Electrically Pumped InP-based Microdisk Lasers Integrated with a Nanophotonic SOI Waveguide Circuit

J. Van Campenhout[1], P. Rojo-Romeo[2], P. Regreny[2], C. Seassal[2], D. Van Thourhout[1], L. Di Cioccio[3], J.-M. Fedeli[3] and R. Baets[1]

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Abstract: We have achieved electrically-injected continuous-wave lasing in InP-based microdisk structures coupled to a sub-micron silicon-on-insulator wire waveguide, fabricated through bonding technology. The threshold current was 0.6 mA with up to 7 μW continuous-wave output power.

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OCIS codes: (140.5960) Semiconductor lasers; (250.5300) Photonic integrated circuits

1. Introduction

In recent years, silicon-on-insulator (SOI) has emerged as a promising platform for passive photonic functions due to the transparency of silicon at telecom wavelengths, its high refractive index contrast and the fact that complementary metal oxide semiconductor (CMOS) technology can be used for fabricating photonic devices with sub-micron features. A major obstacle for large-scale silicon-based electronic-photonic integration is the absence of a compact and efficient silicon-based light source, due to the indirect band gap of silicon. Some strategies for light emission in silicon have been demonstrated [1-3]. However, compact and efficient active devices don't seem feasible in the short term. Efficient active photonic functionality can be added to the SOI platform by bonding a thin film of direct band gap material such as InP on top of it. Lasers and detectors can be fabricated in this thin film and can be coupled to the SOI waveguide circuit [4-5]. Some applications however, such as on-chip optical interconnect, can strongly benefit from dense electronic-photonic integration. Hence, the laser footprint and power consumption should be made very small. Therefore, our work focuses on the heterogeneous integration of ultra-compact InP-based microdisk lasers on the silicon platform, using bonding technology. With this approach, CMOS technology can be used to fabricate and integrate thousands of low-power microlasers on a single die. In this paper we report on first experimental results, showing continuous-wave lasing at room temperature, with substantial coupling into the SOI waveguide. We believe that this device has great potential for on-chip interconnect, but can also enable more advanced functionality such as compact optical memories [6] and on-chip optical neural networks [7] by coupling different microdisk lasers.

2. Device structure and fabrication

A schematic representation of the laser structure is shown in figure 1a. A microdisk is etched in a thin InP-based layer bonded on top of a SOI waveguide wafer. The disk supports whispering gallery modes which are confined to the edges of the microdisk. As a result, a top metal contact can be placed in the centre of the microdisk, without introducing extra optical losses. The bottom contact can be placed on a thin lateral contact layer: this layer doesn't cause substantial optical losses, provided it is sufficiently thin. Another issue in the design of electrically injected thin-film microlasers is how to make a p-type contact with low contact resistance. In a classic substrate laser, this is done by using heavily doped, low-bandgap contact layers. This cannot be done for a thin-film laser structure, as this would cause excessive internal absorption losses. Therefore, we implemented a quaternary Q1.2 tunnel junction (TJ) in combination with another n-type contact, instead of low-bandgap p-type contact layer. The InP-based epitaxial layer structure is about 1 μm thick and contains 3 compressively strained InAsP 6-nm quantum wells in 20-nm Q1.2 barrier layers. The laser mode is evanescently coupled to an underlying SOI wire waveguide, aligned with the outer edge of the microdisk. The wire waveguide has a width of 550 nm and a thickness of 220 nm. The bonding layer thickness is approximately 130 nm.

First, a 200-mm silicon-on-insulator waveguide wafer was fabricated as described in [8], with a 1-μm buried oxide layer. Next, a 750-nm SiO_2 layer was deposited. E-beam alignment features were then etched down to the buried oxide layer. The SOI-wafer was then planarized by chemical-mechanical polishing,

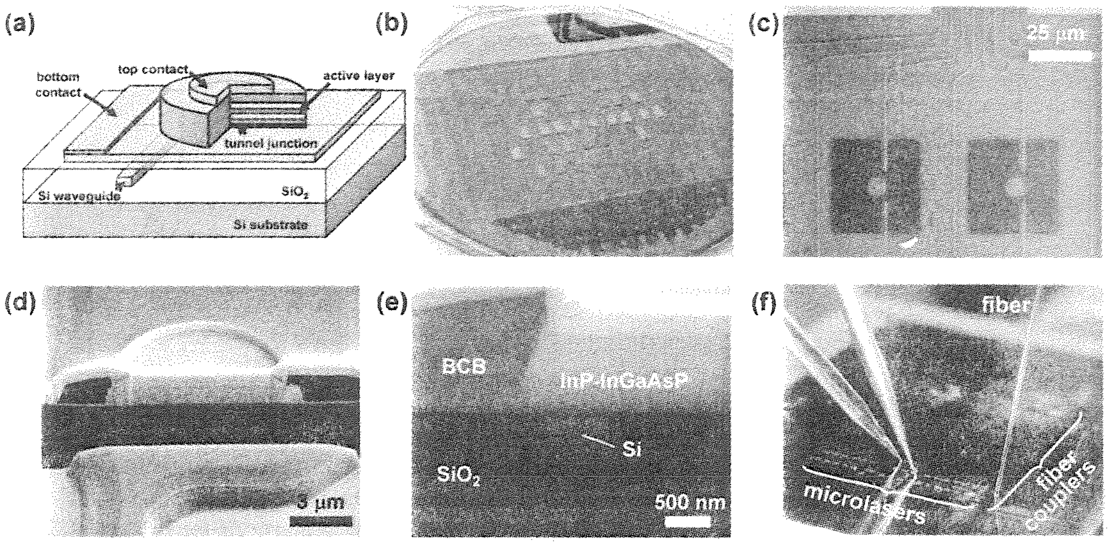

Fig. 1. Schematic representation of the heterogeneous microdisk laser structure (a), 200-mm SOI-wafer with bonded InP dies (b), top view of two microdisk lasers (c), focused-ion-beam cross-section of the microdisk without metallization (d), with a detail of the disk edge showing the SOI-wire (e). The output power in the SOI-waveguides is collected by means of vertical fibre grating couplers (f).

until approximately 120 nm SiO_2 was left on top of the SOI waveguides. The InP-based epilayer structure was grown by Molecular Beam Epitaxy (MBE) on a two-inch InP wafer. A 300-nm sacrificial InGaAs etch-stop layer was also incorporated, for substrate removal. After MBE-growth, a thin 10-nm SiO_2 layer was deposited by Electron Cyclotron Resonance. Then, the III-V wafer was diced into pieces with a dimension of 9x5 mm^2. These dies were molecularly bonded to the SOI waveguide wafer, with only a coarse alignment. Finally, the InP substrate and the InGaAs etch stop layer of the dies were removed by HCl and $FeCl_3$ solutions. On this SOI wafer with bonded laser dies, a 150-nm SiO_2 hard mask was deposited. The microdisk structures were defined by e-beam lithography, aligned to the SOI waveguides using the e-beam alignment features, and transferred to the hard mask. After this step, the SOI wafer was diced and the further processing was done on individual dies (using standard contact lithography). However, in principle, wafer scale technology could be used. First, the microdisk cavities were partially etched by reactive ion etching, leaving a thin bottom contact layer of about 100 nm. The etching depth was controlled by in-situ laser interferometry. The bottom contact layer was then removed where is not required. A 1.5-µm benzocyclobutene (BCB) layer was then spun on top of the laser structures. In this BCB layer, contact windows were etched, both for the bottom contact and the top contact. Finally, Ti/Pt/Au metal layers were deposited and annealed to form the bottom contact, and a Au-based layer was deposited as top contact. Au was chosen as a top contact to minimize any possible metal absorption losses due to non-perfect BCB patterning. Some images taken at various stages of the fabrication process are shown in figure 1b-e.

3. Measurement results

The microdisk lasers were characterized by applying a positive voltage to the bottom contact. The output power was collected at one end of the output SOI waveguide, using a fibre grating coupler [9] as shown in figure 1f. For microdisk lasers with 7.5-µm diameter, we observed continuous-wave lasing at room temperature. Figure 2a shows the output power and the device voltage versus the input current. The threshold current is 0.6 mA, which is equivalent with 1.35 kA/cm^2, under the assumption of uniform injection. The threshold voltage is about 1.7 V. The lasing spectrum at 0.9 mA is shown in figure 2b. It reveals clear single-mode lasing at 1.6 µm. The free spectral range of the fundamental modes is 32 nm, which is equivalent with a group index of 3.4. The slope efficiency was estimated to be 15 µW/mA, based on a fibre coupler efficiency of 20 % at the lasing wavelength and 2dB on-chip propagation losses. The maximum continuous-wave output power is about 7 µW. The early thermal roll-over is caused by a high thermal resistance, which was found to be 10 K/mW. In pulsed operation, output peak powers up to 100µW

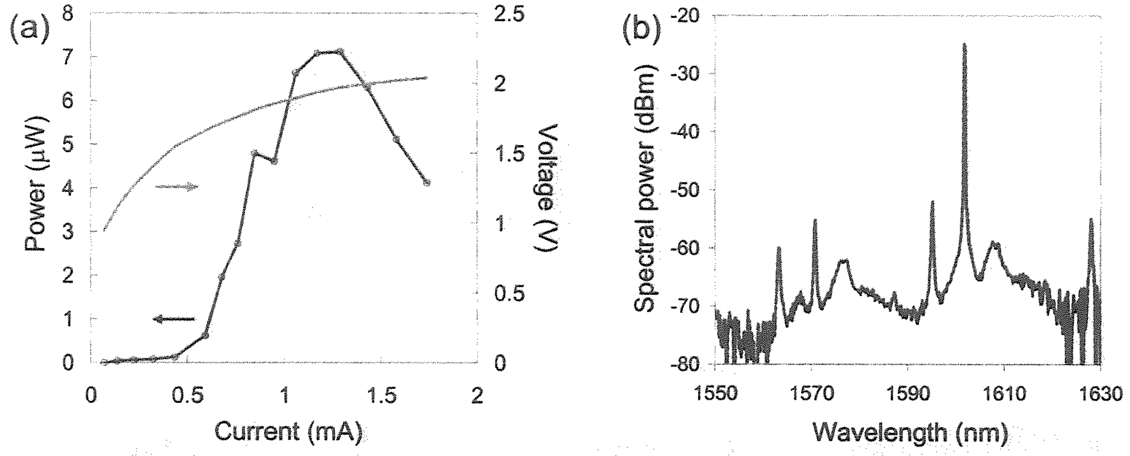

Fig. 2. Continuous-wave lasing characteristics at 20 °C for a 7.5-μm disk (a) and lasing spectrum for 0.9 mA (b).

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We have demonstrated electrically-injected continuous-wave lasing at room temperature in microdisk lasers integrated on and coupled to a nanophotonic silicon-on-insulator waveguide circuit. The microdisks were defined in a thin InP-based film, which was directly bonded to the SOI-wafer. CMOS technology can be used for fabrication on wafer scale. The threshold current was 0.6 mA and the maximum unidirectional continuous-wave output power was 7 μW. This device has great potential for dense and cost-effective electronic-photonic integration.

5. References

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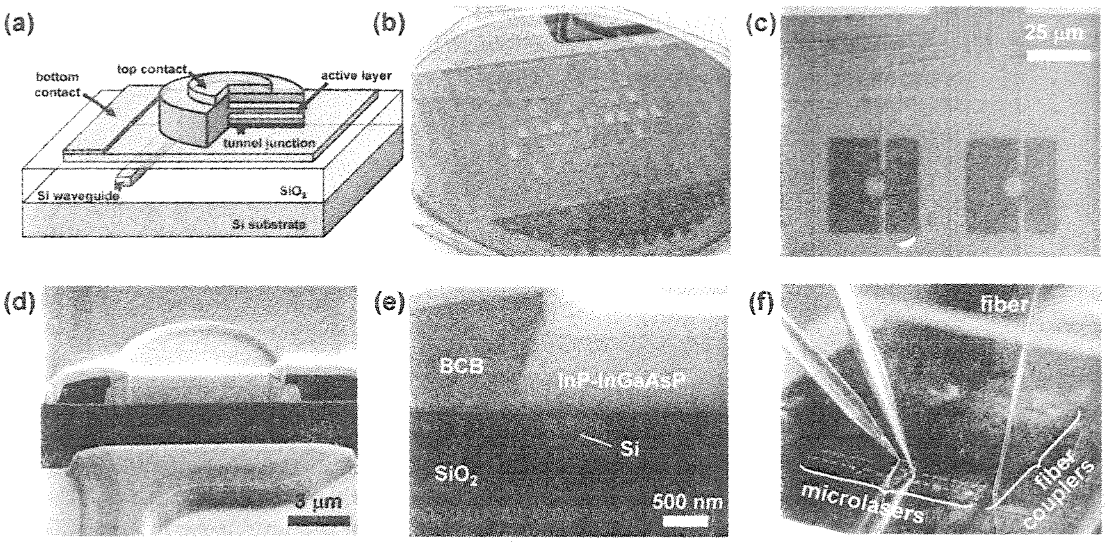

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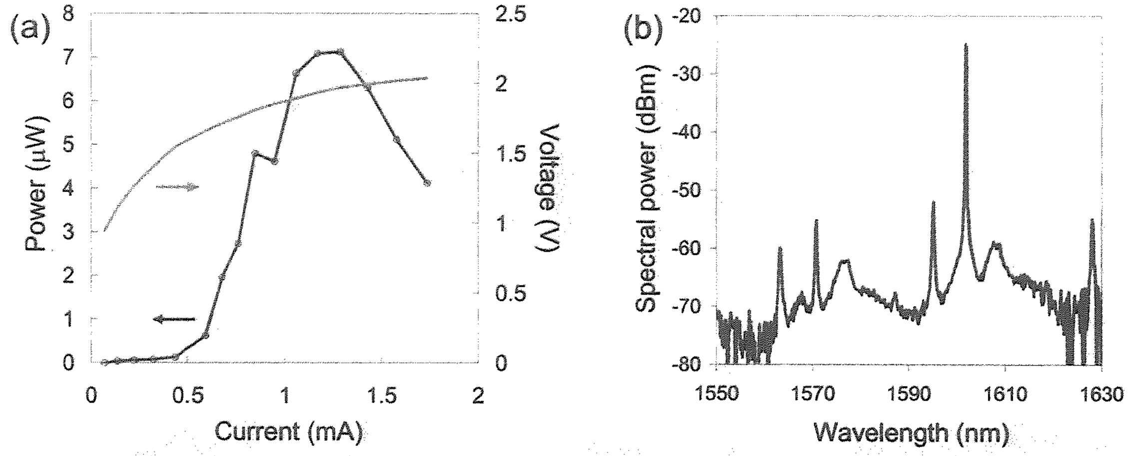

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