Compound Semiconductor Nanowire Laser Integrated in Silicon Photonic Crystal

Masato Takiguchi, Atsushi Yokoo, Kouta Tateno,
Guoqiang Zhang, Eiichi Kuramochi, and Masaya Notomi

Abstract

Compound semiconductor nanowires were integrated in silicon photonic crystals to form nano-cavities in arbitrary places, achieving the first nanowire laser that oscillates continuously at communication wavelengths. High-speed modulation at 10 Gbit/s was demonstrated. This laser is the ultimate heterostructure material hybrid device, having gain material only within the cavity.

Keywords: photonic crystal, nanowire, nanolaser

1. Fusion of heteromaterials with nanophotonics

The integration of compound semiconductors on silicon is very important for optoelectronic devices for optical interconnection, optical computing, and on-chip devices. Wafer bonding is generally used to bond compound semiconductors and silicon, which are dissimilar materials. Although that method enables the integration of heteromaterials such as compound semiconductors on silicon, it involves problems such as the difficulty of bonding and the difficulty of obtaining the utmost optical function of the optical elements, which themselves are compounds, due to overheating.

In our work, we have adopted a configuration in which high-performance optical elements made of optically low-loss silicon are prepared and compound semiconductor nanowires are placed as gain parts in the necessary locations. This fabrication process does not involve heating, so damage due to overheating does not occur. Moreover, the optical loss is low because the device is based on silicon. Another advantage is that the environmental impact is very low because there is minimal use of the compound semiconductor. Accordingly, this device can be considered an ideal heteromaterial hybrid optical device.

The device described here is a new nanolaser with a hybrid structure comprising silicon photonic crystal and a compound semiconductor. The nanowire is a one-dimensional structure that can be fabricated on a substrate in large numbers at one time. The nanowire can serve various purposes, including a quantum well, quantum dot, and p-i-n (p-type, intrinsic, n-type semiconductors) junction, which can be controlled by switching the gas that is supplied during growth. However, the nanowires themselves are too small to efficiently provide strong light confinement. Silicon photonic crystal, on the other hand, can provide very efficient light confinement without optical loss, but silicon is an indirect transition semiconductor and cannot itself emit light.

In our work, we fabricated a nanolaser by introducing an indium arsenic phosphide and indium phosphide (InAsP/InP) nanowire quantum well into a silicon photonic crystal to form a micro-cavity (**Fig. 1**). This combination can be considered a landmark structure that compensates the weak light confinement of the nanowire and the absence of light emission by the photonic crystal with the light emission of the nanowire and optical confinement of the photonic crystal. This type of structure was used to demonstrate the world's first nanowire laser that operates

Compound semiconductor nanowire

Silicon photonic crystal
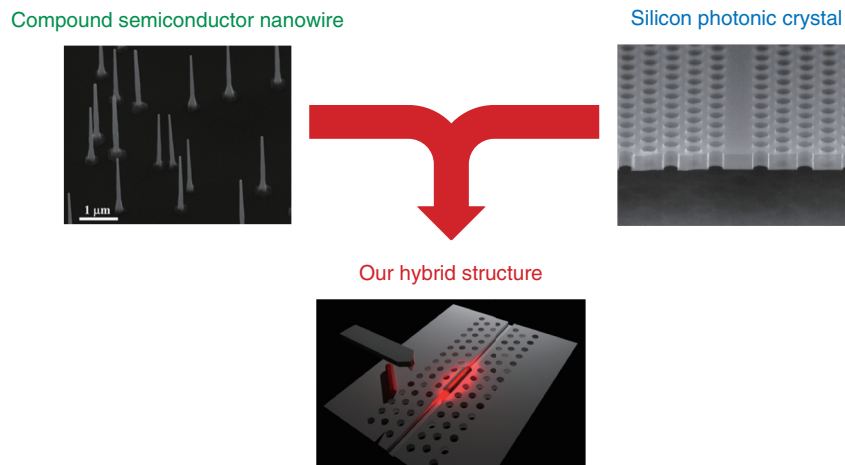
Our hybrid structure

Fig. 1.   Conceptual diagram of hybrid structure of nanolaser.

continuously in the communication wavelength band [1].

2.   Fabrication of hybrid nanowire devices

This device is fabricated by transferring nanowires onto a silicon substrate and then moving them onto the photonic crystal with the probe of an atomic force microscope (AFM)[*1] [2]. This method makes it possible to place any nanomaterial freely on a photonic crystal or other optical circuit.

The nanowires used here were fabricated by the VLS (vapor-liquid-solid) method using metal-organic vapor phase deposition [3]. The InP nanowires are grown from gold particles 40 nm in diameter that are dispersed on an InP (111) B substrate. One hundred InAsP layers are formed internally by supplying arsenic for a short time during the nanowire growth.

The light emission characteristic of the nanowire quantum well has a spectrum peak in the 1.3-μm band, and the polarization direction of the emitted light is controlled to be perpendicular to the nanowires. The nanowires are 2.4-μm long and have an average diameter of 114 nm (82 nm minimum and 144 maximum). The silicon photonic crystal has a diameter of 200 nm, a lattice constant of 370 nm, a trench width of 150 nm, and a depth of 115 nm. The nanowires are placed in grooves in the prefabricated photonic crystal. The photonic band at the location where the nanowires are placed is shifted towards shorter wavelengths, and the optical characteristics are changed only at those locations. Because light of particular wavelengths is confined in those locations, cavities

are formed. Such photonic crystal cavities are called mode gap cavities (**Fig. 2(a)**).

The polarization of the cavity mode is consistent with the polarization of the nanowire itself, so light can be extracted efficiently. From simulations of the light intensity when nanowires are placed in the photonic crystal (**Fig. 2(b)** and **(c)**), we can see clearly that oscillators are formed, and light is strongly confined at the nanowire locations. Because cavities are formed in the optical waveguide by simple placement of nanowires, this is a very convenient structure.

3.   Nanowire laser

Next, we investigated the oscillation of the laser produced by the nanowires. A conceptual diagram of the measurement and the measured spectra before and after oscillation produced by placement of the nanowires on a photonic crystal are presented in **Fig. 3(a)** and **(b)**. Light emission was measured using the microscopic photoluminescence method. The device was illuminated with light to excite the nanowires, and the light emitted by the nanowires was measured with a detector. The specimen was cooled to a temperature of 4K. The emission spectrum is steep, as seen in Fig. 3(b). That is the spectrum of the nano-oscillator induced in the photonic crystal by the nanowire. Furthermore, when the

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*1   AFM: An instrument that can visualize the surface of a specimen by using a sharp probe attached to the tip of a cantilever to scan the surface and measure the inter-atomic force acting between the probe and the specimen surface. In the process reported here, the scanning function of the probe is used to position nanowires.
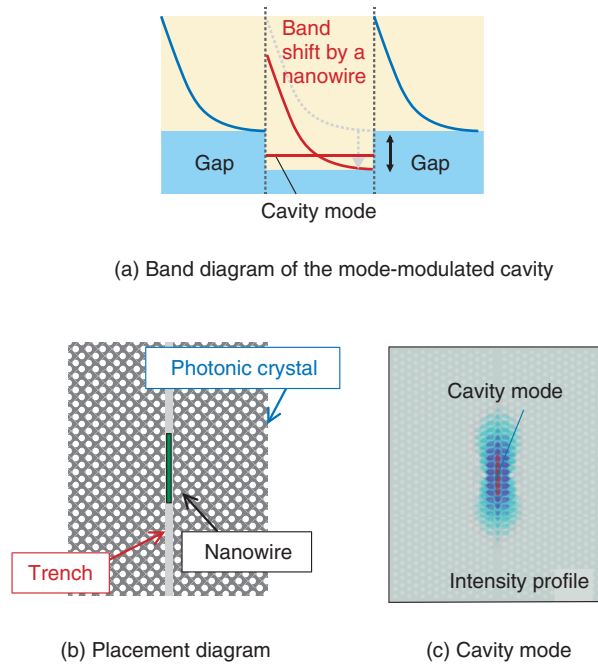
(a) Band diagram of the mode-modulated cavity

(b) Placement diagram

(c) Cavity mode

Fig. 2.   Nanowire induced photonic crystal cavity.
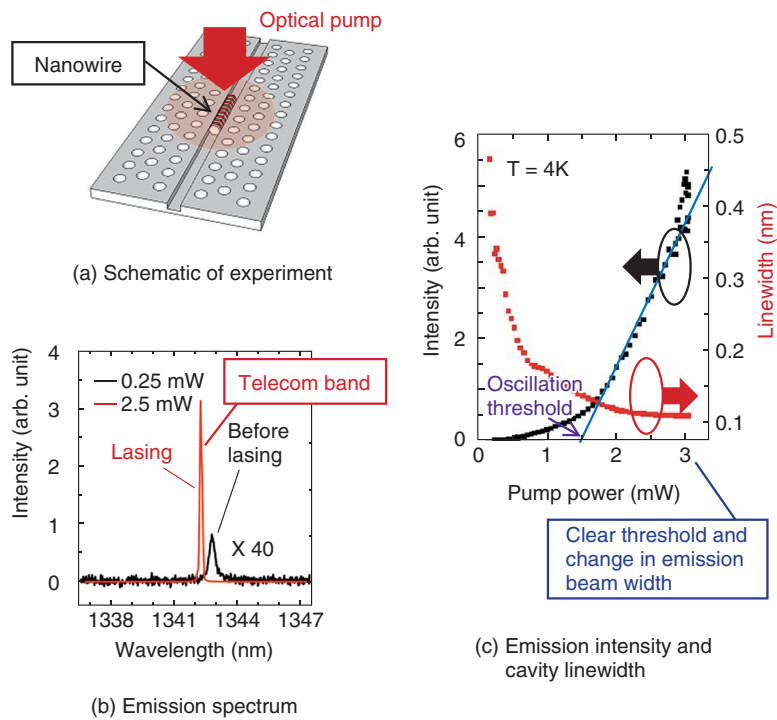
(a) Schematic of experiment

(b) Emission spectrum

(c) Emission intensity and cavity linewidth
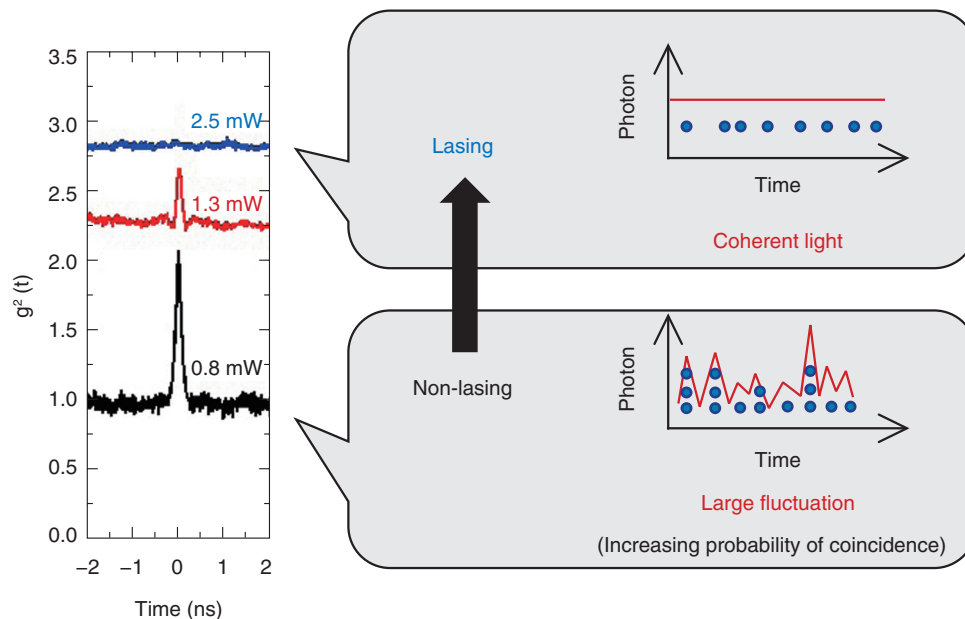
Fig. 3.   Measurement of nanowire laser.

Fig. 4.   Photon correlation measurement of nanowire laser.

excitation power is high, the laser oscillates with sharp increases in emission intensity. We investigated this effect in detail by measuring the nanowire emission while varying the excitation power (**Fig. 3(c)**) (light-in, light-out (L-L) measurement). The dependence of the emission and the spectral linewidth of the cavity on the excitation strength is shown in the figure. Generally, the emission sharply increases, and the cavity spectrum width becomes narrow when the laser oscillates, and the result presented here exhibits that behavior. The emission becomes strong at the excitation power of 0.15 mW (the oscillation threshold of the laser), confirming laser oscillation with certainty.

Oscillation of the laser can also be confirmed by investigating photon statistics. Correlation measurements can be used to investigate the time intervals between photons. The light prior to laser oscillation is called spontaneous emission light and is characterized by a large variance in intensity with short time intervals between photons (referred to as *bunching* because the photons are close together). The light after laser oscillation, on the other hand, is called coherent light, because the intensity is stable and there is a uniform distribution of the intervals between photons. The measurements require detection of a photon-level signal, so we used a highly sensitive superconducting single-photon detector[*2] to determine the correlation function ($g^2(t)$). Prior to oscillation, the correlation for this function is at $t = 0$, and bunching is observed ($g^2(0) > 1$). However, that bunching signal is eliminated once the laser oscillation begins. The effect of change in the excitation power on $g^2(t)$ is that the bunching signal is eliminated and the laser transition occurs (**Fig. 4**). Laser oscillation is confirmed to continue after that point.

Next, we conducted communication experiments with bit signals produced by this laser. The conceptual diagram for the experiment and the input signal, output signal, and eye diagram are presented in **Fig. 5**. The input signal was a 10-Gbit/s pseudorandom pattern produced by a pulse pattern generator. The input light was modulated by an electro-optic modulator, and the signal output from the nanolaser was integrated by the superconducting single-photon detector for measurement. Normally, a sampling oscilloscope and photodetector are used for measurement,

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*2 Superconducting single-photon detector: A system that detects photons by using a superconductor with a current bias that is just below the critical current as an optical detector. A photon is detected when the heat of a single photon breaks the superconducting state, increasing the resistance and producing a voltage pulse that is measured. High-speed photons can thus be measured at very high temperatures.
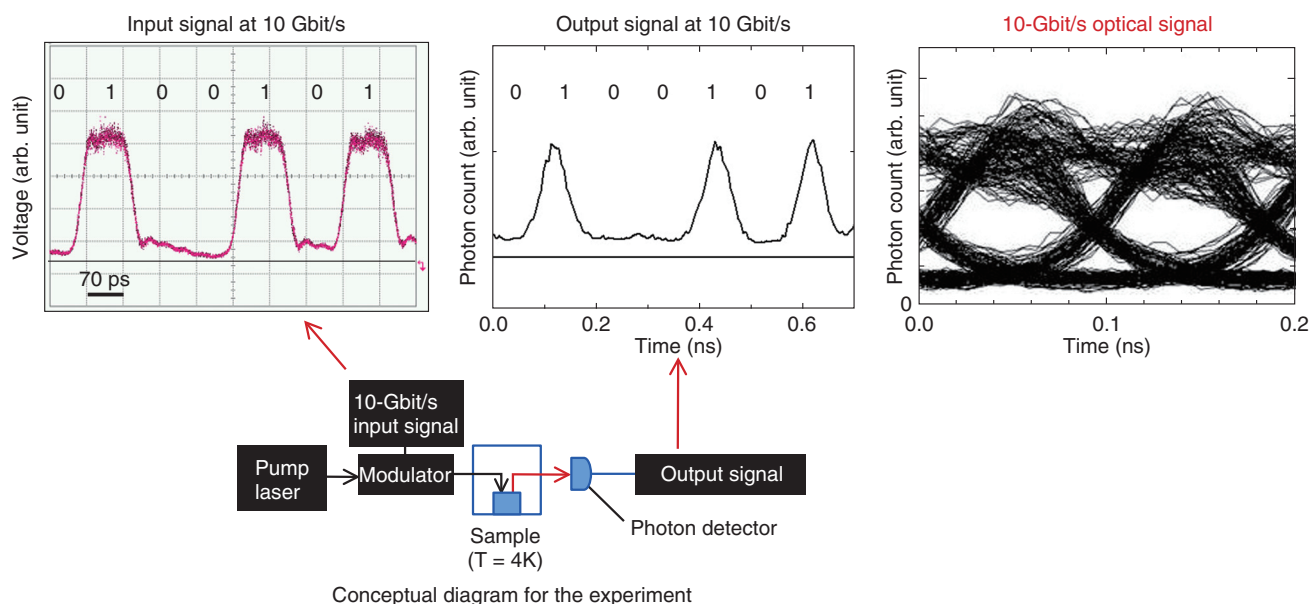
Fig. 5.   Modulation measurement of nanowire laser.

but the extremely weak light emitted by the nanolaser is measured in free space, so a highly sensitive detector is used. The light used for excitation has sufficient power to produce laser oscillation. We can see that the obtained waveform is the same as the waveform of the input signal. We analyzed the signal to obtain an eye diagram. The open center of the eye pattern indicates that correct communication of the bit signal is possible.

4.   Future development

We achieved continuous-wave laser oscillation at communication wavelengths by introducing compound semiconductor nanowires into silicon photonic crystals. We also confirmed that laser oscillation can be evaluated with photon statistics as well as with L-L characteristics. We further confirmed that the laser can be modulated directly at about 10 Gbit/s by modulating the excitation light with a pseudorandom signal. This demonstration of a communication-band nanowire laser and confirmation of modulated operation of a single nanowire laser are world-first achievements.

While the demonstration described here was per-

formed at low temperature, we are aiming for room-temperature operation in the future. The current nanowires and optical confinement are insufficient. Improvement will require thicker nanowires and control of non-emissive re-coupling at the nanowire surface. The structure of the photonic crystal should also be considered. We also plan to fabricate a current injection structure by using nanowires that have a p-i-n structure. In the future, we plan to develop new on-chip devices through on-chip integration of current-injected nanowire lasers, nanowire optical detectors, and nanowire optical modulators.

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Masato Takiguchi
Research Engineer, Photonic Nanostructure Research Group, NTT Basic Research Laboratories and NTT Nanophotonics Center.
He received a B.E. in applied physics from Tokyo University of Science in 2006 and an M.S. and Ph.D. in basic science from the University of Tokyo in 2008 and 2011. He joined NTT Basic Research Laboratories in 2011. His current interests are nanolasers, cavity quantum electrodynamics, quantum optics, and nanowire devices. Dr. Takiguchi is a member of the Japan Society of Applied Physics (JSAP).

Atsushi Yokoo
Manager, Research Planning Department, NTT Science and Core Technology Laboratory Group.
He received a B.E. and M.E. in organic synthesis from Kyushu University, Fukuoka, in 1988 and 1990, and a Dr.Eng. from Tohoku University, Miyagi, in 1998. He joined NTT Opto-electronics Laboratories in 1990. He worked with nonlinear optical devices, especially organic nonlinear optical crystals. He has also investigated photonic crystal and nanostructure fabrication. In 2003–2004 he was a visiting scientist at Massachusetts Institute of Technology, USA. His work has also involved investigating nanofabrication using nanoimprint lithography and related technology. Dr. Yokoo is a member of JSAP.

Kouta Tateno
Senior Research Scientist, Thin-Film Materials Research Group, Materials Science Laboratory, NTT Basic Research Laboratories and NTT Nanophotonics Center.
He received a B.S., M.S., and Ph.D. in chemistry from the University of Tokyo in 1991, 1993, and 2001. He joined NTT Opto-electronics Laboratories in 1993. His current research interests include fabrication technology and physics of nanostructures using semiconductor nanowires, their application to optical nanodevices on silicon and graphene, and artificial photosynthesis using nanowires. Dr. Tateno is a member of JSAP, the Electrochemical Society of Japan, and the Materials Research Society.

Guoqiang Zhang
Senior Research Scientist, Quantum Optical Physics Research Group, Optical Science Laboratory, NTT Basic Research Laboratories.
He received a B.S. in materials science and an M.S. in semiconductor physics and chemistry from Zhejiang University, P. R. China, in 1997 and 2000, and a Ph.D. in electronic materials science from Shizuoka University, Japan, in 2004. From 2004 to 2006, he was involved in studying the synthesis and characterization of zinc oxide nanowires and carbon nanotubes. Since joining NTT Basic Research Laboratories in 2006, he has been working on the growth and characterization of semiconductor-nanowire-based nanostructures, and the design, fabrication, and evaluation of novel optoelectronic devices at the nanometer scale. Dr. Zhang is a member of JSAP and the Japanese Association for Crystal Growth.

Eiichi Kuramochi
Senior Research Engineer, Photonic Nanostructure Research Group, NTT Basic Research Laboratories and NTT Nanophotonics Center.
He received a B.E., M.E., and Ph.D. in electrical engineering from Waseda University, Tokyo, in 1989, 1991, and 2004. In 1991, he joined NTT Opto-electronics Laboratories, where he was engaged in research on semiconductor nanostructures for photonic devices. He moved to NTT Basic Research Laboratories in 1998. His current research involves photonic crystals. Dr. Kuramochi is a member of the Institute of Electrical and Electronics Engineers (IEEE) Photonics Society and JSAP.

Masaya Notomi
Senior Distinguished Scientist, Photonic Nanostructure Research Group, NTT Basic Research Laboratories; Project Leader of NTT Nanophotonics Center.
He received a B.E., M.E., and Ph.D. in applied physics from the University of Tokyo in 1986, 1988, and 1997. He joined NTT in 1988. Since then, his research has focused on controlling the optical properties of materials/devices using artificial nanostructures (quantum wires/dots and photonic crystals). In addition to his work at NTT, he has also been a professor in the Department of Physics, Tokyo Institute of Technology, since 2017. He received the IEEE/LEOS (Lasers & Electro-Optics Society) Distinguished Lecturer Award (2006), the JSPS prize from the Japan Society for the Promotion of Science (2009), a Japan Academy Medal (2009), and the Commendation for Science and Technology by the Japanese Minister of Education, Culture, Sports, Science and Technology (2010). Dr. Notomi is an IEEE Fellow and a member of JSAP, the American Physical Society, and the Optical Society (OSA).