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QNERC Quantum Nanoelectronics Research Center

Silicon Photonics to boost transmission bandwidth

The benefits of carrying out research in QNERC, besides the outstanding facilities, says Yuya Shoji, is that he can pursue his interest in silicon photonics. Shoji joined QNERC from the National Institute of Advanced Industrial Science and Technology (AIST) in Tsukuba five years ago and was appointed an associate professor in March.

As a Tokyo Tech PhD candidate in 2008 he developed a way to fabricate a waveguide optical isolator on a silicon substrate. The normally incompatible surfaces of the two materials are exposed to a plasma charge in a high vacuum chamber, then directly bonded together. This had never been done before. Now his group is a leader in fabricating such silicon-based optical devices.

Laser diodes are a key element in fiber optic transmission. But they are sensitive to backwards-reflected light, which can destabilize the transmission signals. So they require the protection of waveguide optical isolators.

“A hot research topic in silicon photonics is short-range optical interconnections between devices for data transmission,” says Shoji. “For example, in data centers and in supercomputers where transmission speeds have become a bottleneck for performance, optical interconnections are an attractive approach to improve transmission bandwidth.”

Yuya Shoji

Consequently, he and his colleagues are developing optical switches. “The advantage of using optical signals is that we can transmit several signals at the same time using different wavelengths—wavelength-division multiplexing,” says Shoji. “The silicon waveguide-selective switch I’m working on is for WDM transmission, and it can choose a wavelength for each signal.”

As data centers and supercomputers grow larger and more powerful, copper cabling will have to be replaced with something more efficient. Shoji believes that after perfecting his optical devices, fiber optics and silicon-based photonic technology will be that replacement.

Advanced communications technology for a happy society

Two years have passed since Japan’s Ministry of Education, Culture, Sports, Science & Technology (MEXT) launched a joint academia-industry project to create a happier society based on advanced communications. The ten-year project has undergone a number of changes, yet its fundamental goals of enriching the life of residents of Japan with the aid of advanced technologies remain the same.

Seventeen member organizations including universities, major corporations, hospitals and local governments are collaborating to develop new technologies and intelligent modes of communication for the project. And Tokyo Tech, as the core institution involved, has 45 faculty members and many more staff participating, explains QNERC’s Shunri Oda, who has been appointed Research Leader of the project.

One aim is to foster more empathetic understanding between individuals, groups and generations, and to help people gauge each other’s true intentions. If successful, this could help reduce incidents of bullying, suicide and loneliness, while also encouraging people to actively participate in building a more fulfilling society. Such heart-to-heart communication is called ishin-denshin in Japanese.

Innovative services are being developed to provide instant recall of past events and meetings, vivid telepresence communications, and flexible work schemes that will connect people together based on common intentions and goals.

“The technologies we’re developing to provide these services include fuzzy-searchable databases made up of our memories and experiences,” says Oda. “Such data will be collected and processed automatically via highly sensitive sensors, actuators and wearable digital technologies.”

Shunri Oda

These low-powered devices won’t require charging. Rather, they will harvest energy from our movements, temperature changes and surrounding radio waves, for instance.

“Of course, this is an enormous challenge,” Oda notes. “And it will take longer than ten years to realize all our goals. But by then, we will be able to see what’s achievable and how we can further proceed.”

ODA Lab website http://odalab.pe.titech.ac.jp/

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World's first all-digital PLLs using ADC phase detector and SAR ADC based TDC

A phase-locked loop (PLL) is an extremely important mixed signal circuit core to generate highly accurate clock signals for digital LSIs and highly pure frequencies for wireless and wired communications. Low timing jitter, phase noise and power, as well as a small area are required. A conventional PLL still uses analog circuit techniques, however it has serious issues, namely, a large capacitance and area, and less adaptability. Therefore recently all-digital PLLs have been developed. However, the jitter and phase noise or power consumption are not sufficiently low due to the insufficient time resolution of time to digital converters (TDC).

We have proposed two new techniques to address these issues: one is the analog-to-digital converter (ADC) phase detector and the other is the successive approximation register (SAR) ADC based TDC.

1. All-digital PLL using ADC phase detector

An output signal of the digitally controlled oscillator is sampled directly and digitized by the ADC (Fig. 1) and the effective time resolution can be increased by using the sharp slope of RF signal. The world's first all-digital PLL (AD-PLL) using ADC phase detector was fabricated in 65 nm CMOS technology. The oscillation frequency is 2.2 GHz and the power consumption is 4.2 mW. The in-band phase noise is -112 dBc/Hz and the timing jitter is 380 fs. The world's best FoM of -242 dB was achieved.

2. All-digital fractional-N PLL using SAR ADC based TDC

A fractional-N PLL still requires TDC, however a conventional TDC uses an inverter delay chain and it is essentially difficult to increase the time resolution and decrease the power consumption. Thus we have proposed TDC that uses a charge pump and a SAR ADC (Fig. 2). The time difference is converted to charge by the charge pump and digitized by SAR ADC. This method can increase the time resolution easily without any serious increase of power consumption. The world's first all-digital fractional-N PLL (AD-PLL) using SAR ADC based TDC was fabricated in 65 nm CMOS technology (Fig. 3). The oscillation frequency is 3.6 GHz and the power consumption is 9.7 mW. The in-band phase noise is -110 dBc/Hz and the timing jitter is 415 fs. The FoM of -238 dB was achieved.

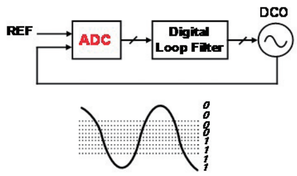

Fig. 1
ADC phase detector [1]

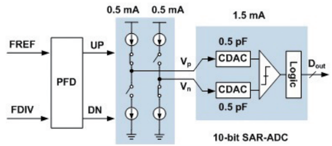

Fig. 2
SAR-ADC based TDC [2]

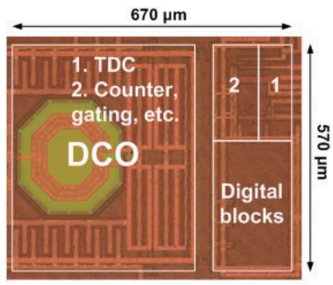

Fig. 3
ADPLL using SAR-ADC based TDC [2]

[1] Teerachot Siriburanon, et.al (9 other authors)
"A 2.2GHz -242dB-FOM 4.2mW ADC-PLL Using Digital Sub-Sampling Architecture,"
IEEE International Solid-State Circuits Conference (ISSCC), San Francisco, CA, pp. 440-441, Feb. 2015.
[2] Z. Xu, M. Miyahara, and A. Matsuzawa,
"A 3.6 GHz Fractional-N Digital PLL Using SAR-ADC-Based TDC with -110 dBc/Hz In-Band Phase Noise", IEEE Asian Solid-State Circuits Conference (A-SSCC), Xiamen, China, pp. 321-324, Nov. 2015.

Collaboration between members of the Department of Physical Electronics, Tokyo Tech., and Quantum Nanoelectronics Research Center, Tokyo Tech.

Shigehisa Arai

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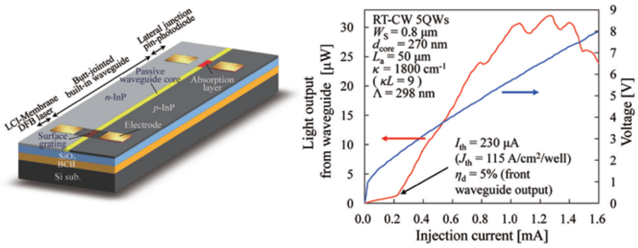
Membrane Single-mode (DFB and DR) Lasers for Optical Interconnections

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

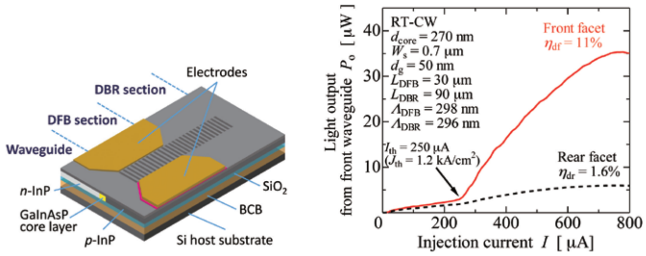
Shigehisa Arai and his colleagues have been engaged in research of electrically driven membrane lasers for on-chip optical interconnections. They successfully realized an extremely low threshold current operation of lateral current injection (LCI) membrane-based distributed feedback (DFB) laser and distributed reflector (DR) lasers bonded on a Si substrate. A threshold current of 230 μA and a differential quantum efficiency of 5% from the front side were attained for the DFB laser with a stripe width of 0.8 μm and cavity length of 50 μm. Moreover, a high-speed direct modulation capability with a record high modulation efficiency of 9.9 GHz/mA$^{1/2}$ was achieved. Integration of PIN-photodiode was also achieved.

In order to enhance the differential quantum efficiency for the light output from one side, a membrane DR laser, which consists of a DFB section and a passive distributed-Bragg-reflector (DBR) section, was realized. Not only a low threshold current of 250 μA but also an improved differential quantum efficiency of 11% from the front side were attained for the device with a stripe width of 0.7 μm and DFB section length of 30 μm.

These experimental results suggest that this membrane structure has great potential for photonic global wiring in future LSI circuits.



Schematic diagram (left) of membrane DFB laser integrated with PIN-photodiode and light output property (right) of a membrane DFB laser.



Schematic diagram (left) of membrane DR laser and its light output property (right).

T. Hiratani[1], D. Inoue[1], Y. Atsuji[1], T. Tomiyasu[1], K. Fukuda[1], T. Amemiya[2], N. Nishiyama[1], and S. Arai[1,2],

IEEE J. Sel. Top. Quantum Electron., vol. 21, no. 6, 1503410 (2015).
Optics Express, vol. 23, no. 6, pp. 7771-7778 (2015).
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Optics Express, vol. 23, no. 22, pp. 29024-29031 (2015).
Appl. Phys. Express, vol. 8, no. 6, 112701 (2015).

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Nano-Carbon Terahertz Sensors

Because the terahertz (THz) frequency region is located between the electronic and photonic bands, even basic components like detectors and sources have not been fully developed, compared to the other frequency spectra bands. THz waves also have the problem of low imaging resolution due to their two to three order of magnitude longer wavelength than visible light.

Yukio Kawano and his colleagues at Tokyo Tech, along with collaborators from Rice University and Sandia National Laboratories in the USA, have created a low-noise, highly sensitive THz detector by utilizing an array of highly-aligned carbon nanotubes. The researchers found that the noise of this detector was close to the Johnson noise limit (Fig. 1). Furthermore, the use of graphene devices has enabled frequency-selective THz detection. These carbon-based THz detectors provide interesting possibilities of novel THz sensing devices.

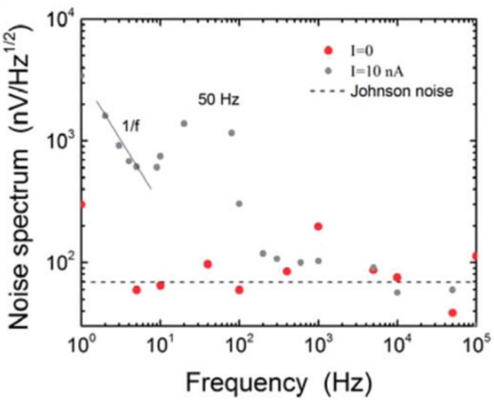


Figure 1
Noise spectrum for a CNT-array THz device.

Kristopher J. Erickson[1], Xiaowei He[2], A. Alec Talin[1], Bernice Mills[1], Robert H. Hauge[3], Takashi Iguchi[4], Naoki Fujimura[4], Yukio Kawano[4], Junichiro Kono[2], François Léonard[1]

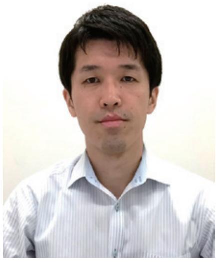
Figure of Merit for Carbon Nanotube Photothermoelectric Detectors
ACS Nano 9, 11618–11627 (2015)
Digital Object Identifier (DOI): 10.1021/acsnano.5b06160

[1]Sandia National Laboratories, [2]Department of Electrical and Computer Engineering and [3]Department of Chemistry, Rice University, [4]Quantum Nanoelectronics Research Center, Tokyo Institute of Technology

Yukio Kawano

Terahertz Response of Carbon Nanotubes and Graphene
Journal of the Physical Society of Japan 84, 121010-1-9 (2015)
Digital Object Identifier (DOI): 10.7566/JPSJ.84.121010

Quantum Nanoelectronics Research Center, Tokyo Institute of Technology



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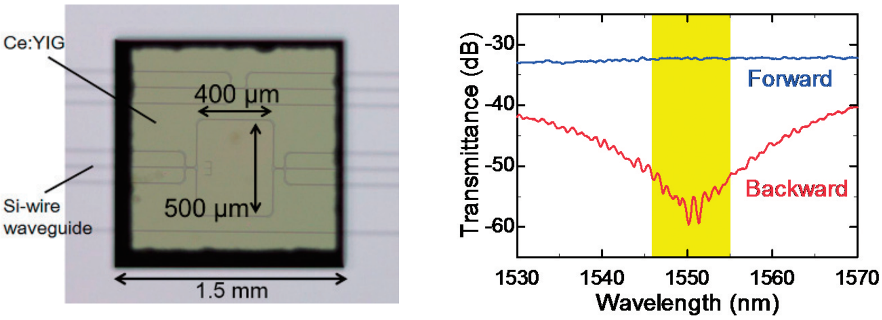
Silicon Waveguide Optical Isolator for Integrated Optical Transceivers

Silicon-based integrated optical transceivers are being developed for short-reach optical interconnections.

Yuya Shoji and his colleagues have developed an ultra-compact optical isolator with Si waveguides which allows stable and high-coherence operation of laser diodes by preventing backward reflections. The isolator is fabricated with directly bonded Ce:YIG by using a surface activated bonding technology. The researchers demonstrated the world's first Si-based isolator and the world's widest operation bandwidth.

The high-performance isolator can be integrated on a silicon platform to realize high-speed integrated optical transceivers.



Si-based waveguide optical isolator and its performance.

Y. Shoji[1], K. Miura[2], and T. Mizumoto[2]

Optical nonreciprocal devices based on magneto-optical phase shift in silicon photonics
Journal of Optics, vol. 18, p. 013001 (2016).

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Ge/Si core/shell nanowires for advanced electronics and photonics

Germanium (Ge) nanowires covered with silicon (Si) shell structures are promising materials for advanced transistors, sensors, light-emitters, and photovoltaic devices.

Shunri Oda and co-workers at QNERC, Tokyo Tech fabricated Ge nanowire core (20nm in diameter) and Si shell (2nm in thickness) structures by the vapor-liquid-solid chemical vapor deposition (VLS-CVD) method. The unique feature of this method is the low-temperature (280°C) growth of Ge nanowire using GeH_4 followed by Si shell deposition at 450°C using Si_2H_6 gas. TEM observation clearly showed that the Si shell film had grown epitaxially onto Ge core nanowires. This property is the basis for achieving very high quality interfaces between the Ge core and Si shell, which was demonstrated by the high quality electrical transport characteristics obtained by experiments as shown in Figure 1.

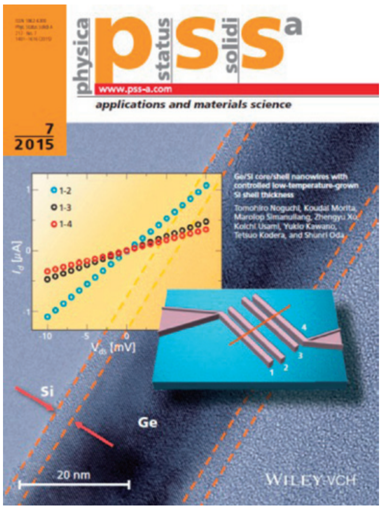

Fig. 1.
Front cover page of the July 2015 issue of Physica Status Solidi A. TEM image of a Ge/Si core/shell nanowire. Lattice image confirms epitaxial growth of Si shell with a high-quality interface between Ge core and Si shell. Electrical characteristics show highly confined holes in Ge quantum well structure.

Tomohiro Noguchi, Koudai Morita, Marolop Simanullang, Zhengyu Xu, Koichi Usami, Yukio Kawano, Tetsuo Kodera, and Shunri Oda

Ge/Si core/shell nanowires with controlled low temperature grown Si shell thickness
Phys. Status Solidi A 212, No. 7, 1578–1581 (2015)
DOI 10.1002/pssa.201532340

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3D integrated nanocrystalline Si particles produced by dip-coating method

Printable technologies using silicon nanoink, where nanocrystalline silicon (nc-Si) quantum dots are dispersed in solvents, are promising for novel electron and photonic device applications.

Shunri Oda and co-workers at QNERC, Tokyo Tech applied the dip-coating method for the first time to fabricate three-dimensionally integrated structures of nc-Si quantum dots with a uniform size of 10nm prepared by the very high frequency plasma decomposition of silane gas.

They have clarified the major problem of the dip-coating method, which is the formation of stripe structures. To circumvent this problem, they proposed two methods: coating onto line-and-space-patterned substrates and utilization of electrophoresis force. They successfully demonstrated the control of the position and number of layers of nc-Si by using a line-and-space-patterned substrate, however, with a limited shape. They clarified the conditions for the formation of stripe-free regions by varying applied voltage and nc-Si concentration in the electrophoresis method.

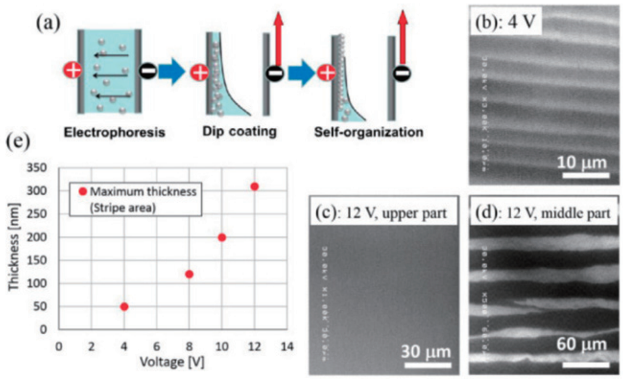

Fig. 1.
Schematic image of the model of the dip-coating method with electrophoresis. (b)–(d) SEM images of nc-Si particles coated on the silicon substrate. The electrophoresis voltages are (b) 4, (c) 12 (upper part of the substrate), and (d) 12V (middle part of the substrate). (e) Voltage dependence of the maximum thickness of nc-Si film in the stripe area.

Shotaro Yamazaki, Yoshifumi Nakamine, Ran Zheng, Masahiro Kouge, Tetsuya Ishikawa, Koichi Usami, Tetsuo Kodera, Yukio Kawano, and Shunri Oda

Formation of three-dimensionally integrated nanocrystalline silicon particles by dip-coating method
Japanese Journal of Applied Physics 54, 105001 (2015)
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