An Optical Interconnect Layer on Silicon

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Abstract: *We demonstrate an optical interconnection link on silicon. Compact InP-based micro-disk lasers and photodetectors (PDs) are connected via Si photonic waveguides on top of a Si wafer. The photonic devices are fabricated in a way compatible with wafer scale processing steps, guaranteeing compatibility towards future generation electronic IC processing. Device design, fabrication, integration scheme and preliminary measurements of the full optical link are described in this paper.*

Introduction

For future generation electronic ICs, a bottleneck is expected at the interconnect level. The integration of optical sources, waveguides and detectors forming a photonic interconnect layer on top of the CMOS circuitry is a promising solution, providing bandwidth increase, immunity to EM noise and reduction in power consumption [7, 6, 1]. This solution is investigated within the European project PICMOS[1]. In that context, an interconnect layer is built as a passive Si photonic waveguide layer and InP-based photonic sources and detectors are fabricated with wafer scale processing steps. A possible integration technique that is investigated here assures compatibility towards future generation electronic ICs and is based on a die-to-wafer bonding technology [2]. In this paper we present compact laser and photodetector structures that can be used for the above mentioned optical interconnections. The design, fabrication, and characterization of the optical link are described.

Design

In our approach, light from an electrically driven InP-based micro-disk laser is coupled into the Si waveguide in the interconnection layer. The optical power is carried by the Si waveguide over the link (6-7 mm) and is coupled into a detector structure by means of an InP membrane coupler. As shown in Fig. 1, two types of link were implemented: laser-to-detector point-to-point (P2P) links and broadcast links. A schematic draw of the micro-disk laser-to-detector P2P link is shown in Fig. 2. Grating fiber couplers were designed in the Si photonic waveguide layer to allow characterization of lasers and detectors without the need of a full optical link manufacture. Such gratings are described more in detail in [4].

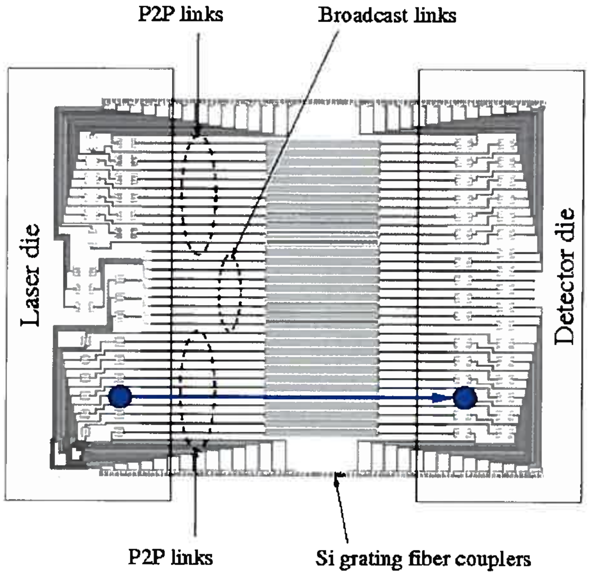

Fig. 1: Optical link scheme. On the left (right) the position of the source (detector) die is drawn. Micro-disk lasers are connected to detectors via point-to-point and broadcast links. The Si photonic waveguide pattern is shown in the scheme background. The point-to-point link schematically drawn in Fig. 2 is indicated.

The micro-disk laser is built as a InAsP multi-quantum well active layer in the n.i.d. InGaAsP structure core, which is sandwiched by highly n- and p-doped InP contact layers. We refer to [5] for more details about the source design. The PD structure is built as an n.i.d. 700 nm InGaAs absorption layer sandwiched between a highly p-doped 50 nm InGaAs contact layer and a highly n-doped 250 nm InP layer, which is also used for realizing a membrane waveguide acting as a coupling structure. The detector mesa footprint is $5 \times 10\,\mu\mathrm{m}^2$. Source and detector layer stack were chosen to reach a trade-off between the ease of integration (see [5]) and device performance. More details about the detector structure design can be found in [9].

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[1] Photonic Interconnect Layer on CMOS by Wafer-Scale Integration (PICMOS), http://picmos.intec.ugent.be

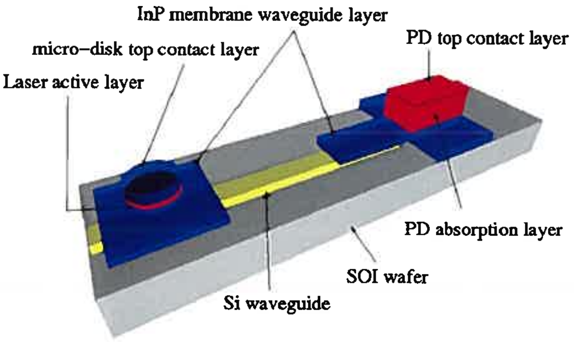

Fig. 2: Schematic diagram of a point-to-point photonic link. Electrically pumped micro-disk laser (left) launches an optical signal into the Si waveguide. Light is collected by the detector structure (right).

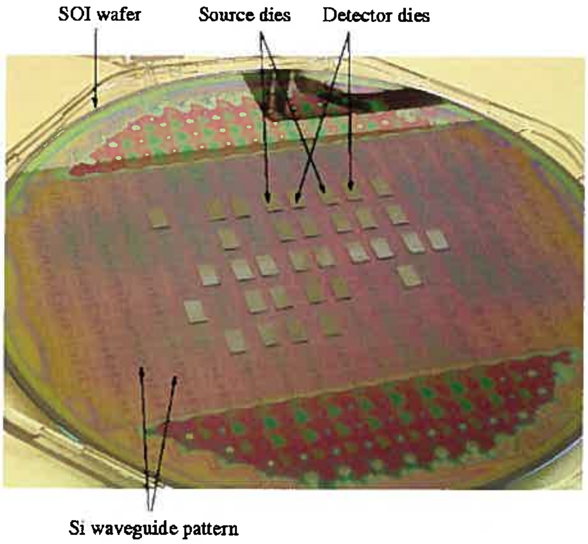

Fig. 3: Source and detector InP-based dies bonded on an SOI wafer.

Fabrication

Two InP-based 2 inch wafers with the laser and the PD layer stacks were epitaxially grown by Solid Source MBE and by MOVPE, respectively. The wafers were diced in 9×7 mm^2 pieces, which were then bonded upside down on an SOI wafer (see Fig. 3), in which the Si waveguide pattern had been defined. A SiO_2 layer was grown on top of the SOI and InP wafers to provide a silica-to-silica interface for the molecular bonding. We refer to [2] for the details about such bonding technique, while details about design and fabrication of the Si photonic waveguides are extensively presented in [8]. Afterwards, the die substrate was wet-chemically removed and lasers and PDs pattern was defined by e-beam lithography and transferred to a 150 nm thick SiO_2 hard mask. The SOI wafer was sawn into samples containing both source and PD dies and test samples with only the source or the detector die. We proceeded with the serial processing of the sources and of the detectors, by covering with thick protective photoresist one die while processing the other. The SiO_2 hard mask was used to dry-etch the microdisks in the laser die, while in the PD die it masked the dry-etch of the membrane waveguides and of the PD bottom contact areas, which share the same n-InP layer. The silica mask on top of the detectors was then dry-etched away and the mesas were wet-chemically etched. The following common processing steps were finally done to complete the chip. A benzocyclobutene (BCB) layer was deposited to planarize the chip surface and provide electrical isolation. Device top- and side-contact windows were opened by a combination of O_2 plasma-etch and RIE, and metal was evaporated and patterned by lift-off. Top and bottom PD contacts were metallized with a Ti/Pt/Au layer stack, as well as the bottom laser contacts, while a Ti/Au layer stack was used for sources top contacts. Fig. 4 shows a picture of the fabricated devices.

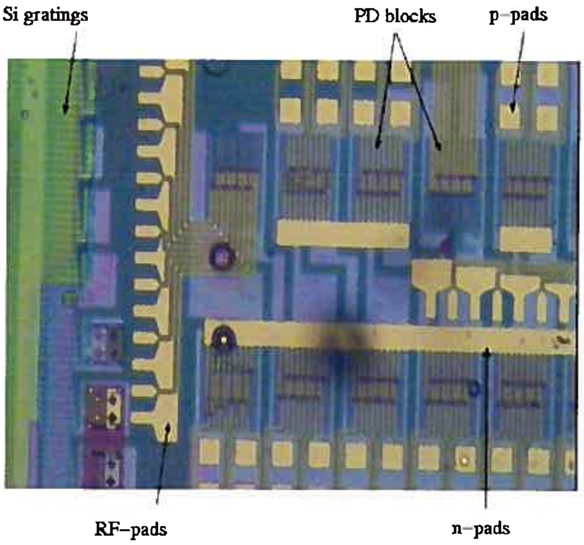

Fig. 4: Picture of the fabricated chip. Ten PD blocks (8 devices/block) are shown in this picture. DC and RF p- and n-contact pads are also visible, as well as the Si grating couplers (on the very left).

Measurement Results

We performed preliminary measurements of the P2P full optical link. The characterization was done by electrically biasing the micro-disk laser in pulsed regime while recording the detector generated photocurrent through a Keithley read-out unit, which was also used to provide reverse bias voltage to the PD. The laser output power was monitored by coupling the emitted signal into an optical fiber aligned over the Si grating and connected to an optical spectrum analyzer (OSA). We registered a laser average output power of tens of nW, depending on the driving current and the emitted pulses parameters. We measured optical links at different pulsed working regimes, as can be seen in Fig. 5. The detector generated photocurrent measured

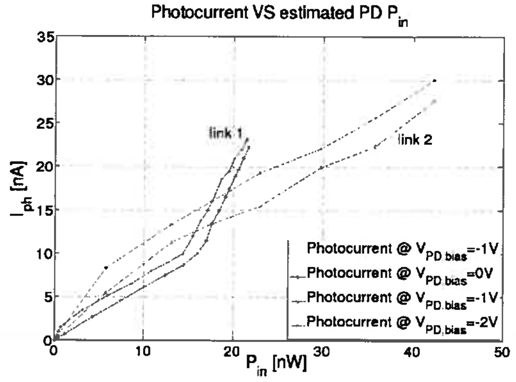

Fig. 5: Detector average photocurrent measured in CW for two different links as a function of the estimated power in the Si waveguide at the PD input. In link 1 (link 2), the laser emits 125 ns (45 ns) wide pulses with a duty cycle of 2.5% (4.5%).

in CW is plotted in the figure, for two different links. In link1 (link2) the laser emits 125 ns (45 ns) wide pulses with a duty cycle of 2.5% (4.5%), while the PD is biased at 0 V and -1 V (-1 V and -2V). When the laser is OFF, a dark current of 10-13 nA flows through the photodiode when biased at -1 V. When the laser is ON, an average photocurrent of up to 22 nA (30 nA) is measured.

Conclusions

We demonstrated a photonic interconnection layer on silicon. The InP membrane-based micro-disk lasers and photodetectors were manufactured. Device design, integration scheme and fabrication were described. First measurements performed with electrically driven lasers working in pulsed regime and detectors working in CW demonstrate working optical link.

Acknowledgments

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