Heterogeneous integration of electrically driven microdisk based laser sources for optical interconnects and photonic ICs

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Abstract: A new approach for an electrically driven microlaser based on a microdisk transferred onto Silicon is proposed. The structure is based on a quaternary InGaAsP p-i-n junction including three InAsP quantum wells, on a thin membrane transferred onto silicon by molecular bonding. A p++/n++ tunnel junction is used as the p-type contact. The technological procedure is described and first experimental results show a laser emission in pulsed regime at room temperature, with a threshold current near 1.5 mA.

OCIS codes: (130.5990) Semiconductors; (140. 2020) Diode lasers; (140. 5960) Semiconductor lasers.

References and links

1. D. Liu and C. Svensson, "Power consumption estimation in CMOS VLSI circuit," IEEE J. Solid-State Circuits **29,** 663-670 (1994).
2. G. Tosik, F. Gaffiot, Z. Lisik, I. O'Connor, and F. T. Drissi, "Optical versus electrical interconnections for clock distribution in new VLSI technologies," PATMOS **2799,** 461-470 (2003).
3. R. Orobtchouk, A. Layadi, H. Gualous, D. Pascal, A. Koster, and S. Laval, "High efficiency light coupling in a submicron SOI waveguide," Appl. Opt. **39,** 5773-5377 (2000).
4. Kazmierczak, M. Brière, E. Drouard, P. Bontoux, P. Rojo-Romeo, I. O'Connor, X. Letartre, F. Gaffiot, R. Orobtchouk, T. Benyattou. "Design, simulation, and characterization of a passive optical Add-Dropfilter in SOI technology," IEEE Photonics Technol. Lett. **17,** 1447-1449 (2005).
5. W. Bogaerts, R. Baets, P. Dumon, V. Wiaux, S. Beckx, D. Taillaert, B. Luyssaert, J. Van Campenhout, P. Bienstman, D. Van Thourhout, "Nanophotonic Waveguides in Silicon-on-Insulator Fabricated with CMOS Technology," J. Lightwave Technol. **23,** 401-412 (2005).
6. T. Baba, M. Fujita, A. Sakai, M. Kihara, R. Watanabe. "lasing Charactéristics of GaInAsP-InP strained Quantum-Well microdisk injection lasers with diameter of 2-10 µm," IEEE Photonics Technol. Lett. **9,** 878-880 (1997).
7. M. Fujita, A. Sakai , T.Baba. Ultrasmall and ultralow threshold GaInAsP-InP Microdisk Injection Lasers: design, fabrication, lasing characteristics, and spontaneous emisión factor. IEEE J. Sel. Top. Electon. **5,** 673-681 (1999).
8. L. Zhang, E. Hu. "Lasing from InGaAs quantum dots in an injection microdisk," Appl. Phys. Lett. **82,** 319-321 (2003).
9. R. Ushigome, M. Fujita, A. Sakai, T. Baba, Y. Kokubun. "GaInAsP microdisk injection laser with Benzocyclobutene polymer cladding and its athermal effect," Jpn. J. Appl. Phys. **41**, 6364-6369 (2002).
10. M. Fujita, R. Ushigome, T. Baba, A. Matsutani, F. Koyama, K. Iga "GaInAsP microcylinder (microdisk) injection laser with AlInAs(Ox) claddings," Jpn. J. Appl. Phys. **40,** 5338-5339 (2001).
11. H. Hattori, C. Seassal, E. Touraille, P. Rojo-Romeo, X. Letartre, G. Hollinger, P. Viktorovitch, L. Di Cioccio, M. Zussy, L. El Melhaoui, J.M. Fedeli, "Heterogeneous integration of microdisk lasers on silicon strip wageguides of optical interconnects," to appear in IEEE Photon. Technol. Lett. (2006).
12. C. J. Seung, K. Djordjev, S. J. Choi, and P. D. Dapkus," Microdisk lasers coupled to output waveguides," IEEE Photon. Technol. Lett. **15,** 1330-1332 (2003).
13. H. Park, A. W. Fang, S. Kodama, J. E. Bowers. "Hybrid silicon evanescent laser fabricated with a silicon waveguide and III-V offset quantum wells," Opt. Lett. **13,** 9460-9464 (2005).

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14. http://alioth.debian.org/projects/tessa/
15. For such a large structure (~300 µm^3), we cannot accurately evaluate quality factors higher than a few 100000 with a reasonable calculation time.
16. M. Ortsiefer, R. Shau, G. Böhm, F. Köhler, G. Abstreiter, M-C. Amann, "Low-resistance InGa(Al)As Tunnel Junctions for Long Wavelength Vertical-cavity Surface-emitting Lasers," Jpn. J. Apl. Phys. **39,** 1727-1729 (2000).

1. 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 (see Fig. 1) in a "above IC approach" and offer an alternative to conventional metallic interconnects [2].

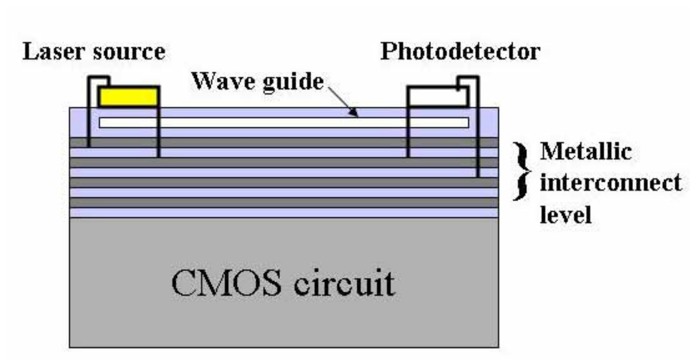

Fig. 1. Schematic description of an optical link in the framework of an above IC approach.

To offer an attractive alternative, these links should exhibit properties such as low power consumption and small footprint. SOI wafers have demonstrated their potential to build passive dense microphotonic circuits based on high refractive index Si waveguides [3-5]. Several groups addressed the specific problem of electrically driven microsources and laser structures based on microdisks with electrical injection have been realized [6-10]. The total thickness of the III-V heterostructure microdisks is usually high, in the range of 5µm. The microdisks lay on a pedestal obtained by selective wet etching, which may result in a lack of robustness. The bottom electrical contact consists of the substrate itself, allowing a small value of the contact resistance. 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].

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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.

2. Structure design

The heterostructure has been grown by Solid sources Molecular Beam Epitaxy (SSMBE) on a two inches InP wafer supplied by InPact S.A. The laser structure 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.

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 2.

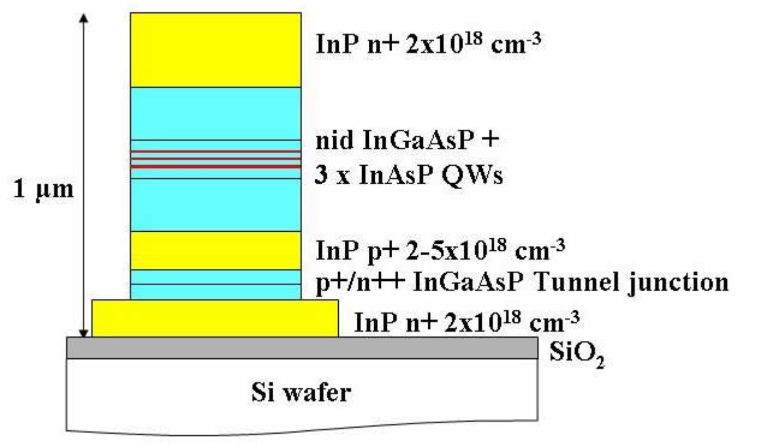

Fig. 2. Description of the laser structure.

3. Influence of the bottom contact slab

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) n+ InP layer that is left below the microdisk, during the disk etch, as shown in figure 3. 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).

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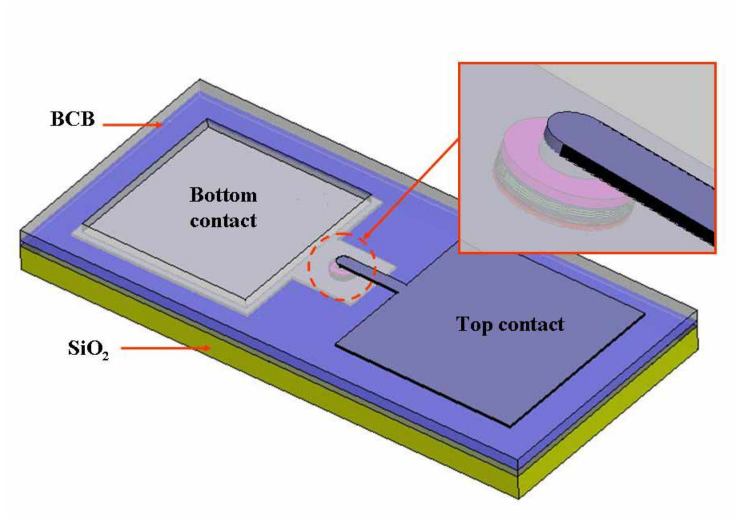

Fig. 3. Membrane microdisk laser showing the bottom (left) and top (right) contacts.

With respect to the optical 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 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].

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

	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

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 4).

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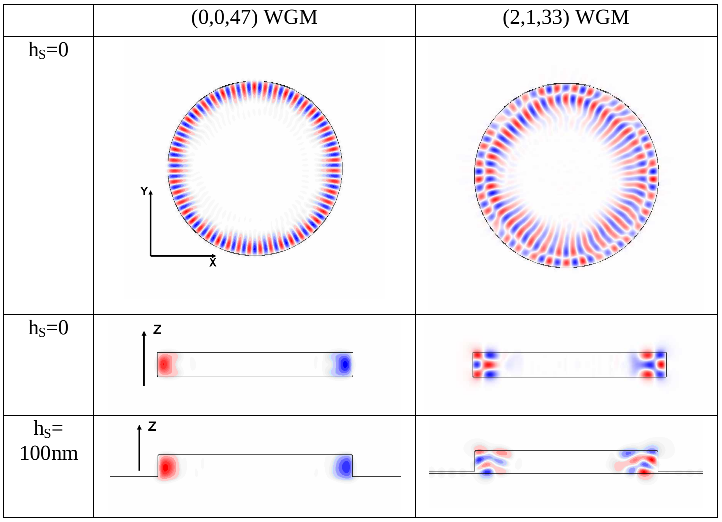

Fig. 4. Field maps (h_z component) for 2 WGM, with and without contact slab.

To conclude 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.

4. 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 structures. The heterostructure is composed by a 40 nm InGaAsP tunnel junction on a 500 nm P-type InP buffer grown on a semi insulating InP substrate. On top of the tunnel junction, a 200 nm thick n+ InP layer and a 100 nm thick InGaAs contact layer are grown. The distance L between contacts varies from 5 to 160 µm. the contact width is 200 µm. Ni/AuGe alloys are used for metallic ohmic contacts, on top of the n+ GaInAs contact layer. The contact resistivity is in the range 10^{-5} Ωcm^2. The tunnel junction specific resistance value $\rho_c = 2x10^{-4}$ Ωcm^2 is extracted from linear I-V measurements. For the microdisk contacts, Ni/GeAu alloy on a n+ GaInAs layer cannot be used, because of the absorption of GaInAs at 1.5µm. They are replaced by low contact resistivity Ti/Au ohmic contacts (section 5).

5. 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 sidewall roughness of the microdisks is estimated from SEM pictures at some tens of nanometers. The disk sidewalls are not totally vertical but exhibit a slope of approximately 5 degrees with respect to the vertical axis. Sidewall roughness and slope are mainly due to the RIE process, and contribute to the high value of the threshold current (see section 6). 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

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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.

6. 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 5 shows a 8 µm diameter microdisk under pulsed electrical injection. From DC I-V measurements, a series resistance R_S = 350 Ω is extracted at current levels over the threshold.

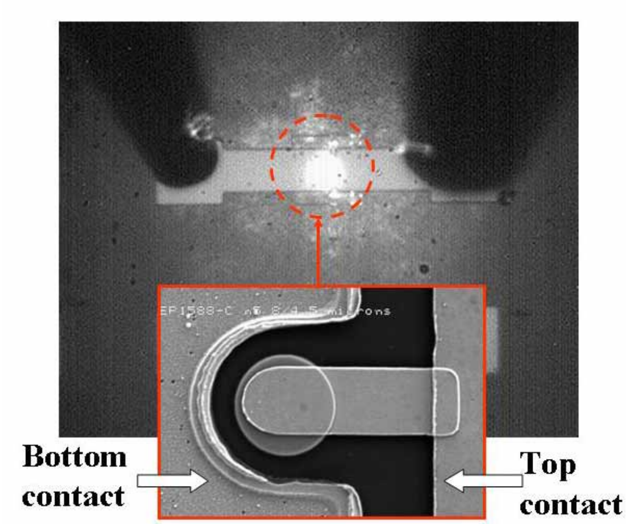

Fig.5. IR image of a 8 µm microdisk under electrical pulsed injection. The pulse duration is 6 ns at 3 MHz.. The pulse current value is 2.7 mA.

The main contribution to R_S is due to the tunnel junction, with approximately 250 Ohms. The other contributions come from the top and bottom contacts, and the bottom contact membrane. These values are in the same order of magnitude. However, non-uniformity in the epi-layer thickness (10-15% for a 2 inch wafer) and in the RIE etch speed (10%) may affect the contact resistance value. 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.

The spectral response of the microsource is depicted in the Fig. 6, together with the P-I curve. At low injection current, we observe several high-Q peaks corresponding to the whispering gallery modes of the microdisk. For higher injected currents, and particularly above 1.5 mA, the magnitude of the peak at 1520 nm is specifically increased. Moreover, the observed high-Q peaks exhibit a different behavior. For the peak at 1420nm, both the magnitude and the Q-factor remain roughly constant, with a Q value of 470. Indeed, the modal gain of the InAsP quantum wells, centered at 1500 nm, is very low at 1420 nm and

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cannot compensate the optical losses. The Q-factors of the peaks at 1500 and 1544 nm first increases linearly with the current, as light re-absorption in the quantum wells is saturated, and then saturate at an injection current of 1.8 mA. The maximum values of the quality factors are 3400 at 1500 nm and 3100 at 1544 nm. On the contrary, the quality factor of the peak at 1520 nm increases linearly and no saturation is observed, up to Q = 6070 at a current value of 2.7 mA. Indeed, this value is close to the maximum of our setup and no measurements could be done at higher injection levels. For these reason, we conclude that laser emission occurs on this device at 1520nm, with a threshold of 1.5mA

The value of the current threshold remains relatively high, 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. The microdisk is driven in pulsed mode in order to avoid a degradation due to excess temperature during the operation. However, even in pulsed mode, a local temperature increase is observed, leading to an optical gain decrease and to a higher threshold. The sidewall roughness of the disk also contribute to the high threshold, by adding optical losses. 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 [16]. An important effort in epitaxial growth is currently done in our group to increase the tunnel junction quality.

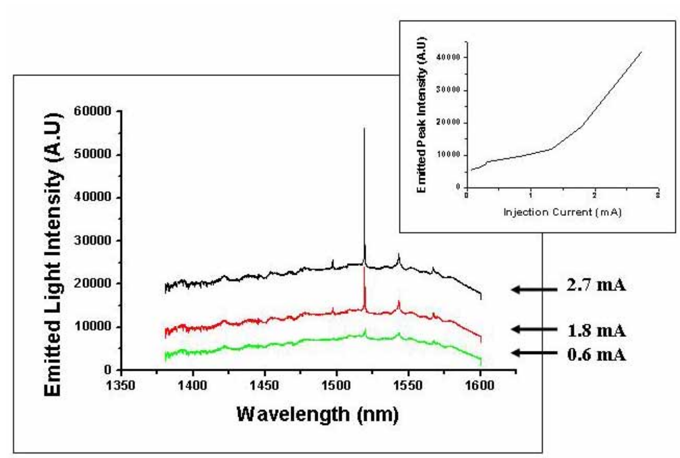

Fig 6: Spectral response , and P-I curve of the 1 µm thick 8 µm diameter microdisk under electrical pulsed injection. The pulse duration is 6 ns at 3 MHz..

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.

7. 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

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will consist in the reduction of the series resistance, in order to decrease the thermal dissipation and the laser threshold. This series resistance, partly 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. An effort is also done to improve the quality of the disk sidewalls, in order to reduce the optical losses.

This kind of device can be used, among possible applications, for the optical clock distribution in a Si integrated circuit, or as part of an Optical Network on Chip (ONoC).

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