A Thermally Tunable III–V Compound Semiconductor Microdisk Laser Integrated on Silicon-on-Insulator Circuits

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***Abstract*—A thermally tunable microdisk laser integrated on a silicon-on-insulator waveguide circuit is demonstrated. A local heater is fabricated surrounding the microdisk cavity for tuning/trimming the lasing wavelength through the thermo-optical effect. The proposed device can be easily implemented without adding extra fabrication steps. A tuning efficiency of 0.35 nm/mW is obtained. A 2-nm smooth tuning with 20-μW constant lasing power is also demonstrated.**

***Index Terms*—Heterogeneous integration, microdisk laser, silicon-on-insulator, thermo-optical tuning.**

I. Introduction

HETEROGENEOUS integration based on die-to-wafer or wafer-to-wafer bonding of III–V compound-semiconductor (CS) and silicon-on-insulator (SOI) has been demonstrated as a versatile platform for integrated active devices on a silicon chip [1]–[9]. Among them, the laser devices built are the most relevant since it is very difficult to obtain gain from monolithic crystalline silicon at communication wavelengths. Microdisk or microring lasers made of III–V CS and integrated on an SOI waveguide circuit have been demonstrated with promising performance [5]–[7]. Single-mode lasing with 120-μW output power in the SOI waveguide was achieved recently using a 7.5-μm-diameter disk [7]. This kind of compact laser may have many applications in future photonic integrated circuits, e.g., as a multiwavelength laser source [8], or an all-optical flip-flop memory element [9]. In these applications, the lasing wavelengths from multiple microdisks have to be aligned to each other or to a predefined channel grid. The wavelengths can be controlled, to some extent, by using high accuracy patterning tools, e.g., deep ultraviolet [10] or electron-beam lithography [5], [8]. However, deviations in the final lasing wavelengths of different devices are always expected. Wavelength variations of ± 0.5 nm have been observed for 7.5-μm-diameter (nominal value) microdisk lasers across the same die [8].

In this letter, we demonstrate a tunable microdisk laser built on the heterogeneous integration platform. A local heater in the form of a III–V CS ring surrounding the microdisk cavity is designed for tuning/trimming the lasing wavelength of the devices through the thermo-optical effect. The best obtained tuning efficiency is 0.35 nm/mW. A 2-nm tuning with 20-μW constant output lasing power is also demonstrated with the proposed device.

II. Device Design and Fabrication

Fig. 1(a) shows a schematic structure of the proposed tunable microdisk laser, which is composed of a III–V CS microdisk laser cavity, and a concentric ring made of the same material. The III–V CS layer, which consists of three compressively strained InAsP quantum wells for providing transverse-electric mode gain and a tunnel junction for a low-loss p-contact, is integrated on top of an SOI wire waveguide (dimension: 500 nm $\times$ 220 nm) through adhesive bonding technology using the divinylsiloxane–benzocyclobutene (DVS-BCB) polymer [3]. The heater and the laser cavity share the same bottom metal contact, but have two isolated top contacts, so that they can be driven separately. Fig. 1(b) shows a picture of the fabricated microdisk and the ring heater after the III–V CS etching. Instead of a full ring, the heater here is designed to be an arc shape, so that the heater section would not lie on top of the underlying SOI waveguide. This avoids extra losses to the light propagating in the waveguide [8]. Fig. 1(c) also shows a finished device, in which the whole structure is embedded in a DVS-BCB isolation layer and only the metal wires and vias to different contacts are visible. The SOI waveguide is terminated with grating couplers for characterization purposes [5]. We refer to [7] for further details on the epitaxial layer and the fabrication.

The gap g [see Fig. 1(b)] between the microdisk cavity and the ring heater is a critical parameter. If the gap is too wide, the tuning efficiency (defined as the ratio of the lasing wavelength shift to the amount of heating power applied on the heater) would be low due to an increased thermal resistance between the heater and the disk. On the other hand, a small gap may

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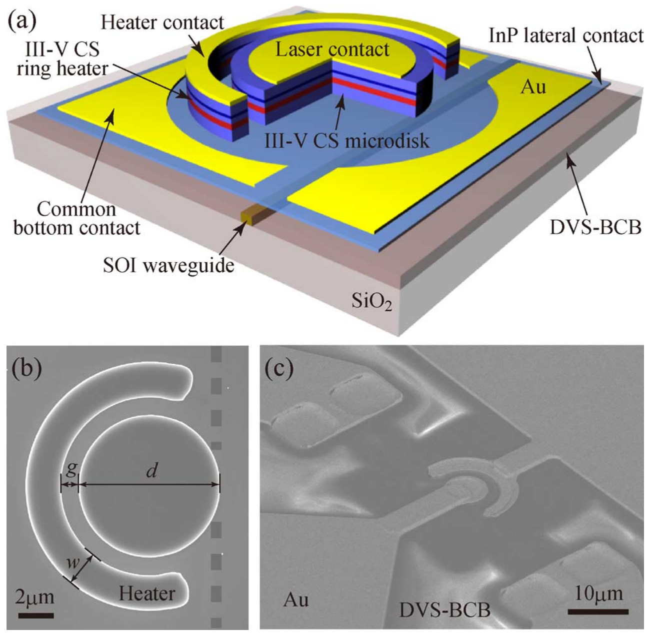

Fig. 1. (a) Schematic drawing of the proposed tunable microdisk laser integrated on an SOI waveguide. (b) Top-view of a fabricated device after the III–V CS etching. The gray dashed line indicates the SOI waveguide beneath the III–V CS layer. (c) Bird's-eye view of a finished device.

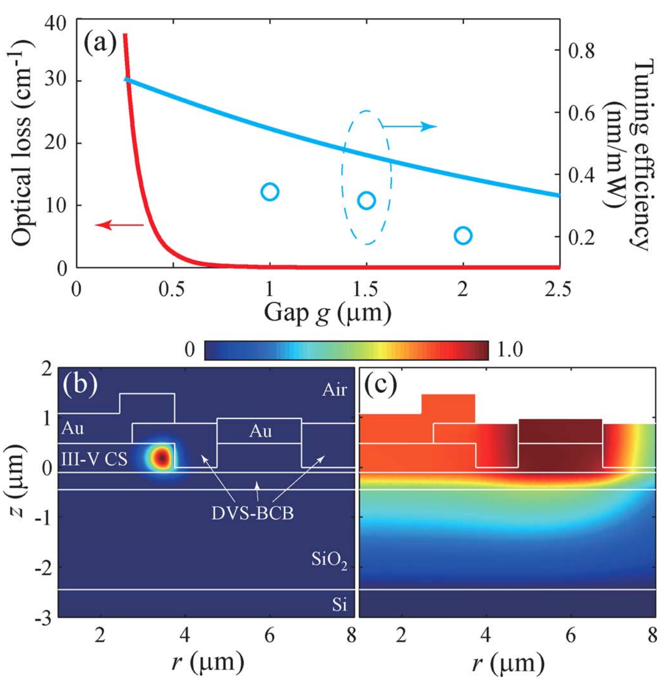

Fig. 2. (a) Simulated optical loss of the WGM and tuning efficiency with different values of g for a 7.5-μm-diameter disk cavity. Open circles are the experimental data of the tuning efficiency. (b) Optical-mode profile and (c) normalized temperature rise profile for the structure of $g = 1$ μm.

cause leakage of the laser mode, i.e., the whispering gallery mode (WGM) around the edge of the disk cavity, to the heater, and thus give rise to extra optical losses. This would decrease the laser performance, e.g., a higher threshold current. The optical and thermal properties of the proposed devices were first numerically analyzed as shown in Fig. 2. Here, the diameter d of the microdisk cavity is 7.5 μm, and the thickness of the III–V CS layer, the InP lateral contact layer, the DVS-BCB bonding layer, and the buried oxide layer is 583 nm, 100 nm, 350 nm, and 2 μm, respectively. The above figures are measured directly from the fabricated devices. The structure is considered axially symmetric for simplicity, and the underlying SOI waveguide is not included in the simulation. The width w of the ring heater is fixed at 2 μm, considering the resolution of the patterning tool used in the fabrication, i.e., ultraviolet contact lithography. The values for the thermal properties of different materials were taken from [11]. Fig. 2(a) shows the optical loss of the WGM and the tuning efficiency with different values of g. We obtain the tuning efficiency by calculating the temperature rise at the edge of the disk cavity and assuming a temperature sensitivity of the lasing wavelength of 86 pm/K [11]. Both optical loss and tuning efficiency increase as the gap g decreases. Especially, the optical losses induced by the ring heater increase dramatically when g decreases below 0.5 μm. It will dominate over other losses of the cavity, which are estimated to be about 10 cm^{-1} for a standalone disk [4]. Therefore, devices with $g = 1$, 1.5, and 2 μm were fabricated, for which the heater-induced losses are negligible. Fig. 2(b) and (c) shows the optical-mode and normalized temperature rise profiles when $g = 1$ μm. The transient behavior of the structure was also analyzed. It takes 15.9 μs for the temperature at the edge of the disk to reach 95% of the final value at steady state.

III. Measurement and Discussion

The power–current (P–I) curve of one fabricated device ($d = 7.5$ μm, $g = 1.5$ μm) was measured under continuous-wave bias and at a stage temperature of 25 °C. The result is presented in Fig. 3(a). The peak power reaches 36 μW in the waveguide. From the spectrum shown in the inset one can find that the lasing wavelength is around 1580 nm and it works in a single mode with a ∼25-dB sidemode suppression ratio, which is similar to what has been reported for standalone disks [5], [7], [8]. No unidirectional operation or switching between the lasing directions were found here due to a relatively large feedback (originated from reflections of the grating couplers) to the WGM as the coupling strength between the disk and the SOI waveguide is designed higher in this chip [9]. The clear periodic oscillation in the P–I curve is also an indication of the feedback through reflections [8]. The threshold current is 0.3 mA which is very similar to that of standalone disks in the same chip. The voltage–current (V–I) curves for driving the disk cavity and the ring heater separately are also presented in Fig. 3(a), where both of them show the typical response of a forward biased diode. The tuning of the lasing wavelength is demonstrated in Fig. 2(b) by fixing the laser driving current I_L at 1.25 mA and varying the heater driving current I_H. The laser peak shifts to longer wavelengths as I_H increases. The tuning rate is fitted to be 0.32 nm/mW, as shown in the inset. Note that the laser wavelength will also shift when varying I_L. This shift is measured to be 1.2 nm/mW. The heating power is counted as multiple of the current and voltage applied on the heater. Note that the power applied on the heater will be dissipated as both heat and spontaneous emission (no lasing is expected in the heater section due to the high optical losses introduced by the metal and the arc shaped cavity). However, the latter one is inefficient in this structure, and therefore neglected. This result, together with

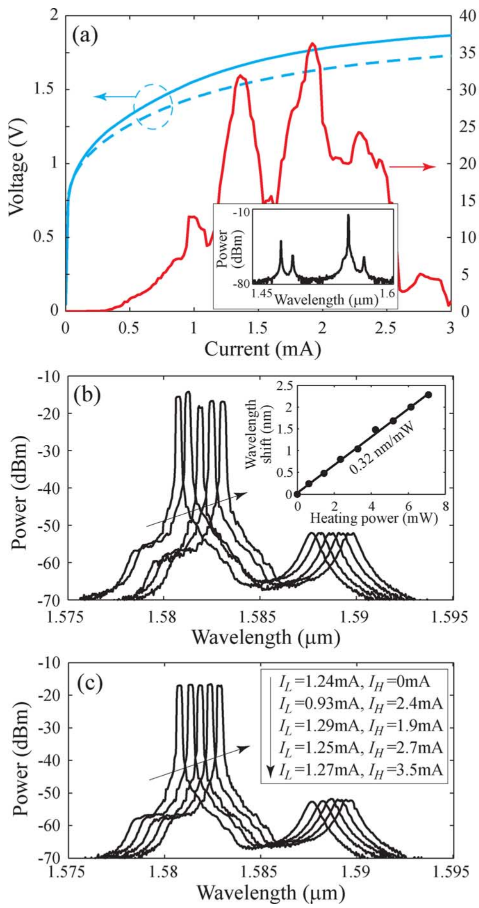

Fig. 3. (a) P–I and V–I curves (solid lines) of a laser with $d = 7.5\ \mu$m, $g = 1.5\ \mu$m, and V–I curve (dashed line) of the heater. Inset shows the laser spectrum with $I_L = 1.25$ mA, $I_H = 0$ mA. (b) Wavelength tuning by varying I_H (0–4 mA with a step of 1 mA along the arrow direction). $I_L = 1.25$ mA. Inset shows the linear fit (line) of the measured wavelength shift (dots) to the heating power. (c) Wavelength tuning with a step of 0.5 nm and with a constant power (20 μW). The driving conditions are marked in the legend along the arrow direction.

those from two other fabricated structures with $g = 1$ and 2 μm, is also plotted in Fig. 2(a). As expected, the highest tuning rate of 0.35 nm/mW is achieved when $g = 1\ \mu$m. No obvious variation of the threshold currents is observed for the three structures, meaning that the inclusion of the ring heater does not influence the lasing characteristics, as was predicted by simulations. However, as shown in Fig. 2(a), the experimental tuning rates are about 40%–50% lower than those obtained from the theoretical model. This is most likely due to the fact that an arc shaped heater is adopted in the fabrication instead of a full ring in the simulations. It is also worthwhile to note that the lasing power varies for about 3 dB (15–35 μW) during the tuning process in Fig. 3(b). The reason is two-fold. First, the wavelength change affects the phase of the feedback to the WGM, and thus the lasing power, which also causes the oscillations in the P–I curve in Fig. 3(a). Another reason lies in the degradation of the lasing performance at higher temperature. The former one can be avoided in some applications, e.g., on-chip interconnect, where no grating couplers are needed. The latter one is intrinsic, and is the limiting factor in further extending the tuning range of the device. Nevertheless, we can use the proposed structure for compensating the wavelength drift resulted from fabrication uncertainties. By fine-tuning I_L and I_H, we demonstrate in Fig. 3(c) smooth tuning over a 2-nm range with a constant lasing power. However, the power here is somewhat compromised, and limited to 20 μW.

IV. Conclusion

We have demonstrated a thermally tunable microdisk laser integrated on an SOI waveguide. The tuning of the lasing wavelength is achieved by electrically heating a III–V CS ring/arc located closely to the microdisk cavity. As compared to the common form of, e.g., a metallic thin film heater which lies on top of the disk, the proposed structure is compact and requires no additional fabrication steps. A maximal tuning efficiency of 0.35 nm/mW has been achieved. A 2-nm tuning with 20-μW constant output power has also been demonstrated. The proposed device can be used for compensating wavelength variations resulted from the fabrication.

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