Heterogeneously Integrated Membrane DFB Laser and Si Mach-Zehnder Modulator on Si Photonics Platform

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Abstract *We demonstrate a heterogeneous integration of a membrane buried-heterostructure DFB laser and a Si Mach-Zehnder modulator on a Si photonics platform with a 220-nm-thick silicon-on-insulator layer. Clear eye openings at 32 Gbit/s are demonstrated up to 80°C using the device.*

Introduction

With the rapid increase in Internet traffic, there is a growing demand for high-capacity optical transmitters. To increase the data capacity, a polarization rotator/splitter/combiner and optical wavelength multiplexer are essential elements for polarization and wavelength multiplexing. A Mach-Zehnder modulator (MZM) is also an important element because it provides high throughput with advanced modulation formats. Large-scale photonic integrated circuits on a Si photonics platform have great potential for integrating these elements with low cost because mature CMOS technology can be employed for the fabrication[1].

Wafer-scale integration of lasers on a Si photonics platform is primarily important for reducing the footprint and fabrication cost of transmitters. Lasers and other active photonic devices integrated with Si photonic circuits have been developed, where a vertical *p-i-n* junction with total III-V layer thickness of ~2 μm is used[2]. These lasers are implemented on a Si waveguide to ensure a waveguide mode with optical gain, through which the waveguide evanescently couples to the III-V layer. To control the optical mode between the Si and III-V layers, their effective indices should be comparable. For this purpose, the optically coupled Si waveguide needs to be as thick as at least 400 nm.

On the other hand, in Si photonics devices, it is important to use Si waveguides with a thickness of 200–300 nm to attain a small bending radius in the single-mode condition for compactness. Indeed, many Si photonics foundries are using silicon-on-insulator (SOI) wafers with 200–300-nm-thick Si. For these reasons, there is a large mismatch in the Si layer thickness for fabricating lasers and Si photonics devices.

We have proposed a membrane buried-heterostructure (BH) with III-V layer thickness less than 350 nm as a laser[3]. Since the effective index of the III-V layer is comparable to that of a 220-nm-thick Si waveguide, the III-V layer enables us to construct an optical supermode in the Si waveguide and control the optical confinement factor in both the III-V and Si layers by changing Si waveguide width[4],[5]. Additionally, low-loss coupling between a laser and a Si waveguide can be achieved even in a short tapered waveguide[4]. Therefore, the membrane lasers are candidates for wafer-scale integration on a Si photonics platform. In the context, we have developed membrane lasers integrated with a 220-nm-thick Si waveguide[4],[5].

As the next step, it is important to investigate the feasibility of integrating membrane lasers with Si photonics devices incorporating MZMs on a Si photonics platform. Here, we demonstrate an integration of a membrane BH DFB laser and Si MZM on a Si photonics platform, where the Si layer thickness of 220 nm is widely used. The integrated device performs 32-Gbit/s modulations up to 80°C.

Device structure and fabrication

Figure 1 shows cross-sectional and top views of a device consisting of a membrane BH DFB laser and a Si MZM. The laser consists of an optically coupled III-V/Si waveguide. The III-V layer has an InGaAsP-based multiple quantum well (MQW) core buried in a membrane InP layer, and it has a lateral *p-i-n* junction. To construct a DFB laser along the 500-μm, a SiN

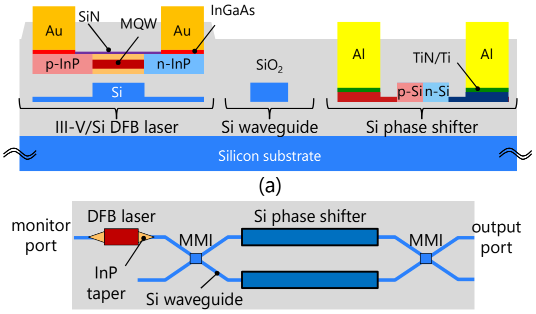

Fig. 1: (a) Cross-sectional and (b) top views of device consisting of membrane laser and Si MZM.

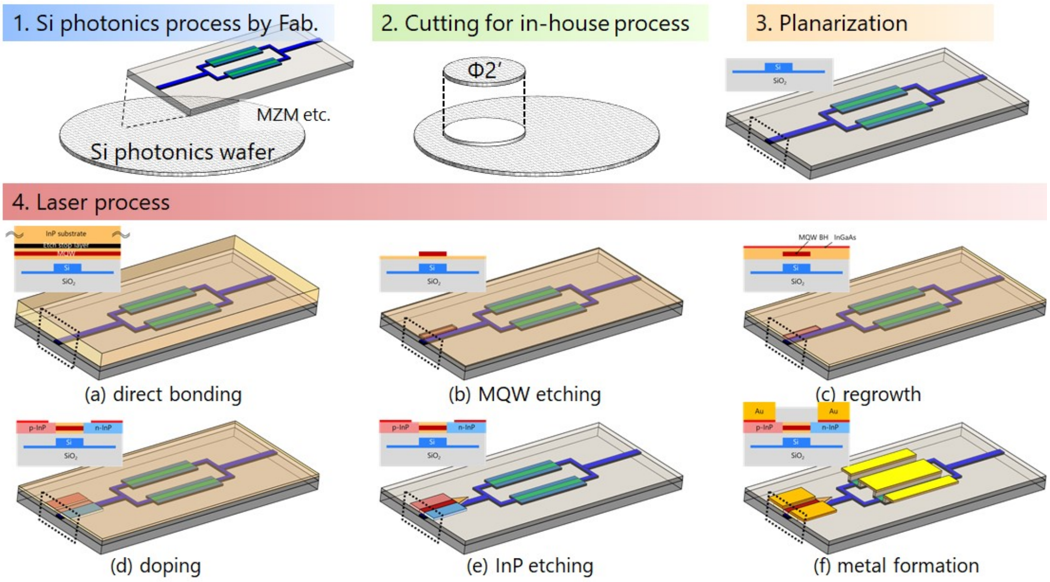

Fig. 2: Fabrication process for device consisting of membrane laser and Si MZM.

grating with a λ/4-phase shift is formed on the top surface of the III-V layer. The light emitted from the DFB laser is coupled to the Si waveguide through the 50-μm length InP inverse-taper waveguide. The Si waveguide is connected to the Si-MZM. The Si-MZM consists of multimode interferometers (MMIs) and 4-mm-long depletion-type Si phase shifters.

The device fabrication procedure is as follows (Fig. 2). The base 8-inch wafer was designed in-house and then fabricated in a Si photonics foundry. It comprises MZMs with depletion-type phase shifters, a Si wire waveguide, and other test element groups. Next, the wafer was cut into 2-inch wafers for our in-house process. For wafer bonding, the SiO_2 film on the SOI wafer was planarized by chemical mechanical polishing. After that, an InP wafer containing the InGaAsP-based six-period MQWs and an etch stop layer was directly bonded onto an SOI wafer by oxygen-plasma-assisted bonding (a). After removal of the InP substrate, the MQW layer was etched to form the 600-nm-wide core, with the very thin InP template layer remaining (b), and the InP was regrown to form the BH on the template (c). An InGaAs layer was also grown as a contact material. After that, p- and n-type InP was formed by doping (d). A SiN grating with a λ/4 phase shift was formed on the top surface of the III-V layer. Then, the entire InP layer was removed except for the laser area containing the InP taper waveguides (e). Finally, metal electrodes were fabricated (f). Note that the SOI wafer with a 220-nm-thick Si layer can be used for wafer-scale laser integration on a Si photonics platform.

Measured characteristics

First, we measured the characteristics of the integrated laser through the monitor port [Fig. 1(b)]. Figure 3(a) shows a measured optical spectrum with a bias current of 49.4 mA at a stage temperature of 25°C. The optical spectrum was measured through a lensed optical fiber. The single mode lasing at a wavelength of 1553 nm with a side-mode suppression ratio of 42 dB was obtained. Figure 3(b) shows the maximum output power and threshold current as a function of the stage temperature. The optical power was measured by a large-area photodiode placed in front of the monitor port facet. We obtained lasing in the temperature range of 25–80°C, while the maximum output power decreased and the threshold current increased with increasing stage temperature. Even at the stage temperature of 80°C, the maximum output power of 1.4 mW with a threshold current of 15 mA was obtained. It is expected that light with that power can be input to the Si waveguide connected to the MZM, because the laser has a symmetric structure along the cavity direction. Although the laser on Si substrate has relatively large thermal impedance, we achieved high-temperature operation. This is because the membrane BH laser exhibits low threshold operation due to the small active area and low heat generation at the threshold current[4],[5].

Next, we measured the output power dependence of the reverse bias voltage applied to the Si phase shifter. From this measurement, the modulation efficiency was estimated to be $V_{\pi}L$ of 2.4 Vcm, which is almost the same as normal Si MZM performance[1]. These results

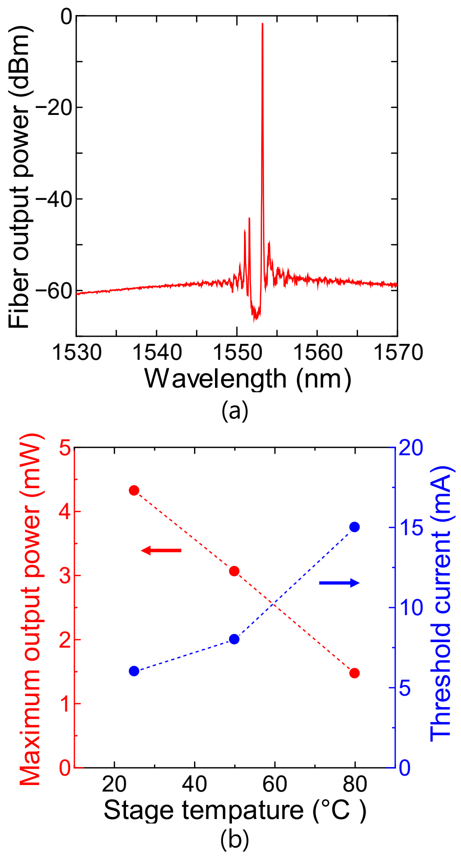

Fig. 3: (a) Lasing spectrum at injection current of 49.4 mA and stage temperature of 25°C. (b) Stage temperature dependence of output power and threshold current .

confirmed that the integrated laser and MZM can be operated on the platform. This is the first time that the BH laser has been integrated on the Si photonics platform including the MZM, by employing direct wafer bonding and regrowth techniques.

Finally, we measured the dynamic characteristics of the integrated device. Figure 4(a) shows the experimental setup. The laser was biased around 45 mA. Electrical signals were input to the one-side phase shifter from a pulse pattern generator (PPG) through a linear amplifier, in which pre-emphasis was applied to the pulse patterns. Light output from the device was coupled to the lensed optical fiber and then amplified by an erbium doped fiber amplifier (EDFA) to adjust the optical power within the detectable range. A *p-i-n* photodetector was used for signal detection. Figure 4(b)–(d) shows eye diagrams with 32-Gbit/s non-return-to-zero (NRZ) signals with a 2^{31}-1 PRBS in the temperature range of 25–80°C. Clear eye openings with extinction ratios over 5 dB were observed in the temperature range. These results were obtained owing to the superior characteristics of the integrated device—high-

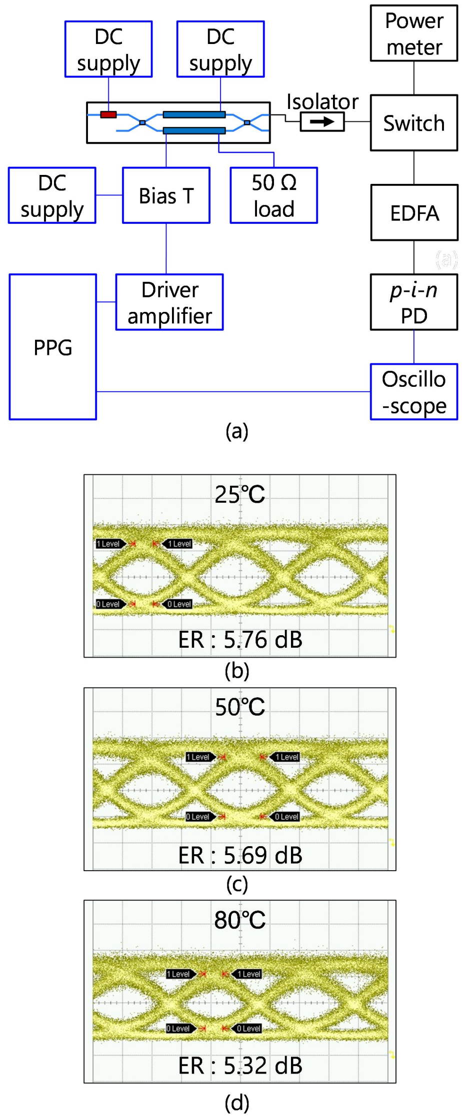

Fig. 4: (a) Experimental setup for measuring dinamic characteristics. (b)-(d) Eye diagrams for 32-Gbit/s NRZ signals in stage temperature range of 25–80°C.

temperature operation of the membrane BH laser and small temperature dependence of the Si MZM which uses just the carrier-plasma effect. The operating temperature of the integrated device indicates its applicability to semi-cooled transmitter modules for saving power consumption.

Conclusions

We have demonstrated a heterogeneous integration of a membrane BH DFB laser and Si MZM on a Si photonics platform. The integrated device was fabricated on an SOI wafer with 220-nm-thick Si layer. The integrated device performed 32-Gbit/s modulations in a temperature range of 25–80°C. These results indicate that our device has great potential as a future compact high-capacity transmitter.

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