Heterogeneous Integration of Microdisk Lasers on Silicon Strip Waveguides for Optical Interconnects

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***Abstract*—A new approach is proposed to realize an optical link for intrachip optical interconnects. This link 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 nano-fabrication procedures is emphasized. The technological procedure is described and first experimental results show that, with an adequate configuration, 35% of light could be coupled from the optically pumped microlaser to the waveguide, as a result of the vertical evanescent coupling.**

***Index Terms*—Heterogeneous integration of III–V materials and silicon, microdisk lasers, optical interconnects, semiconductor lasers.**

I. 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 with microelectronic circuits (see Fig. 1) and offer an appealing alternative to conventional metallic interconnects [2].

In order to be attractive, 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 microphotonic circuits based on high refractive index silicon waveguides. They could be integrated on top of a microelectronic circuit; this is typically an above integrated circuit (IC) approach. In order to couple light into a passive photonic circuit, a hybrid approach is generally put forward, that consists of standard laser sources aligned with the input of the waveguides. This implies sophisticated designs of tapers and couplers [3]. A more upstream proposal consists of generating light in silicon itself [4]. Our approach relies on a light source integrated above the optical layer and made of a high optical gain III–V semiconductor heterostructure bonded onto silicon waveguides. Then, among many alternatives, the most promising solutions would be to use low threshold laser sources based on microdisks and photonic crystal microresonators [5], [6].

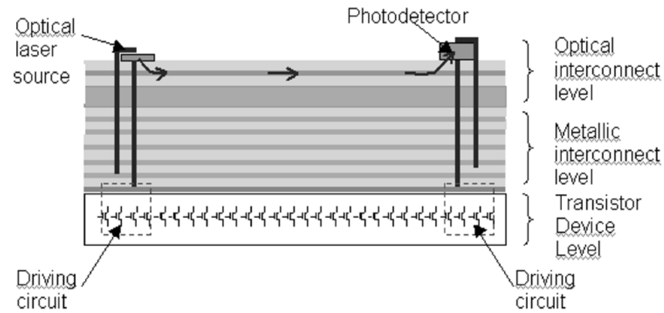

Fig. 1. Schematic description of an optical link in the framework of an above IC approach.

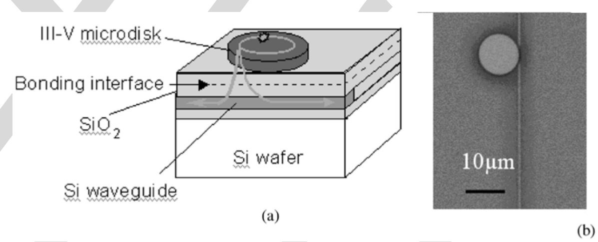

Fig. 2. (a) Schematic description of the microlaser coupled to a silicon waveguide and (b) top view of fabricated device.

Our long-term goal is to realize an optical layer on top of a silicon IC to replace the longest wire links. Such a layer consists of silicon waveguides connected to a laser and a photodetector. This letter is focused on the integration of microdisk lasers and passive waveguides. Key points are the ability to fabricate a laser on top of a silicon wafer including waveguides and the optimization of light injection from the laser to the waveguide. Therefore, in our approach, the technology used for heterogeneous integration of III–V semiconductors and silicon is of prime importance and geometrical parameters must be well controlled.

II. Device Design and Fabrication

In previous articles, we have demonstrated that microdisks [7] could be used to realize microlasers bonded onto a silicon wafer. In this letter, we demonstrate an efficient evanescent coupling between an InP-based optically pumped microdisk laser, emitting at 1.5 μm, and a photonic waveguide of submicron section, as schematized in Fig. 2(a). Coupling of a microdisk mode

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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.* [8] proposed a technological scheme to integrate such elements, all made of III–V compounds. In our case, we report the fabrication of a III–V microdisk laser coupled to a silicon waveguide.

The passive photonic circuit, fabricated on a 200-mm SOI wafer, includes a 320-nm-thick silicon layer on top of a 1-μm-thick buried oxide layer, in order to prevent guided mode leakage to the substrate. On this wafer, 300- and 600-nm-wide silicon strip waveguides are fabricated using deep-ultraviolet lithography, silica hard mask, and reactive ion etching with HBr–Cl. Then, the passive photonic circuit is embedded in silica and planarized by chemical and mechanical polishing to obtain the proper thickness of silica upon the guides. The active heterostructure is grown by molecular beam epitaxy on a 2-in InP wafer supplied by Inpact. It consists of a 500-nm $In_{0.53}Ga_{0.47}As$ sacrificial layer, a 100-nm-thick InP layer, four 5-nm-thick strained $InAs_{0.65}P_{0.35}$ quantum wells separated by 20-nm InP barriers, and covered by a 100-nm InP layer. The quantum wells are designed to emit around 1.5 μm. A thin 10-nm electron cyclotron resonance silica layer is then deposited on top of the active layer and the III–V wafer is molecularly bonded at the center of the silicon wafer containing the photonic circuits at room temperature. Before SiO_2-SiO_2 wafer bonding, the silicon wafers were polished to ensure a low roughness and then cleaned. The bonded wafers were annealed at 200 °C for 60 min to increase the bonding energy. The final silica thickness between the passive silicon waveguides and the active layer is a key parameter, since it controls the coupling rate between the laser and waveguide's modes. Decreasing the SiO_2 thickness makes the coupling more efficient but reduces the Q-factor of the lasing mode, which yields a higher laser threshold.

In our case, the thickness of the silica layer between the microdisk and the waveguide (after fabrication) is about 300 nm, which provides a good coupling efficiency and, at the same time, allows for the lasing of the device. Three-dimensional finite-difference time-domain simulations performed with a 50-nm cell size, and considering a refractive index $n = 3.2$ for the heterostructure and $n = 1.45$ for SiO_2, indicate that, for this value of separation between a waveguide (300 nm wide) and a 5-μm diameter microdisk laser sandwiched between two SiO_2 layers, we can achieve a coupling efficiency of 83% for a resonant peak at $\lambda = 1580$ nm. The quality factor for this resonant peak (for a simulation which does not include the material gain) is about 3800. When the same microdisk is isolated (without any waveguide), the quality factor is increased up to 23 000.

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 alignment accuracy better than $\pm$200 nm. With this disk size, the number of whispering gallery modes is sufficiently small to avoid intermode competition. Finally, III–V microdisks are produced by reactive ion etching, using a $CH_4 : H_2$ plasma. The quality of the final devices relies on two main parameters: the ability to control the silica bonding thickness between the microdisk and the ability to align properly the microdisk with the collecting waveguides. Fig. 2(b) presents a top view of a final device.

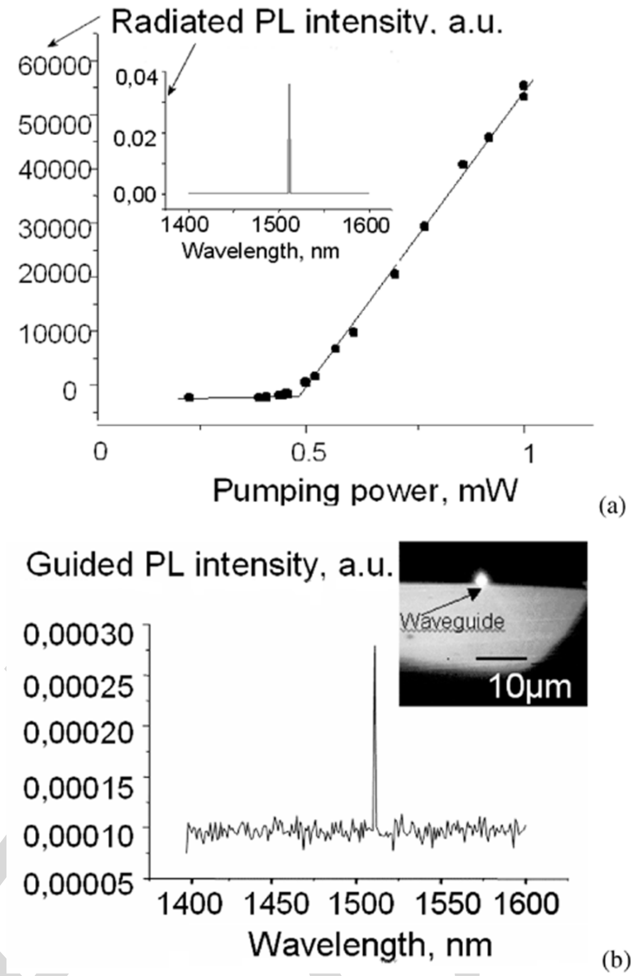

Fig. 3. (a) Radiated intensity versus pumping power for a typical microdisk and spectrum of the radiated light in the inset. (b) Spectrum and IR image (in the inset) of the guided light, collected at the cleaved facet.

III. Results and Discussion

Devices are characterized by using a two axis optical bench. One axis is dedicated to the injection and measurement of radiated light, while the second axis enables the collection and measurement of guided light. Spectral analyses are performed with a 25-pm resolution spectrometer. In the injection axis, the pumping light is generated by a pulsed 780-nm laser diode (duty-cycle of 10% with a repetition rate of 200 ns), and focused onto the sample by using a $\times 10$ infrared (IR) microscope objective lens. The diameter of the pumping light is about 10 μm. The radiated light, generated around 1.5 μm, is collected and analyzed by a spectrometer. The guided light is collected by a $\times 20$ IR microscope objective lens, the signal coming from a cleaved facet of the sample is partially analyzed by the spectrometer, and partially used to display an IR image.

Fig. 3(a) displays the emission characteristics of a microdisk coupled to a silicon waveguide. 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. If we consider the pumping power really absorbed by the InP-based heterostructure (about 1/3 of the incident light), the effective lasing threshold is around 0.5 mW. The spectral analysis of the guided light [Fig. 3(b)] reveals the same features as the radiated light [Fig. 3(a)], in terms of peak 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 the inset of Fig. 3(b).

In order to determine the amount of light that is coupled to the waveguide, a simple comparison of the two former spectra is not sufficient since each of them include inherent loss sources. A more adequate way to determine the amount of coupled light is then to analyze the evolution of the optical losses through the Q-factor, with and without a waveguide positioned under the cavity. The quality factors are determined in a cold cavity, i.e., in the transparency regime. For high Q microcavities, we assume that this regime is very close to the lasing threshold that is determined experimentally.

First, let us call the quality factor of an isolated microdisk laser, operating close to its threshold level Q_0. When this microdisk is coupled to a waveguide (again operating close to its threshold level), its total quality factor drops to a value Q_t. Q_t corresponds to the global losses of this microdisk. Taking into account all these factors and by considering arguments of energy conservation, we can give the following estimate of the coupling efficiency (η_c):

$$\eta_c = \frac{1/Q_t - 1/Q_0}{1/Q_t}. \tag{1}$$

On our sample, three kinds of structures were analyzed: isolated microdisk lasers, microdisk lasers coupled to 300-nm-wide waveguides, and microdisk lasers coupled to 600-nm-wide waveguides. In each situation, several devices have been characterized. The results that shall be presented in the next paragraphs represent average values for each case. However, it can be said that the results were very regular, despite some discrepancies. Moreover, when comparing isolated microdisk lasers and lasers coupled to waveguides, we were sure that both devices worked with similar emission wavelengths, in such a way that the same emitting mode was being characterized.

For 5-μm isolated microdisks (no waveguides), the measured Q_0 is about 14 000. The main lasing mode appears at $\lambda = 1515$ nm. This corresponds to a whispery gallery transverse electric mode (electric field in the plane of the disk). The Q-factor is lower than the predicted value mentioned above, most probably due to roughness on the sidewall of the microdisk, and because the structure is asymmetric (the heterostructure lies between air and a SiO_2 layer). Additionally, the theoretical lasing mode (which operates at $\lambda = 1580$ nm) is different from the experimental one. The effective average laser threshold of the microdisk lasers is about 0.7 mW. The free-spectral range between different whispery gallery modes is about 40 nm. Other modes could be excited by the pumping signal, but they have a much lower Q-factor.

When 5-μm microdisk lasers are coupled to 300-nm waveguides, the quality factor (Q_t) drops to 10 000. This implies $\eta_c = 30\%$ (the waveguide is bilateral, which means that the coupled power propagates in both directions of the waveguide and, in principle, should be equally distributed in these two directions). Their average threshold power is about 0.75 mW. In this case, the difference between the theoretical and measured coupling efficiencies can be explained by possible misalignments between the border of the microdisk and the waveguide. When these lasers are coupled to 600-nm waveguides, Q_t drops to 9000, implying $\eta_c = 35\%$. The average threshold pumping power is about 0.8 mW. The better coupling of microdisk lasers to 600-nm waveguides can be explained by a better overlapping of the fields in the microdisk laser with those in a 600-nm waveguide.

IV. Conclusion

We demonstrated the fabrication and operation of optically pumped microdisk lasers coupled to silicon waveguides, with an achievable coupling efficiency of 35%. In the near future, we plan to integrate this microdisk laser coupled to a waveguide in a full interconnect.

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