ECIO'05: 12th EUROPEAN CONFERENCE ON INTEGRATED OPTICS
- ABSTRACT -

HETEROGENEOUS INTEGRATION OF MICRODISK LASERS WITH SILICON WIRE WAVEGUIDES FOR OPTICAL INTERCONNECTS

[1] Haroldo T. Hattori, Edouard Touraille, Christian Seassal, Pedro Rojo Romeo, Xavier Letartre, Pierre Viktorovitch and Guy Hollinger

[2] Michel Heitzmann, Laurent Mollard, Eric Jalaguier, Lea DiCioccio and Jean-Marc Fedeli

[1]LEOM, UMR CNRS 5512, 36, avenue Guy de Collongue 69131 Ecully Cedex, France
Christian.Seassal@ec-lyon.fr

[2] CEA-DRT/LETI, 17, rue des Martyrs, 38054 Grenoble cedex 9, France
FedeliJM@chartreuse.cea.fr

SUMMARY

In this work, we describe the heterogeneous integration process and demonstrate the optical coupling between an InP-based silicon micro-laser and a silicon wire waveguide.

KEYWORD

III-V compounds, silicon, microlaser, waveguide, optical interconnects

ABSTRACT

We propose an optical link for intra-chip optical interconnects that includes III-V compound based laser sources and photodetectors, and Silicon on insulator based strip waveguides. The heterogeneous integration of an InP-based microdisk laser with a silicon waveguide using SiO_2/SiO_2 molecular bonding and nanofabrication procedures is emphasized. The technological procedure is described and first experimental results show that around 50% of light could be coupled from the optically pumped micro-laser to the waveguide, via vertical evanescent coupling.

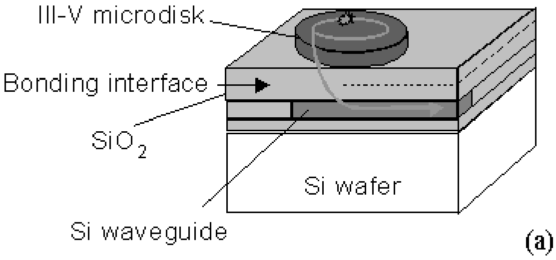
I. INTRODUCTION

The increase of the integration density in the field of microelectronics will lead to a technological bottleneck with respect to interconnects. More precisely, the use of traditional metallic connections will yield a dramatic increase in power consumption as well a lack of synchronism, particularly for the longest links positioned on top of the circuits [1]. An optical link that includes a laser source, an optical waveguide and a photodetector, could be the basis for future optical interconnects. Indeed, such a link could be integrated with microelectronic circuits and offer an appealing alternative to metallic interconnects.

These links should exhibit properties such as low power consumption and small footprint. Silicon on insulator (SOI) wafers offer a way to build passive dense micro-photonic circuits based on high refractive index silicon waveguides. They could be integrated on top of a microelectronic circuit; this is typically an “above IC” approach. In order to couple light into such a passive photonic circuit, a hybrid approach is generally employed, which consists of standard laser sources aligned with the waveguides' input. This implies sophisticated designs of tapers and couplers. A more upstream proposal consists in generating light in the silicon itself. Our approach here relies on a light source integrated above the optical layer, and made of a high optical gain III-V semiconductor heterostructure bonded onto the silicon waveguides circuit. Then, among many alternatives, the most promising solutions would be to use low threshold laser sources based on microdisks or photonic crystal micro-resonators.

Our long-term goal is to realise an optical layer on top of a silicon integrated circuit, to replace the longest metallic wire links. Such a layer consists of silicon waveguides connected to a laser and a photodetector. This paper is focused on the integration of micro-lasers and passive waveguides. Key points are the ability to fabricate a laser on top of a silicon wafer including waveguides, and the optimisation of light injection from the laser to the waveguide. Therefore, in our approach, the technology used to perform heterogeneous integration of III-V semiconductors and silicon is of prime importance, and topological parameters must be well controlled.

In previous papers, we demonstrated that microdisks [2] or photonic crystals [3] could be used so as to realise microlasers, bonded onto a silicon wafer. In this letter, we demonstrate efficient evanescent coupling between an InP-based optically pumped microdisk laser, emitting at 1.5 µm, and a photonic waveguide of sub-micronic section, as schematised in figure 1a. Coupling a microdisk mode to a waveguide is a tricky problem since the emission of radiated light is little directive. One solution is to couple the evanescent field from the microdisk to the underlying waveguide. Choi et al. [4] proposed a technological scheme to integrate such elements, all made of III-V compounds. We report here the achievement of a microdisk laser source integrated on a silicon photonic circuit. Apart from the advantage of giving access to materials well suited to required functions, this last heterogeneous approach benefits from high index contrast confinement in the vertical direction.



(a)

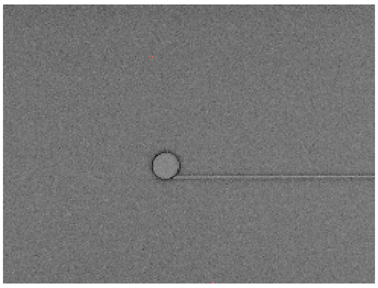

(b)

Fig. 1 : Schematic description of the micro-laser coupled to a silicon strip waveguide (a) and top view of the fabricated device (b).

II. DEVICES DESIGN AND FABRICATION

The passive photonic circuit, fabricated in a 200mm SOI wafer, includes a 320 nm thick silicon layer on top of a 1µm thick buried oxide layer, in order to prevent guided mode leakage to the substrate. Using this wafer, 0.3 to 1µm wide silicon strip waveguides were fabricated. For this study, electron beam lithography, hard mask, and reactive ion etching with HBr/Cl were used. Then, the passive photonic circuit is embedded in silica and planarised by CMP so as to obtain the proper thickness of silica upon the guides. The active heterostructure has been grown by molecular beam epitaxy (MBE) on a 50mm InP wafer supplied by INPACT. This epilayer contains four InAsP quantum wells at mid-thickness of a $\lambda/2n$ InP layer and an InGaAs etch-stop layer. The quantum wells are designed to emit at 1.5 µm. A 10nm thin Electron Cyclotron Resonance silica layer is then deposited on top of the active layer and the III-V wafer is molecular bonded at the centre of the silicon wafer containing the photonic circuits. The final silica thickness between the passive silicon waveguides and the active layer is a key parameter, since it controls the coupling coefficient between the laser mode and the guided mode. Decreasing the SiO_2 thickness makes coupling more efficient but reduces the Q of the lasing mode, which yields a higher laser threshold. On the basis of simple prediction by the coupled mode theory, we predicted that with a SiO_2 thickness in the 200-600 nm range, it is possible to maintain Q around 10000 for the microdisk whispering gallery modes.

After bonding, the InP wafer is chemically etched from the backside in HCl solution until the InGaAs etch-stop layer is reached, then this layer is removed in a $FeCl_3$ solution. Electron beam lithography is used to pattern 5 µm in diameter microdisks with an accuracy for the alignment better than ± 200nm. With this disk size, the number of whispering gallery modes is small enough to avoid intermode competition. Finally, the III-V microdisks are produced by reactive ion etching, using a CH_4:H_2 plasma. Fig 1b represents a top view of a final device.

III. RESULTS AND DISCUSSION

The devices are characterised using a two axis optical bench. One axis is dedicated to excitation and measurement of the radiated light, the second axis enables the collection and measurement of the guided light. Spectral analyses are performed with a 25 pm resolution spectrometer. On the first axis, the pumping light at 780nm is focused onto the sample using a ×10 IR microscope objective lens. The radiated light, generated around 1.5µm, is collected and analysed by the spectrometer. The guided light is collected by a ×20 IR microscope objective lens, the signal coming from the cleaved facet of the sample is partially analysed by the spectrometer, and partially used to display an IR image.

A first analysis of radiated light from a coupled microdisk shows that laser emission is maintained although light coupling to a waveguide induces additional losses. The spectral analysis of the guided light (figure 2c) reveals the same spectrum features as the radiated light (figure 2a), in terms of wavelength and linewidth. Hence, we can assert that the laser light emitted by the microdisk is transmitted and guided in the photonic circuit. The IR image and the light spectrum of the guided mode measured at the output of the waveguide, at the cleaved facet, are displayed in figure 2b.

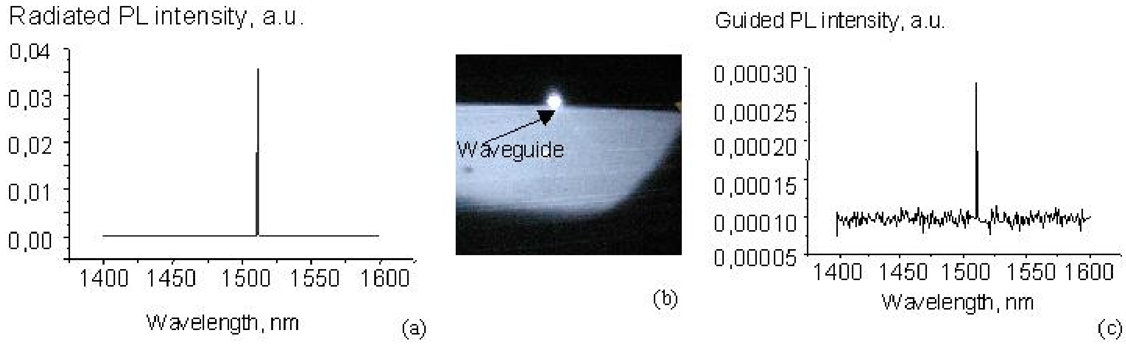


Fig 2 : Spectrum of the radiated light from the microdisk (a), IR image of the cleaved facet (b), and spectrum of the guided light, collected at the cleaved facet (c)

We consider microdisks with a diameter of 5 µm. Below these microdisks there were either no waveguides (for reference purposes) or waveguides with widths between 300 nm and 600 nm. The thickness of the silica layer between the waveguides and microdisks was about 270 nm. The measurements were made for structures in which the waveguides were bi-lateral and the microdisk was located at the edge and on top of the waveguide. This is illustrated in Fig 3. The idea behind the positioning of the waveguide at the edge of the waveguide was to easily couple the whispering gallery mode of the microdisk into the waveguide by evanescent coupling. There were also other configurations like the one illustrated in Fig. 1(b), that have not been characterized yet.

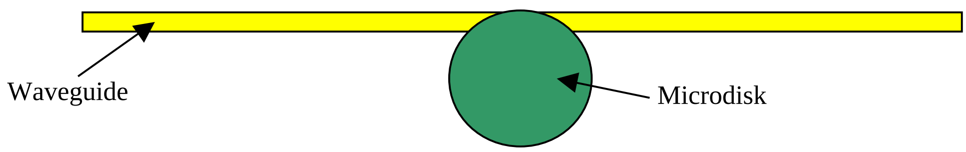


Fig 3: Structure under analysis

Initially, quality factors for these microdisks (without the waveguide) were measured for reference purposes. Unless otherwise stated, these quality factors were measured close to the threshold of the device under test. An average Q of 14000 was found for these microdisks in the absence of waveguides. The emission wavelength was situated around 1515 nm, while the threshold power was about 2 mW.

When waveguides are present, the quality factor of the structure is observed to drop. Based upon the drop of this quality factor, it is possible to estimate the coupling efficiency of light into the waveguide. If we assume that for the microdisk alone the quality factor is Q_o, which is reduced when the waveguide is present to Q_t, with

$$1/Q_t = 1/Q_o + 1/Q_c \quad (1)$$

where Q_c corresponds to the additional coupling losses. Then, the minimum coupling efficiency (h_c) is given by

$$h_c = \frac{1/Q_c}{1/Q_o + 1/Q_c} \quad (2)$$

Indeed, the real efficiency is larger because the gain material in the microdisk laser "partially" compensates for the extra losses induced by the coupling to the waveguide.

When 300 nm wide waveguides were present, the Q dropped to an average value of 10000, without significant change of the emission wavelength. If we consider that this reduction is mainly due to the coupling of light into the waveguide, we can estimate that the coupling efficiency is greater than 30% in this case. The corresponding threshold power was about 2.2 mW. A typical steady-state response of this microdisk laser coupled to a 300 nm waveguide is shown in Fig.4.

When 600 nm wide bottom waveguides were present, the Q dropped to an average value of 9000, also without significant change of the emission wavelength. In this case, the coupling efficiency is superior to 36% in this case and the threshold power is about 2.4 mW.

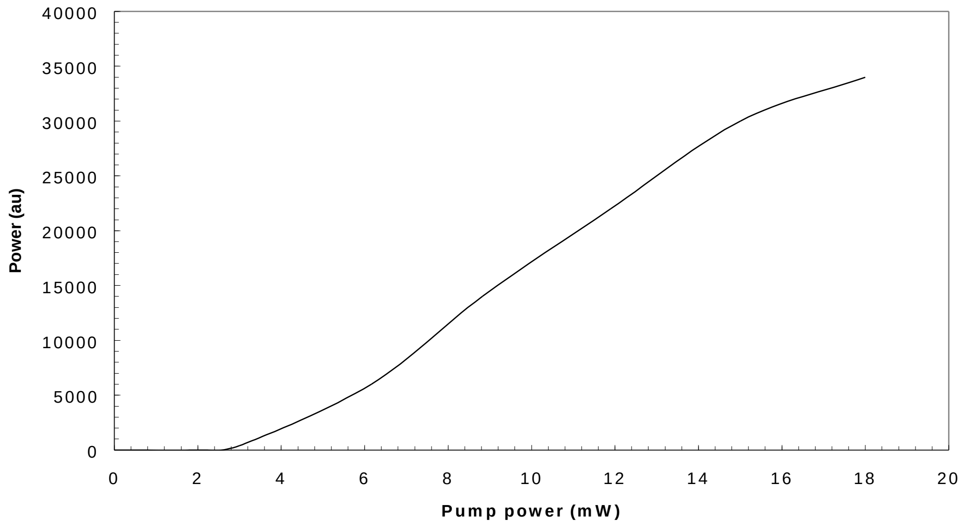


Fig. 4 Radiated power as a function of the optical pumping power for a microdisk laser of 5 µm of diameter coupled to a 300 nm wide waveguide.

V. CONCLUSION

In brief, we have described the fabrication process of the microdisk lasers based on III-V materials and coupled to silicon waveguides. The coupling efficiencies were higher than 30% and this coupling of light into waveguides did not result in significant degradation of the performance of the microdisk laser. Therefore, we believe that the combination of source and waveguide presented here will find applications in the field of optical interconnects.

References

[1] Liu, D. and Svensson, C. : 'Power Consumption Estimation InCMOS VLSI Circuit', *IEEE J. Solid-State Circuits*, 1994, **29**, pp. 663-670

[2] Seassal, C., Rojo-Romeo, P., Letartre, X., Viktorovitch, P., Hollinger, G., Jalaguier, E., Pocas, S. and Aspar, B. : 'InP microdisk lasers on silicon wafers : CW room temperature operation at 1,6 µm', Electron. Lett. 2001, 37, no. pp. 222-223

[3] Monat, C., Seassal, C., Letartre, X., Viktorovitch. P., Regreny, P., Gendry, M., Rojo-Romeo, P., Hollinger, G., Jalaguier, E., Pocas, S. and Aspar, B., 'InP 2D photonic crystal microlasers on silicon wafer : room temperature operation at 1.55 µm', Electron. Lett. 2004, 37, pp. 764-765

[4] Seung June Choi, Djordjev, K., Sang Jun Choi and Dapkus, P.D. : 'Microdisk lasers vertically coupled to output waveguides', IEEE Photon. Technol. Lett. 2003, 15, pp. 1330-1332