokyo Tech

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Injection-type GaInAsP/InP Distributed Feedback Lasers on Silicon-on-Insulator Substrate for Optical Wiring

Shigehisa Arai and his colleagues have developed a technique for fabricating, on SOI platforms, photonic integrated circuits of membrane semiconductor structure that feature extremely low power consumption. Ohmic heating and the resistive-capacitive delay associated with metal lines present theoretical limits to circuitry integration on silicon. Replacing the metal lines with optical lines could overcome those limits. Researchers are therefore looking carefully at the potential for fabricating photonic devices, such as lasers and optical amplifiers, on SOI platforms.

Arai and his colleagues used direct wafer bonding to fabricate, on an SOI substrate, injection-type distributed feedback (DFB) lasers that have wirelike active regions. They achieved a threshold current of 104 mA and a differential quantum efficiency of 1% with a stripe width of 25 μm and a cavity length of 1,000 μm. The lasers operated in a single mode at a wavelength of 1,543 nm and at a submode suppression ratio (SMSR) of 28 dB at 1.3 I_{th}.

Tadashi Okumura,[1,2] Takeo Maruyama,[3] Hidenori Yonezawa,[1,2] Nobuhiko Nishiyama,[2] and Shigehisa Arai[1,2]

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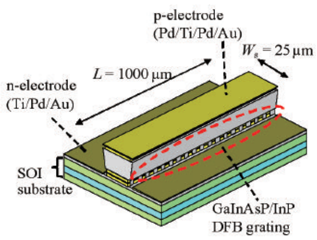
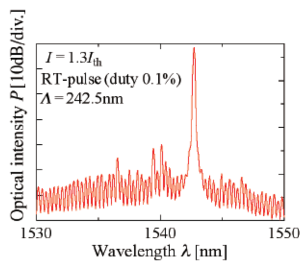
IEEE Photonics Technology Letters (2009)



GaInAsP/InP DFB lasers on SOI.



Lasing spectra.

An Analytical Model of a Single-Electron Transistor That Is Free of Voltage Limitations and That Incorporates the Effects of Spin-Degenerate Discrete Energy States

Single-electron transistors (SETs) are promising candidates for nanoscale integrated circuits of low power consumption and high density. Simulating hybrid circuits featuring SETs in a SPICE environment is accurate, but it is difficult and time-consuming. Monte Carlo simulations are not easily adaptable to design-realistic circuits. Benjamin Pruvost and his colleagues have developed a physically based analytical model based on orthodox theory and valid for a wide range of applied drain-source voltages and temperatures.

The analytical model can be embedded in a SPICE simulator to design hybrid CMOS-SET circuits. Its algorithm allows for solving the master equation efficiently, and the model is faster than other analytical models that have been reported. In addition, the model agrees closely with the results of Monte Carlo simulations. It can account for the discreteness of the quantum energy level, which allows for simulating SET operation at room temperature and for observing quantum mechanical effects. Room-temperature-operating SET simulation is possible and quantum mechanical effects are observable. The model can thus provide a suitable environment for designing CMOS-combined highly functional SET circuits.

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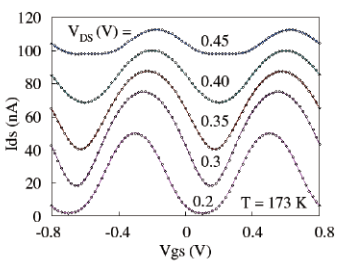


I_{DS}-V_{GS} verification of the model for symmetric devices, where C_G = 0.2 aF, C_D = C_S = 0.15 aF and R_D = R_S = 1 MΩ, at T = 173 K. The symbols indicate the results of Monte Carlo simulations, and the solid lines represent the model.

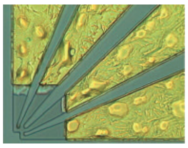
Finding real-world solutions

Scanning Hall Probe Microscopy in Contact Mode

Scanning Hall probe microscopy (SHPM) allows for monitoring (1) localized magnetic fields at the surfaces of ferromagnetic materials and magnetic media and (2) vortices in superconductors. However, the Hall probes, equipped with scanning tunneling microscope (STM) tips, only function with conducting surfaces, and they require extensive electronics to monitor the tunneling current.

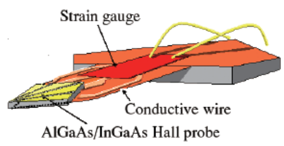
Adarsh Sandhu and his group have developed a robust contact mode SHPM system (CM-SHPM) that offers improved magnetic sensitivity and spatial resolution.

A 2 μm AlGaAs/InGaAs-2DEG Hall probe in the CM-SHPM system takes measurements in physical contact with the samples without relying on STM tips or piezoelectric actuators. Attaching the Hall probe to a flexible polyimide film cantilever allows for measuring the probe-sample separation with a simple Cu-Ni strain gauge integrated into the cantilever. The CM-SHPM offers a simple and highly reliable means of performing magnetic imaging of nonconducting samples over large areas and wide temperature ranges.



An optical image of a 2 μm × 2 μm AlGaAs/InGaAs Hall probe.

Toru Ohashi,[1] Hirotaka Osawa,[1] and Adarsh Sandhu[1,2]



The Hall probe attaches to the edge of the cantilever's Kapton polyimide film, and the strain gauge attaches to the flexible surface of the film. Two wires connect the gauge to a bridge circuit.

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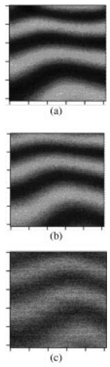
IEEE Transactions on Magnetics **44**, pp. 3252–3254 (2008)



The micrographs are 50 μm × 50 μm images of a 50 μm-thick iron garnet thin film taken in contact mode (a) and at distances of 0.5 μm (b) and 1 μm (c) above the sample. The black and white regions reveal magnetic field variation of ±212 G.

Dr. Adarsh Sandhu

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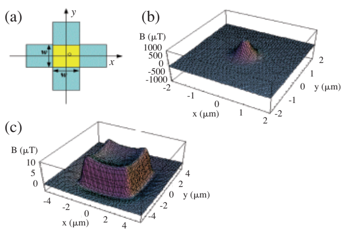
Determining the Sensitivity Variation in Hall Biosensor Arrays with the Position of Superparamagnetic Beads

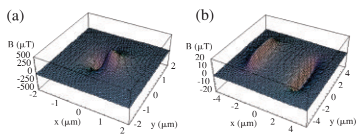
Using superparamagnetic beads (SPBs) as magnetic tags for biomolecular recognition is a promising alternative to conventional—less-sensitive and more-expensive—optically based protocols. However, commercial applications for Hall biosensors will require a quantitative grasp of the variation in device sensitivity with respect to the location of the SPBs on the active area of the sensors.

Adarsh Sandhu and his group conducted numerical and experimental analyses of the variation in the magnetic sensitivity of the active surface region of Hall effect biosensors. They conducted their analyses with AlGaAs/InGaAs two-dimensional electron gas Hall effect biosensors.

Theoretical simulations furnished a basis for determining how the magnetization in the vertical and horizontal components of the beads' magnetization influenced the output of the Hall sensor. In an experiment with 5 μm × 5 μm arrays of Hall devices, 10 devices per array, the edges and corners of the Hall sensors showed the greatest sensitivity, exhibited in a linear response.



Simulation criteria and results: Bead's magnetic field perpendicular to the sensor plane
(a) The coordinate system used in the calculations, (b) the perpendicular component of the magnetic field, (c) the magnetic field detected by the Hall sensor as a function of bead position.



Simulation criteria and results: Bead's magnetic field horizontal to the sensor plane
(a) The perpendicular component of the magnetic field and (b) the magnetic field detected by the Hall sensor as a function of bead position.

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