InP-based Optical Devices Integrated on Silicon Photonic Circuits

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Abstract: We review our III-V/Si hybrid integration platform using chip-on-wafer direct bonding technique and the performance of hybrid lasers with InP-based gain regions on Si photonic circuits.

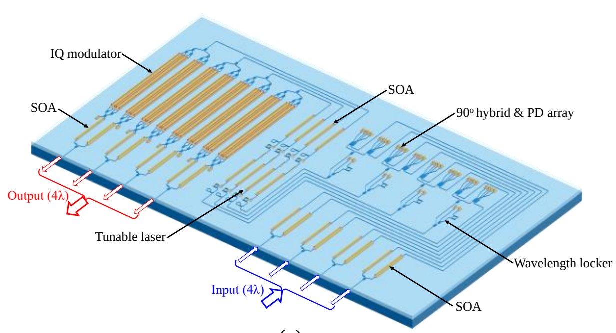
1. Introduction

Toward a smart and sustainable society enabled by diverse ICT applications using next-generation mobile systems (Beyond 5G or 6G), such as autonomous driving, augmented reality (AR), and virtual reality (VR), it is indispensable to expand the transmission capacity of optical fiber networks. Thus, the introduction of multi-tera-bit/s optical transceivers are expected in 2030 and beyond. The key device to demonstrate such transceivers is a photonic integrated circuit (PIC) with multiple channels and low power consumption. Although there have been reported high-performance PICs fabricated on single-material platforms, e.g., InP-based monolithic integration [1] and Si photonics [2], it has been considered that they have limitations in obtaining both high-speed operation and low power consumption at the same time. The III-V/Si hybrid integration which utilizes both advantages of InP and Si photonics is one of the attractive technologies to overcome the limitations, and several III-V/Si hybrid devices have indicated a synergistic effect to provide excellent characteristics compared with single-material devices [3, 4]. Consequently, the monolithically integrated array of III-V/Si hybrid devices is a promising candidate as a future PIC.

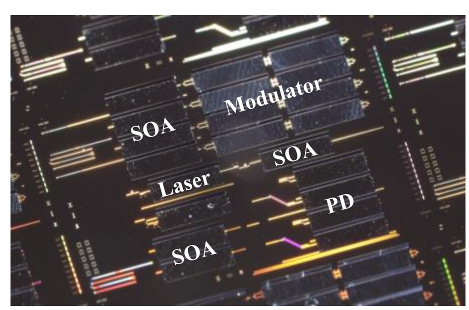
While several III-V/Si hybrid integration methods have been investigated, we have adopted a chip-on-wafer (CoW) direct bonding technique. As compared with a wafer-to-wafer bonding [5, 6], the CoW bonding is suitable for multi-functional integration on a single chip, because it offers the integration of various InP-based epitaxial layer structures at desired positions on a silicon-on-insulator (SOI) wafer. In addition, the direct bonding process contributes to the achievement of high optical coupling efficiency between InP-based active layers and Si photonic circuits. After the bonding process, InP-based structures are precisely aligned to Si waveguides by the stepper lithography to enhance the coupling efficiency [6, 7]. In this paper, we review our III-V/Si hybrid integration platform using the CoW direct bonding technique and the performance of hybrid lasers with InP-based gain regions on Si photonic circuits.

2. III-V/Si Hybrid Integration Platform

Fig. 1 (a) shows a conceptual diagram of multi-channel PIC consisting of InP-based optical device arrays on Si photonic circuits. For digital coherent transmission employing four-channel wavelength division multiplexing



(a)



(b)

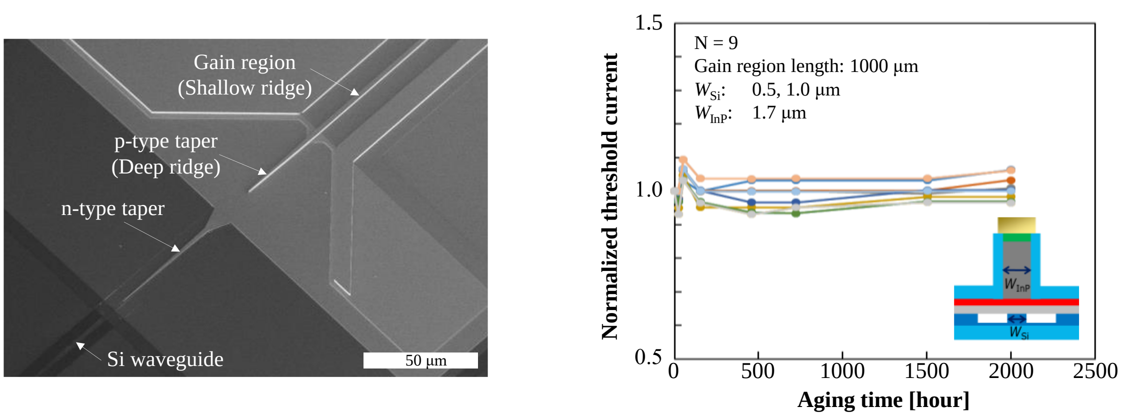
Fig. 1 (a) Conceptual diagram of multi-channel III-V/Si hybrid PIC and (b) photomicrograph for various types of InP chips bonded on Si photonic circuits.

(WDM) and dual-polarization multiplexing, the PIC includes four wavelength tunable lasers, eight In-phase and Quadrature (IQ) modulators (Mach-Zehnder modulator × 16), twenty semiconductor optical amplifiers (SOAs), eight 90° hybrids, and forty-eight p-i-n photodiodes (PDs) including sixteen monitor PDs for modulators and wavelength lockers. Each of the InP-based optical device needs to have appropriate epitaxial layer structure.

The CoW direct bonding process consists of the following four steps. First, InP chips are formed by dicing an InP wafer with epitaxial layers. Their surfaces are cleaned through mega-sonic cleaning and made hydrophilic by ultra-violet (UV)-ozone treatment. Next, they are tentatively bonded on an SOI wafer by using a pick-and-place technique. Subsequently, the SOI wafer is annealed at 150°C with mechanical pressure in a vacuum chamber to complete hydrophilic bonding procedure. Finally, the InP substrate is removed by a chemical mechanical polishing (CMP) and a wet-chemical etching, and only the III-V epitaxial layers remain on the SOI wafer. Fig. 1 (b) shows a photomicrograph for various types of InP chips bonded on Si photonics circuits. Thanks to the CoW direct boding technique, InP chips with four types of III-V epitaxial layer structures designed for lasers, modulators, SOAs, and PDs are successfully integrated at appropriate positions on Si photonic circuits. The size of the InP chip is as small as 1.6 mm × 0.5 mm. After the bonding process, InP-based optical devices are fabricated by conventional InP process including photolithography and dry etching.

One of the critical topics for the III-V/Si hybrid integration is the configuration of an optical coupling structure between InP-based active layers and Si waveguides. The optical coupling loss at the interface induces not only the increase in power consumption but the characteristics degradation of active devices. To reduce the coupling loss, we have employed the two-step taper structure including p- and n-type taper waveguides. Especially for hybrid lasers, the InP-based two-storied ridge structure has been introduced for the p-type taper as shown in Fig. 2 (a). It consists of the deep-ridge taper and shallow-ridge waveguide. These two structures allow the reduction of the optical coupling loss in InP-based active layers and the constriction of the current path, respectively [5, 6].

In order to verify the reliability of InP-based optical devices on Si photonic circuits fabricated by the CoW direct bonding technique, we conducted an aging test of hybrid lasers under an injection current of 200 mA at 85°C. During this test, the light-output characteristics were measured under continuous-wave (CW) condition at 25°C after the aging time of 0, 24, 150, 500, 750, 1,500, 2,000 hours. Fig. 2 (b) shows the normalized threshold current of lasers versus aging time. No failure or degradation is observed in all 9 devices, and the variation of threshold current is less than 10% after the 2,000-hour aging test. Consequently, it is revealed that InP-based optical devices integrated on Si photonic circuits by using the CoW direct bonding technique exhibit stable CW operation [7, 8].

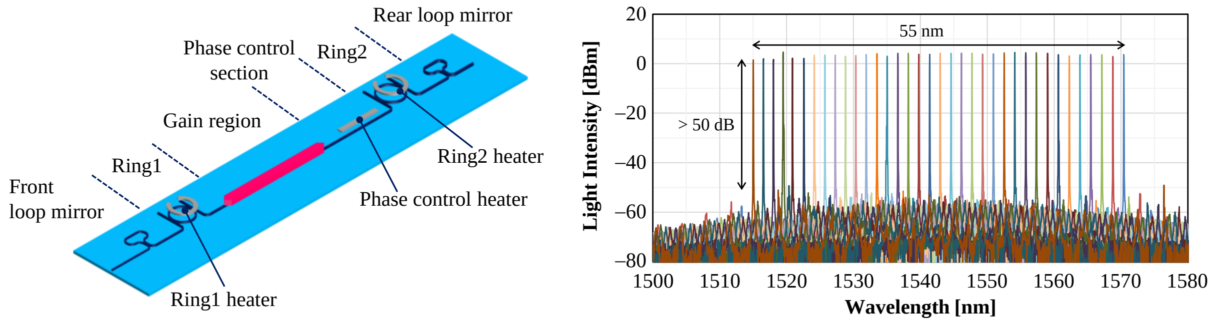


(a) (b)

Fig. 2 (a) SEM image of the optical coupling structure between III-V active layers and Si waveguides with the two-step taper structure [6] and (b) normalized threshold current versus aging time for III-V/Si hybrid lasers fabricated by the CoW direct boding technique [8].

3. Demonstration of III-V/Si Hybrid Tunable Laser

As an InP-based optical device integrated on Si photonic circuits, we have demonstrated a III-V/Si hybrid tunable laser. Fig. 3 (a) shows its schematic diagram. The length of the gain region is 1.1 mm, and the gain region is sandwiched by micro-ring resonators and loop mirrors. A phase control section is placed between the gain region and micro-ring resonator. The two micro-ring resonators have different circumference length, and the reflectivity of front and rear loop mirror is designed to be 30% and more than 90%, respectively. Three micro heaters are deployed



(a) (b)

Fig. 3 (a) Schematic structure and (b) measured superimposed spectra of III-V/Si hybrid tunable laser with double ring resonators.

on the SiO_2 upper cladding layer of the micro-ring resonators and the phase control section. By heating them, fine wavelength tuning is achievable.

To evaluate the fabricated hybrid tunable laser, the light-output characteristics were firstly measured under CW condition at 25℃. The threshold current is measured to be 39 mA. The maximum output power over 10 dBm is also obtained by the same device. Next, we investigated the wavelength tunability of the fabricated laser. Through a coarse tuning with the control of two micro-ring resonators and a fine tuning with the control of phase, the quasi-continuous wavelength tuning range as wide as 55 nm is achieved by the Vernier effect. Fig. 3 (b) shows the superimposed spectra at the laser current of 120 mA. Single-mode operation with the sub-mode suppression ratio (SMSR) of more than 50 dB for the entire tuning range is observed. Finally, we evaluated the spectral linewidth. By multiplying π in the frequency noise level at 200 MHz, the spectral linewidth is estimated to be less than 60 kHz in the entire wavelength tuning range. With these results, we have successfully demonstrated that our III-V/Si hybrid tunable laser is very promising as the light source which is capable of the monolithic integration on multi-channel III-V/Si hybrid PICs.

4. Conclusion

We have reviewed our III-V/Si hybrid integration platform and the performance of hybrid lasers with InP-based gain regions on Si photonic circuits. By adopting the CoW direct bonding technique, InP chips with several types of epitaxial layer structures are successfully integrated on Si photonic circuits. The reliability of hybrid lasers is verified through the 2,000-hour aging test. Furthermore, the fabricated hybrid tunable laser achieves the single-mode operation and narrow spectral linewidth in the entire wavelength tuning range in addition to the wavelength tuning range as wide as 55 nm. Therefore, we substantiate that our III-V/Si hybrid integration technology is very promising to realize next-generation PICs with multiple channels and low power consumption.

5. Acknowledgment

This work is based on results obtained from a project, JPNP16007, commissioned by the New Energy and Industrial Technology Development Organization (NEDO).

6. Reference

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