Low-Footprint Optical Interconnect on an SOI Chip Through Heterogeneous Integration of InP-Based Microdisk Lasers and Microdetectors


Abstract—We present a proof-of-principle demonstration of a low-footprint optical interconnect on a silicon-on-insulator (SOI) chip. The optical link consists of a heterogeneously integrated, InP-based microdisk laser (MDL) and microdetector, coupled to a common SOI wire waveguide. Applying an electrical current to the MDL resulted in a detector current up to 1 μA.

Index Terms—Heterogeneous integration, microdisk laser (MDL), optical interconnect, silicon photonics.

I. INTRODUCTION

Silicon photonics has emerged as a potentially low-cost technology for applications such as short-range optical interconnect and optical sensing with high sensitivity. A major drawback of the silicon platform, however, is the lack of efficient, compact, and integrated light sources and detectors, due to the indirect bandgap of silicon. Heterogeneous integration with InP-based materials is a promising route to extend the reach of silicon photonics [1], [2]. In this letter, we present first results on a silicon-on-insulator (SOI)-integrated, low-footprint optical link, fabricated through direct bonding technology. We discuss the measured static link performance and give an outlook for future improvement.

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Fig. 1. Schematic diagram of a photonic link on an SOI substrate: The electrically pumped MDL (left) launches an optical signal into the Si waveguide. Light is collected by the detector structure (right).

II. DESIGN

In our optical link, transverse-electric polarized light from an electrically driven InP-based microdisk laser (MDL) is coupled evanescently into the Si waveguide in the interconnection layer. The optical power is carried by the Si waveguide (500 × 220 nm² in cross section) over the link and is coupled into a photodetector (PD) structure by means of an InP membrane coupler: A schematic drawing of the MDL-to-PD point-to-point link is shown in Fig. 1.

The MDL is built around a InAsP multiquantum-well active layer in a nonintentionally doped (n.i.d.) InGaAsP structure core, which is sandwiched by an n-type contact layer and tunnel-junction-based p-type contact [1].

The PD structure is implemented as an n.i.d. InGaAs absorption layer sandwiched between a highly p-doped InGaAs contact layer and a highly n-doped InP layer, which is also used for realizing a membrane waveguide acting as a coupling structure. The microdisk and the detector mesa footprints are 50 μm².

The laser and the detector layer stacks were chosen to reach a trade-off between the ease of integration and device performance. More details about the detector structure design can be found in [3].

III. FABRICATION

Two InP-based 2-in wafers with the MDL and the PD layer stacks were epitaxially grown by solid-source molecular-beam
Fig. 2. Laser and detector InP-based dies bonded on a 200-mm SOI wafer.

Fig. 3. Layout of the test chip, showing the position of the bonded laser and detector die, the Si photonic waveguide pattern (background) and the FGCs at the edges of the chip. Pictures of an MDL and a PD taken with an optical microscope before the chip metallization are shown in the inset (scale bar is 10 μm).

IV. MEASUREMENT RESULTS

The static performance of the integrated optical link was tested at room temperature by applying a variable current to the MDL and recording the corresponding PD current. The MDL in the link of interest was 500 nm thick and had a diameter of 7.5 μm. The dimensions of the detector were 30 × 5 μm². The length of the link was 7 mm.

In a first measurement, a pulsed current drive signal (80-ns pulses, 1-μs period) was applied to the MDL in order to avoid excessive self-heating [1], and the average detector current was recorded as function of the laser current. The PD was kept unbiased at 0 V throughout the experiment, as the detectors on this particular sample suffered from relatively large dark currents (several μA) at elevated reverse bias level, most probably due to unexpected erosion of the top p-contact layer, which occurred during the mesa wet-etching step. At the same time, the average optical power in the SOI waveguide was monitored using the FGC at the end of the SOI wire opposite to the one terminated by the detector (Fig. 3). Both curves can be found in Fig. 4(a). The threshold of the laser is reached at an average laser current of 55 μA, or equivalently, a peak laser current of
700 µA, as apparent from the kink in both curves. The waveguide-coupled laser slope efficiency, evaluated just before the FGC, is about 1.8 µW/mA, accounting for an FGC efficiency of 25%. The measured average detector current varies almost linearly with the measured optical power, especially for average laser currents below 200 µA. We can estimate the PD responsivity to be 0.33±0.04 A/W, if we assume that the MDL emits equal amounts of power in both directions of the SOI waveguide and that the propagation losses for both the MDL-FGC and MDL-PD light paths are equal. This responsivity agrees reasonably well with the 0.45 A/W reported in [3]. At the maximum average (peak) laser current of 545 µA (6.8 mA), the recorded average (peak) detector current is as high as 140 nA (1.75 µA).

In a second measurement, the MDL was driven in continuous-wave regime [see Fig. 4(b)]. The lasing threshold is about 600 µA and the slope efficiency just above threshold is 1.6 µW/mA. For drive currents below 1.5 mA, the measured detector current shows a clear correlation with the monitor laser power, with an estimated detector responsivity of 0.35 ± 0.07 A/W, which is consistent with the pulsed experiment. For laser currents above 1.5 mA, the dominant lasing wavelength red-shifts to a lower order whispering-gallery mode at 1625 nm due to self heating, as is shown in Fig. 5. For these higher drive currents, the optical power detected through the monitor FGC was found to fluctuate strongly with drive current. Fig. 4(b) shows the envelope of the recorded values as well as the averaged value. The self heating is also obvious from the thermal rollover of the average light output–current (L–I) curve. The detector current was also found to vary drastically with changing laser drive current. Furthermore, it was found that a drop in laser power at the monitor grating coupler coincides with a peak in detector current and vice versa. Therefore, the laser clearly has a preferential emission direction, which changes with drive current. This is a result of mode competition between the clockwise and counterclockwise laser modes. This mode competition is strongly affected by reflection feedback caused by the FGC, which is stronger at 1625 nm (−10 dB) than at 1590 nm (−15 dB) [5]. Since the phase of this feedback is highly sensitive to the emission wavelength, the preferential output direction can vary abruptly with drive current as the temperature and emission wavelength of the laser cavity drift due to self heating. We speculate that this effect also affects the dominant output direction at high drive currents in the pulsed experiment, causing the laser to emit slightly more power toward the FGC. It is clear that further measures need to be taken to control the directionality of the MDL output, for instance by adding a reflective reflector in the SOI waveguide.

V. DISCUSSION AND CONCLUSION

The current-to-current differential efficiency of the present link is fairly poor at about 0.27 µA/mA (0.027%). The biggest opportunity for improving efficiency is in enhancing the differential efficiency of the MDL. We already have experimentally demonstrated efficiencies as high as 30 µW/mA [1], and a theoretical study shows that slope efficiencies as high as 260 µW/mA are feasible [7]. By optimizing the detector design, we believe its responsivity could be increased to 1 A/W. Therefore, a differential link efficiency as high as 10% seems within reach. The maximum direct modulation bandwidth of the MDL was experimentally assessed elsewhere to be about 5 Gb/s [8]. A fully optimized disk laser is expected to support data rates well above 10 Gb/s. The frequency response of the detector was measured to be rather flat up to 20 GHz [3]. Calculations lead to an expected bandwidth of around 30 GHz.

In conclusion, we have presented a proof-of-principle demonstration of a low-footprint optical interconnect on an SOI chip, fabricated through heterogeneous integration of InP-based MDLs and microdetectors. While the demonstrated (static) link efficiency is rather low (0.027%), optimizing the individual components is expected to yield link efficiencies up to 10%, and a data rate of 10 Gb/s and above.

REFERENCES