InP on Silicon Electrically Driven Microdisk Lasers for Photonic ICs.

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Abstract— An electrically driven microlaser based on a thin InP based microdisk transferred onto silicon is proposed. The technological procedure is described and first experimental results, showing a laser threshold current of 1.5 mA are exposed.
Index Terms—Microdisk lasers, Semiconductor lasers, Optical interconnects, Heterogeneous integration of III-V materials and silicon, electrical injection.

INTRODUCTION

The increase in the integration density in the field of microelectronics will lead to a technological bottleneck regarding interconnects. More precisely, the use of traditional metallic connections will yield a dramatic increase of power consumption as well as 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 integrated over CMOS circuits in a "above IC approach" and offer an alternative to conventional metallic interconnects [2]. SOI wafers have demonstrated a high potential to build passive dense microphotonic circuits based on high refractive index Si waveguides [3-5]. These links should exhibit properties such as low power consumption and small footprint. Several groups addressed the specific problem of electrically driven microsources and lasers based on microdisks with electrical injection have been realized [6-10]. These structures have usually in common a high total thickness, usually in the range of 5 µm, and the use of a piedestal obtained by selective wet etching, to ensure the light confinement in the microdisk, and to allow the current flow from the substrate used as a bottom contact. Nevertheless, a high index substrate may be a drawback for applications such as optical interconnects, where the coupling of the source to a compact waveguide is required.
Electrical contacts are formed by metal deposition on highly doped GaInAs contact layers, which leads to significant absorption at 1.55µm. To limit the optical losses due to these layers, it is necessary to use a thicker membrane layer, in order to place the quantum wells as far as possible from the doped contact layers.
The bottom contact issue should be specifically addressed in order to make such laser usable in photonic integrated circuits.
Concerning the optical response of these lasers, one should note that their radiation pattern is not directional. In order to exploit the laser emitted signal, photons should be funnelled into a waveguide. The coupling of a laser microsource operating under optical pumping to a SOI waveguide has been demonstrated [11, 13].
In this letter, we report on the design, fabrication and characterization of a microdisk laser realized in a thin InP based membrane bonded onto Silicon, for optical interconnects.

INFLUENCE OF THE BOTTOM CONTACT SLAB

The laser source is a microdisk formed by a vertical p-i-n junction. The active region consists of 3 quantum wells (QWs) in the undoped part of the membrane.
In this structure the n+ ohmic contact is on top of the structure. The bottom contact is formed by a thin (50 to 100 nm) doped InP layer that is left below the microdisk, during the disk etch, as shown in figure 1.

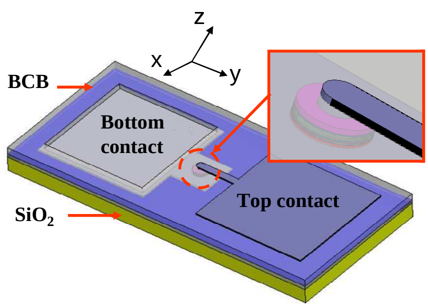

Fig. 1 : Membrane microdisk laser showing the bottom (left) and top (right) contacts.

To evaluate the influence of the contact slab on the optical properties of the resonator, 3D-FDTD simulations [14] have been performed on a 8 µm diameter disk with different bottom contact slab thicknesses (h_S = 0, 50 and 100 nm). The disk thickness is 1 and 0.5 µm.

With respect to the optoelectronics properties of InAsP QW, the simulations were focused on quasi TE modes (electric field mainly lying in plane) with a resonant wavelength around

1.5µm. Whispering Gallery Modes (WGM) can be identified by 3 integers (n,l,m) corresponding respectively to the number of nodes in the vertical direction and to the radial and azimuthal numbers. The main theoretical results are summarized below.

For a 1 µm thick disk :

- For vertically fundamental modes (n=0), the influence of the slab on resonant wavelength is smaller as compared to WGM with larger n (see table 1).
- The quality factors (Q) of WGM with n>0 is drastically decreasing with increasing h_S, from Q > 200000 for h_S = 0 to Q = 5000 for h_S = 50nm and Q = 2000 for = 100nm. On the contrary, for WGM with n=0, Q remains very high (>200000), even with the 100nm thick contact slab [15].

Considering the vertical symmetry of the WGM, these results can be easily explained. For n>0, the field is higher in the region of the contact slab than for n=0 and, as consequences, the resonant wavelength are more shifted and the optical losses are higher. These losses are mainly guided in the contact slab (see figure 2).

	λ(µm) (0,0,47) WGM	λ(µm) (2,1,33) WGM
h_S = 0	1.4874	1.4868
h_S = 50 nm	1.4878	1.4895
h_S = 100 nm	1.4885	1.4910

Table 1 : Influence of the contact slab thickness on the resonant wavelength of 2 WGM.

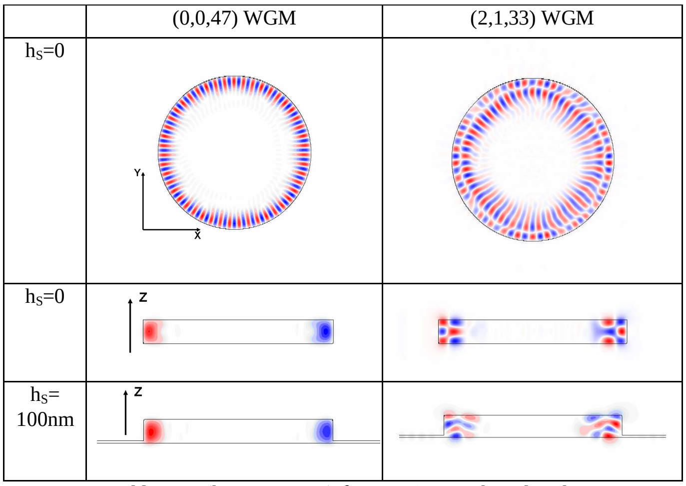

Figure 2 : Field maps (h_z component) for 2 WGM, with and without contact slab.

For a 0.5 µm thick microdisk the effect of the slab is similar. For vertically fundamental modes (n=0), the influence of the slab on resonant wavelength is weaker as for higher n modes : As an example, for the (0,0,45) WGM, Q remains higher than 140000.

The influence of a coupling submicron silicon waveguide, for collection of light, situated below the microdisk was then simulated, for a 0.5 µm thick disk. The waveguide is 220 nm thick and 500 nm wide. The coupling distance is 200 nm. The refractive indexes are 3.2 for the disk, 3.5 for the waveguide, and 1.5 for the low index material. Due to the presence of the waveguide, the (0,0,45) WGM Q value is lowered to 11000. This value remains high enough to allow a laser operation. A misalignment of the guide respect to the disk edge (± 100 nm along the disk radius) has a weak influence on the value of Q. When the waveguide position is moved to the disk center, a decrease of Q from 11000 to 10000 is observed. On the contrary, when the shift is in the other direction, an increase of Q up to 15000 is observed .

As a conclusion on these calculations, a beneficial effect of the slab contact is demonstrated. On one hand, high Q resonant modes (n=0) can be preserved, which is essential to obtain a low threshold. On the other hand, as higher order modes (n>0) become much less resonant, the free spectral range between high Q modes increases, which supports single mode laser operation. The effect of the slab is also a shift of the laser mode wavelength, while the main influence of the coupling waveguide is a change of the quality factor value. Finally, simulations show that a reasonable misalignment of the waveguide with respect to the microdisk, due to the two step lithographic process, do not deteriorate the optical properties of the device [16].

STRUCTURE DESIGN.

Two different structures were used for this work. The heterostructures have been grown by Solid sources Molecular Beam Epitaxy (SSMBE) on two inches InP wafers supplied by InPact S.A. The laser structure S1 was grown at 470°C and consists of a 380 nm thick $5x10^{18}$ cm^{-3} to $2x10^{18}$ cm^{-3} Si doped InP, the undoped multi-quantum wells (MQWs) active layers and a 302 nm thick 10^{18} cm^{-3} to $5x10^{18}$ cm^{-3} Be doped InP. The P type contact is implemented as a thin (40 nm) InGaAsP tunnel junction. The emission wavelength of the quaternary alloy is 1.2 µm (Q1.2 µm) and doping levels for p++ and n++ are respectively $2x10^{19}$ cm^{-3} and 10^{19} cm^{-3}. The active layers are 3-periods of $InAs_{0.65}P_{0.35}$ (6 nm) / Q1.2 (20 nm) strained MQWs emitting at 1.5 µm, sandwiched between two 83 nm thick Q1.2 µm optical confinement layers. The total thickness of the structure is one micron, to reduce optical absorption due to doped and contact layers. A 300 nm sacrificial InGaAs etch-stop layer is grown before for substrate removal.

The structure S2 has the same active layers. The total thickness is reduced from 1 µm to 0.5 µm : the Si doped InP is reduced from 380 nm to 150 nm, the Be doped InP InP layer is lowered to 30 nm, and the Q1.2 µm optical confinement layers are reduced from 83 nm to 51 nm.

After the MBE growth, a thin 10 nm silica layer is deposited on top of the III-V structure by Electron Cyclotron Resonance (ECR). Then the wafer is molecularly bonded to a silicon wafer covered with a 1.2 µm silica layer. Finally, the InP substrate and the InGaAs etch-stop layer are removed in HCl and $FeCl_3$ solutions. The laser structure transferred onto a Si wafer is shown in figure 3.

TUNNEL JUNCTION.

A reverse biased tunnel junction is used as p-type ohmic contact. The tunnel junction properties have been characterized using TLM configuration on specific test heterostructures. A specific contact resistance ρ_c =2x10^{-4} Ωcm^2 is extracted from linear I-V measurements.

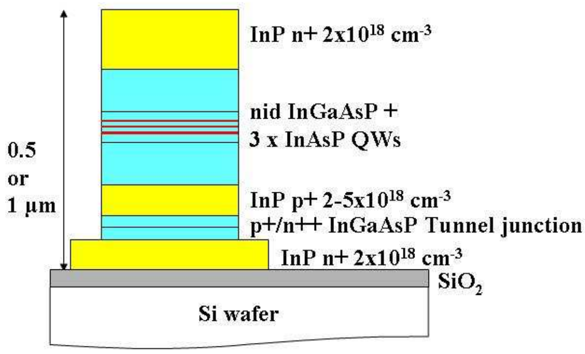

Fig .3 : description of the laser structures. The structure S1 is 1 µm thick, the structure S2 is 0.5 µm thick.

FABRICATION.

In a first step the laser structure is covered by a 150 nm silica hard mask deposited by sputtering. Then, microdisks with diameter in the range 5 to 10 µm are defined by UV photolithography on a AZ 5214 resist. The resist features are then transferred to the hard mask by CHF_3 RIE. III-V layers are etched by RIE, using a CH_4 – H_2 mixture. The etched depth is in situ controlled by interferometry at 675 nm. The III-V etch is not complete and a 80-120 nm thick InP slab remains at the end of the RIE process. In a second step the bottom contact is defined by UV lithography and etched back in a CH_4 – H_2 RIE.
The structure is then covered with a low index dielectric layer (benzocyclobutene BCB) for electric isolation and planarization. The bottom and top contact windows are etched in the BCB layer. Then, Ti-Au ohmic bottom contacts are deposited. At the end, a shiny gold contact with low contact resistivity (10^{-5} Ωcm^2) is deposited on top of the microdisks.

RESULTS

For the electroluminescence measurements, the temperature of the microlasers is maintained at 20°C using a Peltier module that forms the sample holder. DC IV-measurements are performed using a HP4145 DC semiconductor Analyser. For pulsed injection we use a Tektronics PG 501 pulse generator. Pulses are sent to the sample and to a digital microscope through a HP 11667A power splitter. The optical response of the microdisk under electrical injection is observed from above the sample with a Xenics InGaAs linear IR camera. For spectral measurements, light is collected through a lensed fibre and sent to a Triax 500 monochromator and a InGaAs cooled detector array. The fiber is placed at 45° from the disk plane. The positioning of the fibre is assisted by tri-axial high precision (50nm) displacements.

The figure 4 : shows a 8 µm diameter microdisk (structure S1) under pulsed electrical injection. From DC I-V measurements, a series resistance R_S = 350 Ω is extracted at current levels over the threshold. Considering this high resistance value, only pulsed injection is used for the laser characterization. The pulse duration is 6 ns at a frequency of 3 MHz.

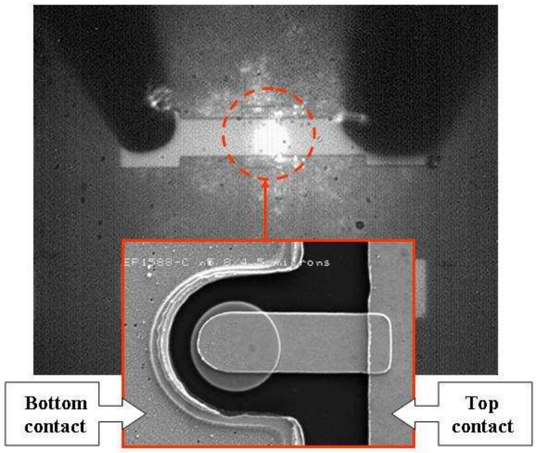

Fig.4 : IR image of a 8 µm microdisk under electrical pulsed injection. The pulse duration is 6 ns at 3 MHz.. The pulse current value is 2.7 mA.

The current threshold is determined at 1.5 mA, which corresponds to a current density of 2.9 kAcm^{-2}. The spectral response of the microsource is depicted in the figure 5.

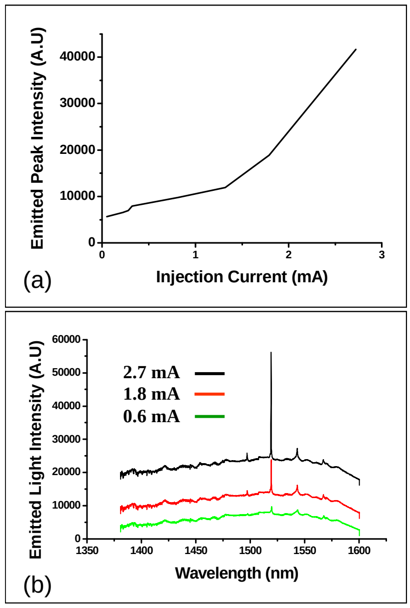

Fig 5: (a): P-I response of the 1 µm thick 8 µm diameter microdisk under electrical pulsed injection. (b): Spectral response. Injection : 6 nm pulses at 3 MHz.

Below the threshold, we observe several high-Q peaks corresponding to the whispering gallery modes of the microdisk. As the injected current increases over the threshold, the magnitude of one unique peak increases drastically while its finesse is increased. The others peaks are not affected. With our apparatus, a quality factor greater than 5000 is measured.

Similar results are obtained on a microlaser fabricated with the structure 2 (0.5 µm thick). A threshold current of ~1.5 mA is also obtained, with log pulses (2.5 µs) at 100 kHz. The lasing wavelength is near 1590 nm (figure 6).

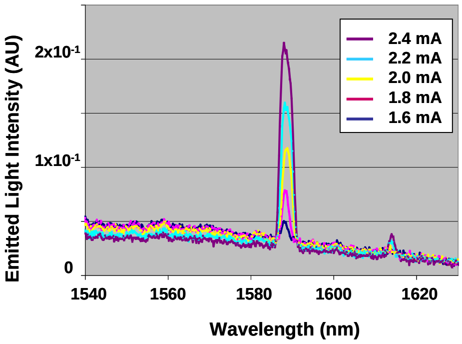

Fig. 6 : spectral response of a 8µm diameter microdisk fabricated on structure 2, under pulsed injection regime.

The value of the current threshold remains relatively high for both structures, most probably due to the high value of the series resistance. This can be accounted for by the influence of the tunnel junction and the bottom contact resistance. Although the p++/n++ tunnel junction provides a much lower specific contact resistance than a p+/InP ohmic contact, a lower value than $2x10^{-4}$ Ωcm^2 is required to achieve a very low resistance contact. Specific contact resistance values down to 10^{-6} Ωcm^2 have been reported [17]. An important effort in epitaxial growth is currently done in our group to increase the tunnel junction quality.

The bottom metal contact is separated from the microdisk by a distance of several microns, and the resistance of the bottom contact layer cannot be neglected. This resistance value is directly related to the thickness of the InP remaining slab after the disk etch step, and may strongly vary with the technology. The thickness of the contact layer must be kept as low as possible to reduce the optical losses. We are currently investigating other contact materials such as conductive oxides like Indium-Tin-Oxide (ITO), with the advantage of a low refractive index that allows using thicker contact layers while keeping a good vertical confinement.

CONCLUSION

In this work we have demonstrated the fabrication and operation of electrically driven microdisk lasers made on a thin InP based membrane transferred onto silicon. Monomode lasing action with a 1.5mA threshold current was achieved in pulsed regime. The next step will consist in the reduction of the series resistance, in order to decrease the thermal dissipation and the laser threshold. This series resistance, mainly due to the bottom contact slab and to the p-type contact tunnel junction, can be reduced by increasing the n and p doping levels of the tunnel junction, and by a more accurate control of the bottom slab thickness. This slab should be as thin as possible to avoid optical losses, leading to an increase of the access resistance value. To overcome this problem, a low index conductive material could replace the InP bottom contact membrane.

The coupling between an electrically pumped microdisk laser and a silicon waveguide was also theoretically demonstrated. Experimental confirmations are under study.

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