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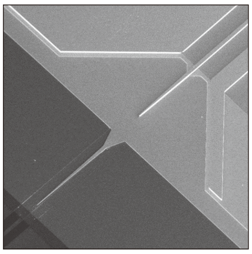

Low Power Consumption Tunable Lasers with Heterogeneous Material Integration

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The development of various IoT applications is accelerating data traffic, and it is anticipated that a data rate of more than 10 Tb/s will be required by 2030. On the other hand, conventional single-material photonic device technologies seem to have limitations to achieve both high-speed operation and low power consumption for 10 Tb/s-class data transmission. To overcome this challenge, heterogeneous integration, which combines the advantages of III-V compound semiconductors for high-speed and high-efficiency operation and Si photonics for high-density integration through device miniaturization, is expected as one of the promising approaches. This paper reports wavelength tunable lasers using heterogeneous integration.

Keywords: heterogeneous material integration, wavelength tunable laser, silicon photonics, bonding technique

1. Introduction

Various IoT*1 applications, such as autonomous driving, telemedicine, smart cities, and smart agriculture, have been proposed and are currently under development. While connecting more objects to the internet will increase convenience, optical communication technology that supports the system is required to be further improved. Against this backdrop, the fifth-generation (5G) mobile communication system has already been deployed as one of the communication networks to achieve a smart society, and the beyond 5G (sixth-generation (6G)) mobile system standard is now being developed. Consequently, a larger volume of data transmission will be required with respect to access and data center networks. It is anticipated that the required transmission speed of optical transceivers used for data transmission will exceed 1 Tb/s by 2025 and reach the order of 10 Tb/s by 2030.

InP-based monolithically integrated devices(1) and Silicon (Si) photonics*2 (2) have been used for the current optical communication system. These single-material devices are difficult to achieve data transmission with the data rate of more than 10 Tb/s for a single wavelength, and multichannel transmission systems with conventional devices will be one of the effective solutions. Although these systems have a great advantage in transmission capacity, they have disadvantages in device size, cost, and consumption power. Even when using compact and low-power-consumption transceivers supporting 800 Gb/s data rates based on cutting-edge device technology, the systems require 16 channels, and their consumption power is estimated to be more than 300 W. A drastic reduction in power consumption is required in devices. Thus, the conventional single-material photonic device technologies seem to have limitations in achieving both high-speed operation and low power consumption, and a technical breakthrough is awaited.

Photonic devices using heterogeneous material integration, which combines the advantages of III-V compound semiconductors*3 and Si photonics, are expected to be one of the promising approaches. III-V compound semiconductors including InP-based materials have the advantages of high-speed and high-efficiency operation, and Si photonics have the advantage of high-density integration, enabling large-capacity transmission. Furthermore, the high-efficiency and low-power-consumption operation which exceeds the performance of single material devices is achieved by the design using these advantages.(3),(4) This paper describes tunable lasers integrated with InP-based gain sections and wavelength filters using Si photonics by a wafer bonding technique.

2. Heterogeneous Material Integration Technique

Various investigations for heterogeneous material integration that combines III-V compound semiconductors and Si photonics have been reported. Representative heterogeneous material integration techniques combining III-V compound semiconductors and Si photonics are shown in Table 1.

Table 1. Heterogeneous material integration techniques combining III-V compound semiconductors and Si photonics

	Butt-coupling	Micro-transfer printing	Wafer/chip bonding
High-density integration	✓✓	✓✓✓	✓✓✓
Alignment accuracy	✓✓	✓✓	✓✓✓
Simplicity of III-V semiconductor fabrication	✓✓✓	✓✓	✓✓

Butt-coupling(5) is a technique to integrate III-V compound semiconductor chips and Si photonics chips by butting their facets. Since each chip can be prepared independently, III-V compound semiconductor devices can be fabricated by using a conventional method. On the other hand, it is required to suppress the optical coupling losses due to the misalignment and reflections at the boundary of chips.

Micro-transfer printing(6)–(8) is an integration technique that picks up devices fabricated on a III-V compound semiconductor wafer and transfers them to desired positions on a Si photonics wafer. This technique allows the high-density integration of the devices with various III-V compound semiconductors, while the optical coupling loss due to misalignment is a problem.

Wafer/chip bonding(4),(9),(10) is a technique that directly bonds III-V compound semiconductor materials on a Si photonics wafer. After the bonding process, the bonded wafer is processed, and integrated devices are formed. By changing the core layer of III-V compound semiconductors, high-density integration of devices with various functions on a chip can be realized. The alignment accuracy of this technique is higher than that of the other two techniques because the patterns are formed utilizing the high-precision alignment of stepper lithography. As a result, the optical coupling loss due to the waveguide misalignment is reduced, and the high optical coupling efficiency between III-V compound semiconductors and Si waveguide can be obtained. On the other hand, this technique requires processing knowledge and skills for both Si and III-V compound semiconductors.

As described above, various heterogeneous material integration techniques have been reported. From viewpoints of its high integration density and alignment accuracy, Sumitomo Electric Industries, Ltd. has adopted the wafer/chip bonding technique for the photonic devices with heterogeneous material integration.

3. InP/Si Hybrid Tunable Laser with Wafer Bonding Technique

Figure 1 shows an overview of an InP/Si hybrid tunable laser using the wafer bonding technique.(11) The tunable laser has an InP-based gain section, which emits light, as well as Si waveguide-based loop mirrors*4 and ring resonators.*5 The InP-based gain section uses a shallow ridge waveguide,*6 and the optical confinement factor to the active layer is determined by the Si waveguide width.(12) In addition, as shown in Fig. 1 (b), the two-step taper structure including n- and p-type tapers is used as the optical coupling structure between the InP-based gain section and the Si waveguide.(13),(14) The p-type taper uses the two-storied ridge structure consisting of the shallow ridge waveguide and the deep ridge waveguide.*7 This structure enables low optical coupling losses and low wavelength dependence.(12) Figure 2 shows (a) the transmittances of the two ring resonators and (b) the transmittance of the double-ring filter. By combining two ring resonators with slightly different free spectral ranges, the Vernier effect is introduced to this double-ring filter. This has the peaks at the positions where these spectra just overlap, and the spacing between these resonant peak wavelengths is determined by the difference of these two free spectral ranges. A wide wavelength tuning range can be obtained by widening spacing between resonant peak wavelengths for the double-ring filter, and the operating wavelength is controlled by thermo-optic effect through the microheaters on the ring resonators.

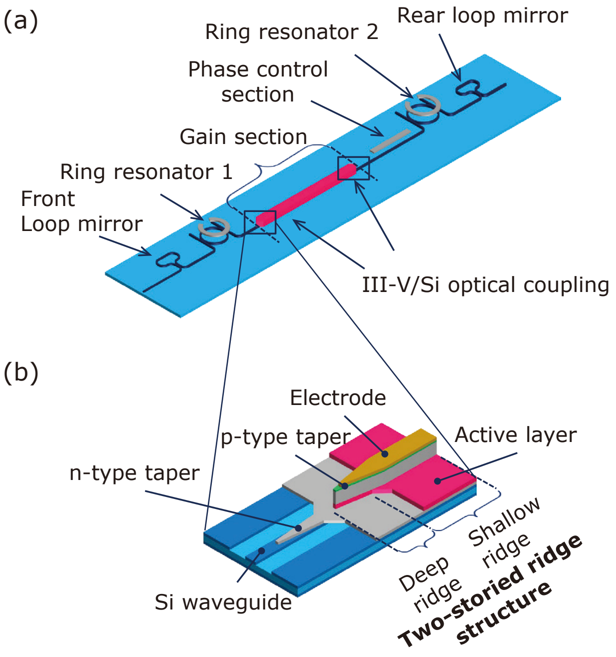

Fig. 1. (a) Overview of an InP/Si hybrid tunable laser using wafer bonding, and (b) an InP/Si optical coupling structure

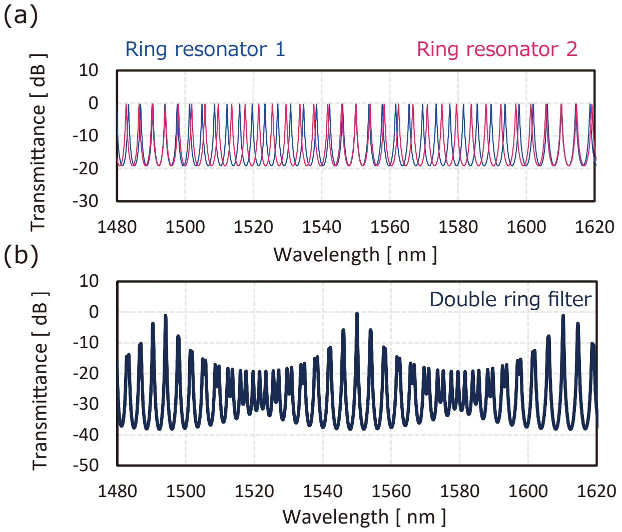

Fig. 2. (a) Transmittance of each ring resonator and (b) Transmittance of a double-ring filter

The fabrication flow of an InP/Si hybrid tunable laser using the wafer bonding technique is shown in Fig. 3. First, a Si waveguide is fabricated on a Si-on-insulator (SOI) wafer. Then, an InP wafer which includes a GaInAsP multiple-quantum-well (MQW) layer as a light-emitting layer is prepared, and this InP wafer is directly bonded to the SOI wafer. When the InP substrate is removed by wet chemical etching, the InP-based light-emitting layer remains on the SOI wafer. After that, the two-step taper structure including shallow ridge waveguides and deep ridge waveguides is formed by the photolithography and dry etching processes.

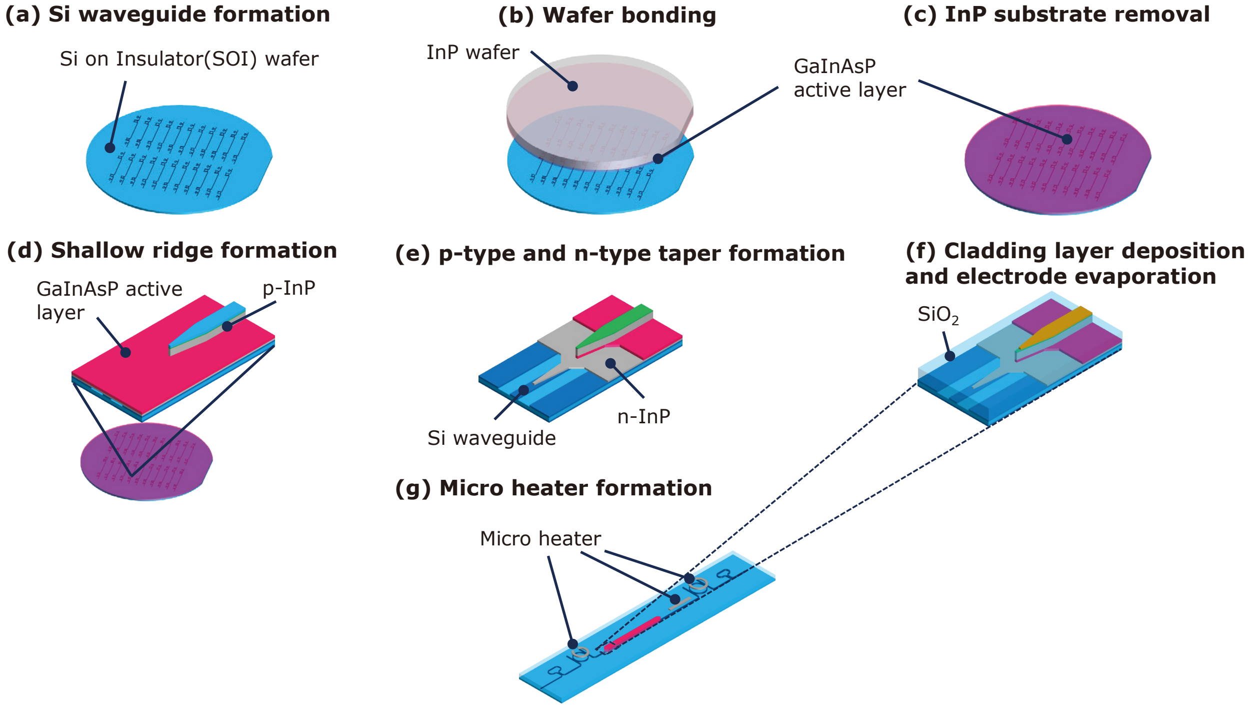

Fig. 3. Fabrication flow of InP/Si hybrid tunable laser using wafer bonding

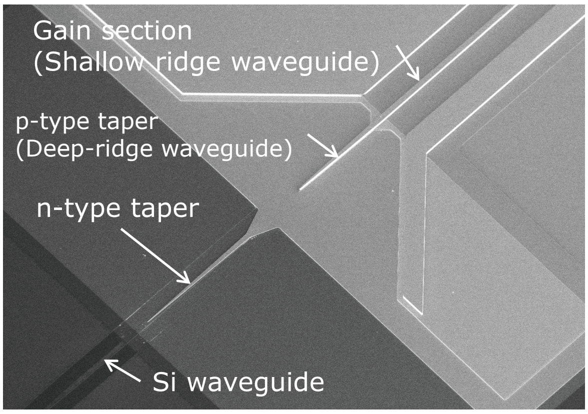

Photo 1. InP/Si optical coupling structure of a fabricated device

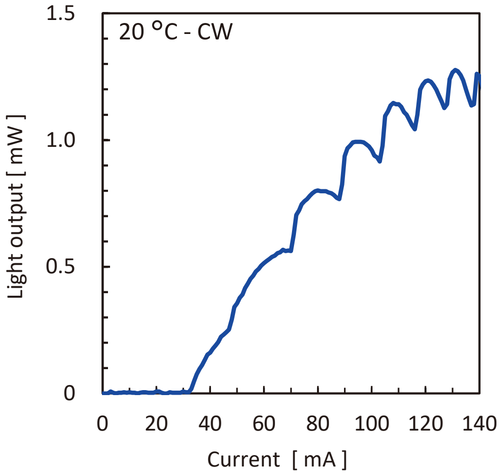

Fig. 4. Current-light output characteristic of the fabricated device

After the deposition of the SiO_2 upper cladding layer, electrodes for the gain section and microheaters for the ring resonators and phase control section are formed. Photo 1 shows a scanning electron microscope image of the optical coupling structure of the fabricated device. It is confirmed that a two-step taper waveguide structure with a two-storied ridge structure is formed on a Si waveguide.

4. Measurement Results

4-1 Characteristics of a tunable laser

For measurements, the facets of fabricated InP/Si hybrid tunable lasers were formed by dicing. The current-light output characteristics of the device with a whole resonator length of 2.5 mm and a gain section length of 1.1 mm are shown in Fig. 4. The threshold current was 32 mA and the maximum light output power was 1.3 mW under continuous-wave operation at a temperature of 20°C. Kinks appeared in the optical output characteristics due to mode hops by the phase changes with the increase of the injection current into the gain section. Such kinks are common in this type of device and do not affect the actual operation.

The wavelength tuning map against heater injection power for the two ring resonators is shown in Fig. 5 (a). By controlling heater injection powers for the two ring resonators, a wide wavelength tuning range by the Vernier effect was obtained. Operation wavelengths against the injection power to the heater for each ring resonator are shown in Fig. 5 (b). Quasi-continuous wavelength tuning can be

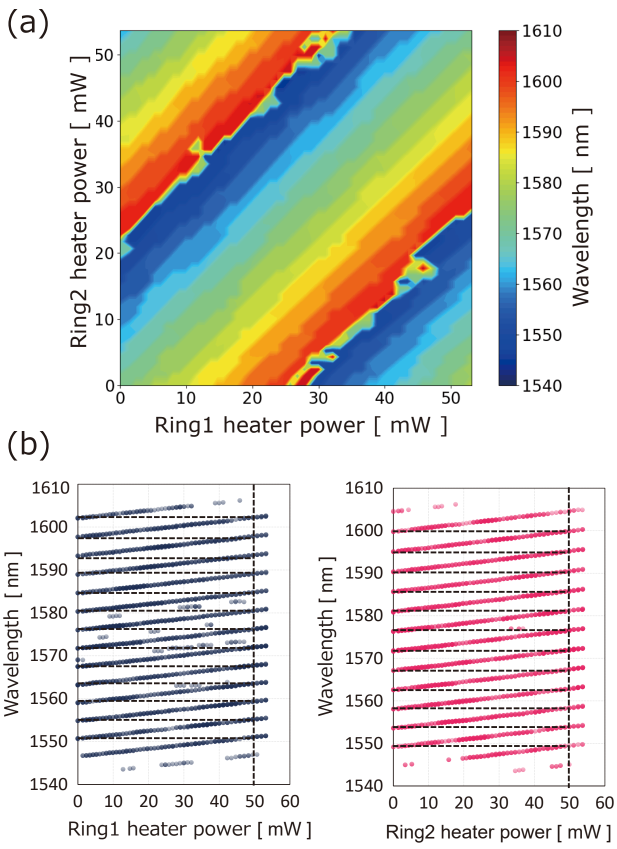

Fig. 5. (a) Wavelength tuning map against heater injection power for the two ring resonators, and (b) Operation wavelengths against heater injection power for the ring resonators

achieved at a heater injection power of 50 mW or less for each ring resonator, that is, a total injection power for wavelength tuning is less than 100 mW.

The superimposed spectra during quasi-continuous wavelength tuning operations by adjustment of injection power for each heater are shown in Fig. 6. The spectra show single-mode operations across a wide wavelength tuning range of 56.2 nm with a side-mode suppression ratio (SMSR) of more than 41 dB. The InP/Si optical coupling structure including a two-step taper waveguide structure contributes to the stable operations with small fluctuations of light output power in a wide wavelength tuning range, because this optical coupling structure has small fluctuations of optical coupling efficiency in the wavelength tuning range.

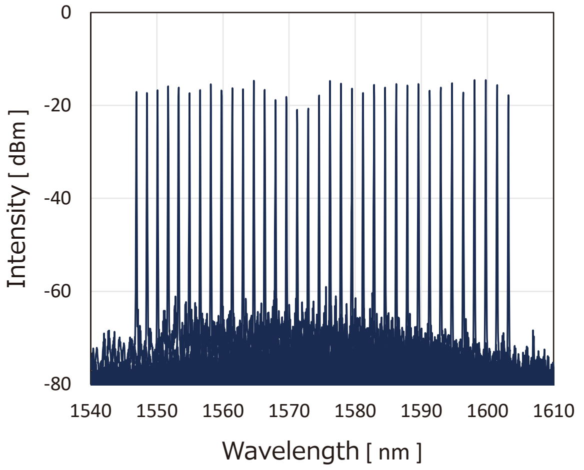

Fig. 6. Superimposed spectra of the fabricated device

4-2 Characteristics of a tunable laser integrated with an SOA

Figure 7 (a) shows the structure of an InP/Si hybrid tunable laser integrated with an SOA.*8 (12) The laser was fabricated by the method shown in Fig. 3, and the gain sections of the laser and the SOA use the same active layer structure. The output light from the tunable laser is equally split between two ports by a 3 dB optical coupler: one does not pass through the SOA to Port 1 and the other passes through the SOA to Port 2.

Figure 7 (b) shows spectra from Ports 1 and 2 at the injection current to the tunable laser of 100 mA and the injection current to the SOA of 100 mA. The spectra show single-mode operations with an SMSR of 41 dB, and the peak intensity difference of 10 dB was obtained from the light output powers of Port 1 and Port 2. These results show that the chip/wafer bonding technique is very promising for the multifunctional integration using III-V compound semiconductor elements on Si photonics.

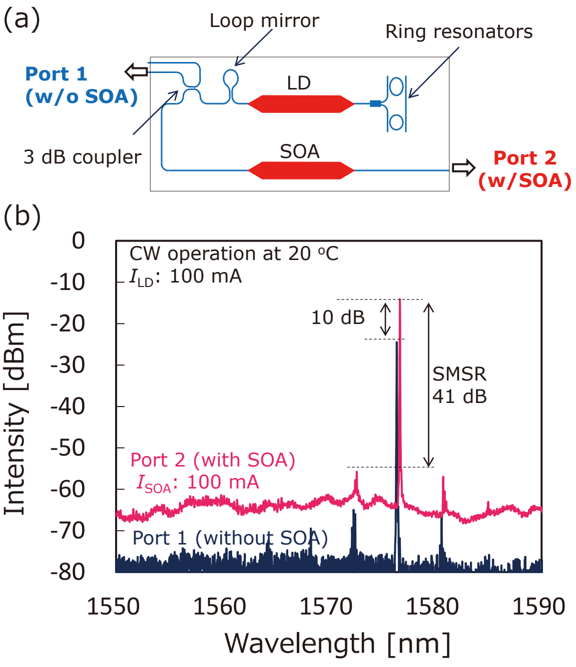

Fig. 7. (a) Schematic structure and (b) Spectrum characteristics of the InP/Si hybrid tunable laser integrated with an SOA

5. Conclusion

In this paper, we demonstrated photonic devices using heterogeneous material integration, which combines III-V compound semiconductors and Si photonics, as one of the approaches toward the compatibility of larger-capacity transmission and low power consumption. We fabricated an InP/Si hybrid tunable laser with a two-storied ridge structure using the wafer bonding technique, which has the advantages of integration density and optical coupling efficiency, and achieved a wide wavelength tuning range of 56.2 nm. This shows that the fabricated tunable laser is a promising light source for the photonic integrated circuits using Si photonics. In addition, we fabricated an InP/Si hybrid tunable laser with an SOA integrated into the same wafer and obtained an amplification of light output by the SOA. The developed technique can be used not only for optical sources but also for various functional elements, and it is expected that it will become a new photonic device technique that supports optical transmission in the future by integrating these elements on Si photonics platforms.

6. Acknowledgments

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Technical Terms

*1 IoT (Internet of Things): A system in which objects are connected to the internet to exchange information with each other.

*2 Si photonics: The application of photonics systems that integrate various photonic devices on Si substrates by using microfabrication techniques. Si waveguides have strong optical confinement properties due to the high refractive index of Si, leading to compactness, and high-density integration.

*3 III-V compound semiconductor: A semiconductor obtained by combining group III elements with group V elements. Due to its direct bandgap properties, a III-V compound semiconductor has high emission efficiency and is used as an optical source for light-emitting devices, such as lasers.

*4 Loop mirror: A reflector that is formed by using an optical waveguide loop. A loop mirror acts as a reflector in such a way that split lights at an optical coupler such as directional couplers are returned by the loop waveguide structure.

*5 Ring resonator: A device that integrates a ring-shaped optical waveguide and optical couplers, such as directional couplers. A ring resonator resonates with a mode spacing that depends on the ring's circumference.

*6 Shallow ridge waveguide: A waveguide that provides optical confinement by processing the cladding layer on the active layer, or the core layer, into a rectangular shape.

*7 Deep ridge waveguide: A waveguide that provides strong optical confinement to the core layer by processing the upper cladding layer and the active layer, or the core layer, into a rectangular shape.

*8 SOA (semiconductor optical amplifier): A semiconductor element that amplifies the input light intensity by stimulated emission.

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