CW operation of III-V microdisk lasers on SOI fabricated in a 200 mm CMOS pilot line

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***Abstract*—Compact InP-based microdisk lasers on SOI completely fabricated in a 200 mm CMOS pilot line are presented. Continuous wave operation is demonstrated with threshold currents of 600 µA and 31 µW output power.**

***Keywords*—optical interconnect; silicon-on-insulator; heterogeneous integration; microdisk laser**

I. Introduction

It has become a wide believe that electrical interconnects will form a major bottleneck in information processing systems as a result of the ever increasing data rates and the bandwidth-length limitation associated with electrical interconnects. Optical interconnects have been proposed to overcome this bottleneck, as they do not suffer from this limitation [1]. Silicon-on-insulator (SOI) based photonics is considered as a promising platform for optical interconnects because of the possibility to realize complex and compact optical networks and the CMOS compatible fabrication process. However, realizing (compact) optical sources in silicon is not trivial. An interesting solution for a compact optical source is an InP-based microdisk laser heterogeneously integrated with SOI [2]. Through the heterogeneous integration process the advantages of III-V and silicon are combined. Moreover, the microdisk laser has small dimensions and low power consumption, which is an important requirement for optical interconnects.

In this paper, we present the realisation of compact InP-based microdisk lasers heterogeneously integrated with SOI which are completely processed in a 200 mm CMOS pilot line. We will first briefly discuss the design of the microdisk laser and the fabrication process. Then, we will present experimental results of both pulsed and continuous wave (CW) operation of these compact microdisk lasers.

II. Design and Technology

A. Microdisk laser design

A microdisk cavity supports so-called whispering gallery modes (WGM), which propagate at the periphery of the disk. The modes which are 0^{th} order in radial and vertical direction and order M in azimuthal direction are preferred because they have the highest Q factor. The modes can propagate both in clockwise (CW) and counterclockwise (CCW) direction and are degenerate in the ideal case. The design of the microdisk laser is shown in Fig. 1(a). A 580 nm thin epitaxial structure which contains 3 compressively strained InAsP quantum wells (QWs) is used as laser material. The area around the disk is not completely etched such that a 100 nm thin layer remains, which serves as the bottom contact. The QWs are sandwiched between an n-doped layer at the bottom and a p-doped layer at the top to form the PIN diode structure. To avoid severe optical absorption a tunnel junction is used at the p-side such that an n-type contact layer can be used instead of a highly absorbing p-layer. The top contact for the laser can be conveniently placed in the middle of the disk as the WGM propagates at the disk periphery. The size of this top contact is critical however, because it needs to be large enough to suppress higher order radial modes, while it will absorb light of the desired 0^{th} order radial mode if it is too large. The light generated in the disk cavity is coupled to an underlying silicon waveguide by means of evanescent coupling. The diameter of the disks varies from 6 to 40 µm in diameter. A more detailed description of the design can be found in [2].

(a)

(b)

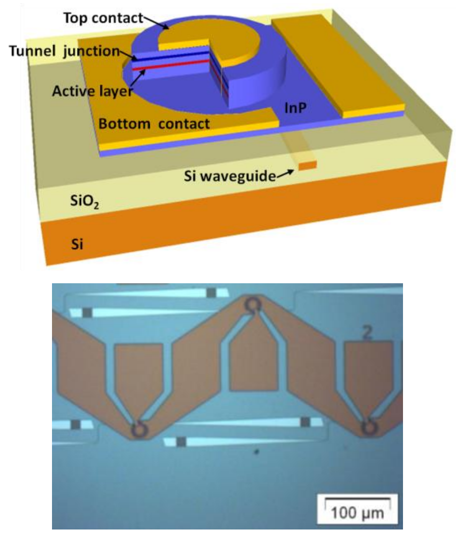

Figure 1. (a) schematic overview of the microdisk laser and (b) top view picture of the fabricated devices.

B. *Fabrication process*

To achieve heterogeneous integration of III-V material with SOI, unprocessed III-V dies or wafers, which are coated with a thin layer of SiO_2, are bonded top side down on a patterned SOI wafer by means of molecular bonding [3]. The patterned SOI wafer is planarized by depositing SiO_2 followed by chemical-mechanical polishing (CMP). After the bonding process the InP substrate and sacrificial layers are removed by chemical grinding and wet etching, so that only the desired epitaxial structure remains. The standard III-V processing steps are modified to comply with a 200 mm wafer scale CMOS environment. 248 nm DUV lithography is used to define the structures and all dry etching, oxide isolation layer deposition and metallization steps are performed at wafer scale. The standard Ti/Pt/Au contacts used in previous designs cannot be used as gold is not allowed in a CMOS environment. Therefore a CMOS compatible Ti/TiN/AlCu metal stack is full sheet deposited [4]. After the lithography step, the metal stack is dry etched with a chlorine based solution. No annealing is performed on the wafers. The specific contact resistance is around $3\times10^{-5}\Omega\cdot cm^2$ for $5\times10^{18}cm^{-3}$ n-InP. A picture of the fabricated devices is shown in Fig 1(b).

III. EXPERIMENTAL RESULTS AND DISCUSSION

Several different wafers were processed, each with a different bonding layer thickness as this is a very important parameter for the coupling from disk to waveguide. The results discussed here are for a bonding layer thickness of ~130nm. Other critical parameters, such as lateral waveguide offset, waveguide width and top contact size were varied through a sweep in the design. Fiber couplers (FCs) are used to couple the generated light from the waveguide to an optical fiber. The FC efficiency had a maximum value of 27% at 1580 nm. The optical power and spectra were recorded with a HP 81532A power sensor and a Yokogawa AQ6375 optical spectrum analyzer, respectively. The microdisk lasers were electrically pumped by an ILX Lightwave LDP-3811 for pulsed mode operation or a Keithley 2400 for CW operation. The measurements were performed at room temperature and at elevated temperatures. The results discussed in this paper are for microdisk lasers with a diameter of 7 µm.

During the first initial measurements it was observed that a burn-in treatment improved the performance of the microdisk lasers considerably. The burn-in treatment was executed by pumping the device at a high current (10 mA) for several minutes. The IV curves were recorded at different time instances and are shown in Fig. 2. The dash-dotted black curve is recorded immediately without burn-in treatment, the red dashed line is recorded after 5 minutes and the solid blue line after 10 min. Clearly, the shape of the IV curves changes significantly during the burn-in treatment. It appears that the contact was slightly rectifying as deposited and became ohmic after the burn-in treatment. Furthermore, it was observed that the maximum optical output increased by a factor of 5 and the threshold current decreased by a factor of 2. This indicates that an annealing procedure is actually required for this metal stack.

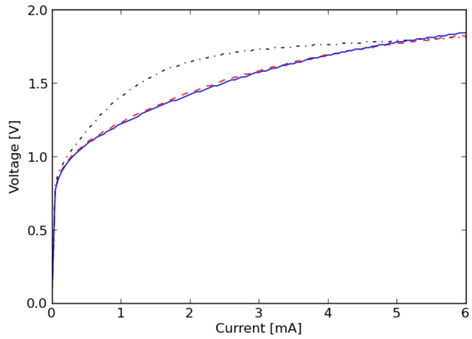

Figure 2. IV curve for different burn in treatments. Black dash-dotted line no burn-in, red dashed line after 5 min. of burn-in and blue solid line after 10 min. burn-in.

To avoid self heating effects the LI curves of the microdisk lasers were first measured in pulsed mode. The result obtained for a pulsewidth of 100 ns and a duty cycle of 2% is shown in Fig. 3. The black line corresponds with the optical output from the clockwise mode (left FC) and the red dashed line with the output from the counterclockwise mode (right FC). It can be seen that the output is unidirectional for this laser as only the clock wise mode shows lasing behaviour. Because the curve is unidirectional directly above the threshold current we believe this is caused by a stronger external reflection from one side than from the other, rather than being caused by intrinsic bistable behaviour [5]. A threshold current of 600 µA and, after correction for the duty cycle, a peak optical power of 15.5 µW were measured in the fiber at an 8 mA drive pulse.

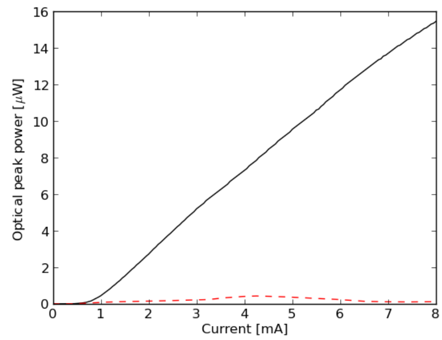

Figure 3. LI curve in pulsed mode that shows unidirectional operation. Black solid line represents the left output and the red dashed line the right output of the microdisk laser.

Fig. 4(a) shows the LI curve measured at both the left FC (black solid line) and right FC (red dashed line) under CW operation. The maximum output power in one direction is 6.25 µW measured in the fiber for a drive current of 4 mA. If the drive current is increased further, thermal roll-over is observed. It can be seen that the outputs of both sides have a complementary nature. The large oscillations in the LI curve between the clockwise and counterclockwise mode are most likely caused by reflections which originate from the fiber couplers. When the drive current is increased, the cavity temperature will increase which results in a wavelength shift. The output light of the laser is reflected back at the FC and constructive and destructive interference is observed due to this wavelength shift. From the figure it can also be observed that there is a jump in output power at a drive current of around 3.7 mA, which is also an indirect result of self heating. As the temperature in the cavity increases and the gain spectrum shifts towards longer wavelengths, mode hopping will occur. This is shown in the spectrum plot in Fig. 4(b,c). The laser first lases at a wavelength of 1535 nm, but when the drive current is increased it hops to the next azimuthal mode at a wavelength of 1565 nm. The FC efficiency was 10% around 1535 nm and 20% around 1565 nm. As the FC efficiency is higher in the latter case, it results in higher power in the fiber. The maximum output power of 6.25 µW in the fiber thus corresponds with 31 µW in the silicon waveguide. The side mode suppression ratio is >25 dB at lower drive currents and >21 dB at drive currents above 3.7 mA.

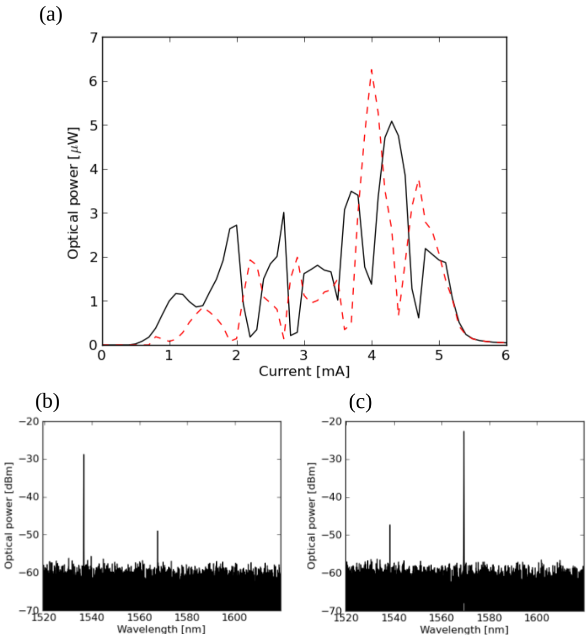

Figure 4. (a) LI curve of both the left (black solid line) and right (red dashed line) output of the microdisk laser (b) spectrum at a drive current of 2.9 mA and (c) spectrum at a drive current of 4 mA

To investigate the relation between cavity temperature and external reflections further, we studied the performance penalty under elevated temperatures. The sample was heated by means of a Peltier element, while keeping pulsed drive conditions to suppress self heating. The temperature was increased from 25 degrees to 70 degrees Celsius. The LI curves for the different ambient temperatures are displayed in Fig. 5. As expected, the threshold current increases gradually with increasing temperatures Fig. 5 (inset) and the slope efficiency drops. At elevated temperatures the LI curve remains smooth and unidirectional under pulsed driving conditions in contrast to the case where CW drive conditions were applied. This implies that the oscillations in the LI curve are a consequence of the gradual increase in temperature rather than the actual temperature in the cavity. Therefore, in future devices special attention should be paid to reduce the reflections from fiber grating couplers and improved heat sinking of the microdisk laser.

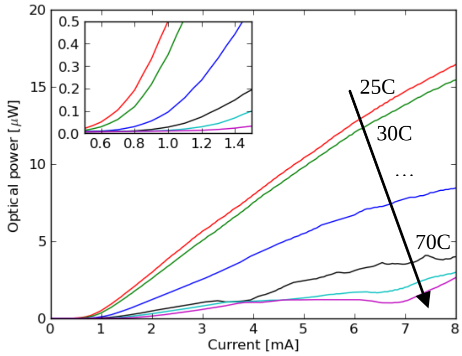

Figure 5. LI curve under pulsed operation at elevated temperatures. The slope efficiency decreases and the threshold current (inset) increases at higher temperatures. The output remains unidirectional.

IV. Conclusion

We have demonstrated continuous wave operation of compact microdisk lasers completely fabricated in a 200 mm CMOS pilot line. Threshold currents of 600 µA and 31 µW output power were measured. Furthermore, we have shown that the oscillations in the LI curve under CW operation are caused by a gradual increase of the cavity temperature in combination with external reflections. The performance of these lasers can thus be improved further by reducing external reflections and better thermal sinking of the laser.

Acknowledgment

This work is supported by the European FP7 ICT WADIMOS project. The work of T. Spuesens is supported by the Institute for the Promotion of Innovation through Science and Technology (IWT) under a specialization grant.

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