Towards a Fully Integrated Indium-Phosphide Membrane on Silicon Photonics Platform

Jorn van Engelen, Vadim Pogoretskiy, Meint Smit,
Jos van der Tol and Yuqing Jiao

Photonic Integration Research Group, Institute for Photonics Integration (IPI),
Eindhoven University of Technology, Netherlands

Recently a uni-traveling-carrier photodetector with high speed (> 67GHz) and a high-gain optical amplifier (110/cm at 4 kA/cm^2*) have been demonstrated using the InP-membrane-on-Silicon (IMOS) integration technology. Passives in IMOS have shown features comparable to SOI platforms due to the tight optical confinement. In this paper a fully integrated membrane photonics platform on silicon is proposed that integrates these active devices with thermally tunable passives and heatsinking capabilities to the silicon carrier.*

Integration

The tight optical confinement (Fig. 1) offered by the IMOS integration technology [1] enables passive devices with the performance and footprint similar to silicon-on-insulator technology. Furthermore the InP material system has the direct bandgap structure needed for the efficient generation of photons. This enables novel devices like a high-gain optical amplifier (SOA) [2], a high-speed uni-traveling-carrier photodetector (UTC-PD) [3], and an electro-optic polymer phase modulator (EOPPM) [4]. Other InP-based membrane integration schemes focus on on-chip and chip-to-chip optical interconnects and have demonstrated high efficiency lasers with low thresholds [5,6]. With the platform proposed here we aim for generic integration of building blocks, so that it can be used in a wider range of applications. First the SOA, UTC-PD and EOPPM are discussed, then an IMOS integration scheme is proposed to combine these devices, together with passive devices, into a full membrane photonics platform.

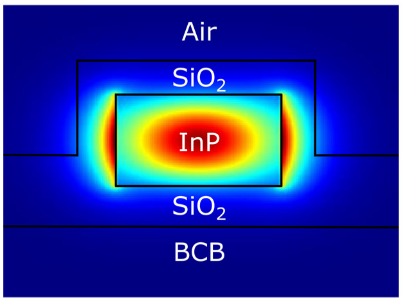

Fig. 1: Electric field intensity in an IMOS passive waveguide.

High-gain optical amplifier

Recently an SOA was demonstrated within the IMOS integration technology [2]. The laser layer stack is placed on top of the passive waveguide layer in a so-called twin-guide configuration (see Fig. 2a). Due to the higher refractive index of the laser MQW core the mode is pulled up from the passive waveguide. A tapering structure (Fig. 2b) is used to maximize power transmission from the passive waveguide into the laser multi-quantum-well (MQW) core.

The gain of this SOA building block was determined to be 110 cm^{-1} at a current density of 4 kA cm^{-2} [2]. This high gain is due to the large number of quantum wells (8 where 4 or 5 is more conventional) and due to the tight optical confinement in the IMOS waveguides which yield a high modal field overlap with the quantum wells. The

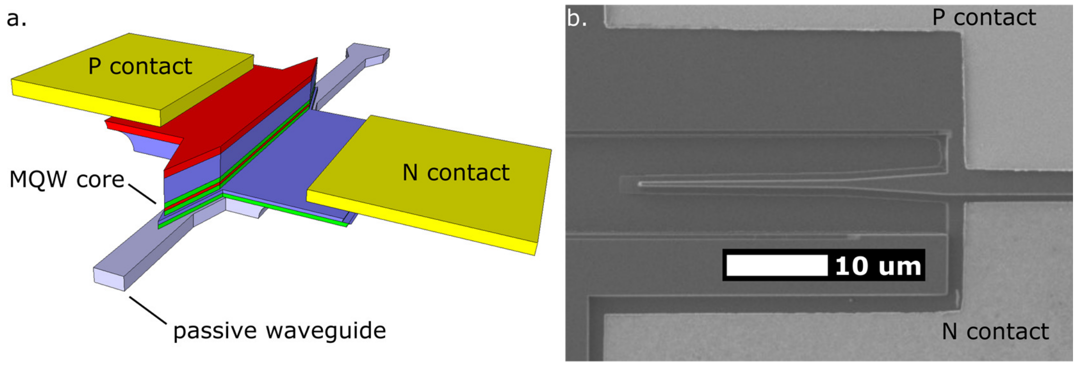

Fig. 2: (a) 3D rendering of the SOA building block, (b) SEM image of the SOA-to-passive taper before bonding (Ref. [2]).

performance per quantum well is comparable to mature generic integration schemes, even though the membrane is thermally isolated. Laser operation of the SOA was demonstrated using both wide-band DBR gratings and 1D photonic crystals. A 610 um long 1D PhC laser [2] showed a threshold current of 20 mA (2 kA cm^{-2}), output power of 1 mW, a series resistance of 5 Ω and 30 dB SMSR at 45 mA. Due to the twin-guide structure of the SOA we are free to introduce additional layers below the waveguide layer. It is therefore straightforward to integrate additional active devices. The IMOS platform proposed in this paper is based on this SOA.

High-speed uni-traveling-carrier photodetector

A high speed UTC-PD was fabricated [3] using an IMOS integration technology that allows for double sided processing of the InP membrane [7]. As is shown in Fig. 3a, a p-doped InGaAs below the i-InP waveguide layer, and a n-doped InP layer above are used to form a p-i-n photodiode. The InGaAs absorption layer has a gradient doping for efficient collection of generated electrons, leading to a responsivity of 0.7 A/W. With careful design of the junction and metals (Fig. 3b, 3c) the capacitance is kept low (5 fF). As a result an electrical bandwidth in excess of 67 GHz and open eye diagram at 54 Gbit/s with on-off keyed signal were demonstrated.

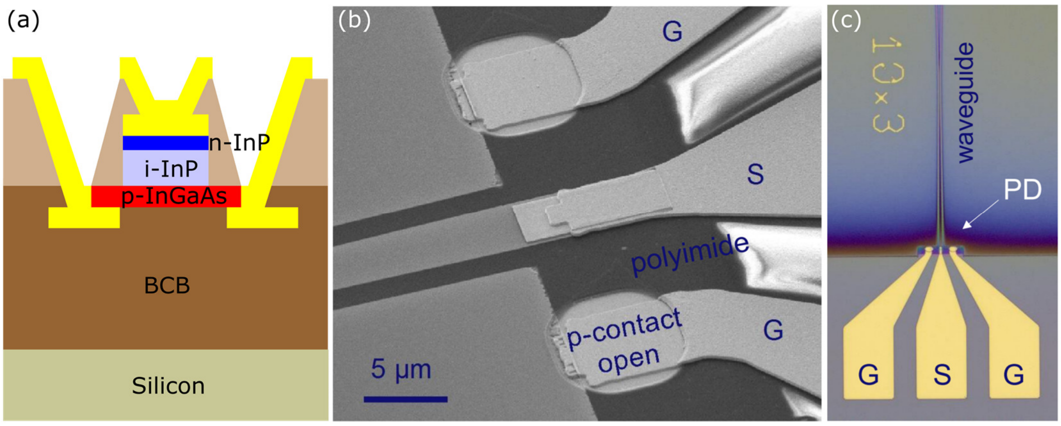

Fig. 3: (a) Schematic cross-section of the UTC-PD, (b) SEM image showing a waveguide (left) entering the UTC-PD (center), (c) optical microscope image of the UTC-PD connected to GSG pads (ref. [3]).

Integrating the UTC-PD with the SOA discussed above is relatively straightforward because the p-InGaAs absorption layer can double as the p-contact layer for the SOA. The SOA layerstack is removed in regions where the PD is desired, we can then overgrow the whole wafer with gradient doped p-InGaAs. Simulations show that the gradient doping in the InGaAs does not increase resistance compared to the original SOA contact.

High-speed electro-optic polymer phase modulator

Modulation is achieved by integrating a phase modulator that is based on a slot waveguide filled with a highly nonlinear electro-optic polymer (Fig. 4a) [4]. A mode converter structure was developed for the rectangular-to-slot waveguide transition (Fig. 4b). The device is predicted to have a $V_\pi \cdot L$ of 0.7 Vmm and a bandwidth exceeding 40 GHz. Integration of such a modulator is relatively straightforward as the n-doped contact layer of the SOA or UTC-PD can be reused to apply an electric field to the slot waveguide. The slot itself is etched in the same step as the passive waveguides, and the light is confined in the lateral direction by an additional shallow etch.

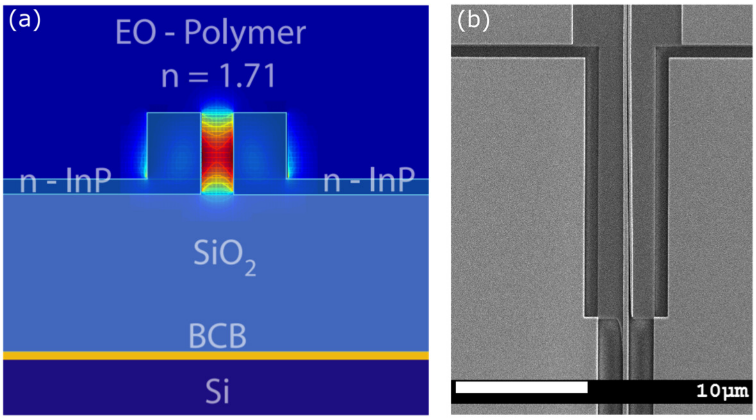

Fig. 4: (a) Schematic cross-section of the EOPPM, (b) SEM image showing the taper from a straight passive waveguide (bottom) to the slot waveguide EOPPM (top) [8].

Integration of actives and passive devices

The proposed platform is based on the high-gain optical amplifier discussed above. As the layers needed for the SOA are located above the i-InP waveguide layer (Fig. 2a), layers are introduced below for use in other devices. The UTC-PD is integrated by placing its n-InP contact layer below the waveguide layer (Fig 5a). After locally etching away the SOA layerstack selectively until the i-InP waveguide, a p-InGaAs layer is overgrown that doubles as the absorption layer of the UTC-PD and as contact layer of the SOA (Fig 5a). The interface between the SOA and UTC-PD layer stacks is removed using selective wet etching to reach the i-InP waveguide layer (Fig. 5b). Processing on the top side of the wafer continues (Fig. 5c) before being bonded to the silicon carrier wafer. After bonding, the InP substrate is removed and processing on the other side of the membrane continues (Fig. 5d). The EO-polymer slot-waveguide phase modulator is realized by reusing the n-InP contact layer of the UTC-PD. Furthermore metal deposition on top of the polyimide (PI) enables high-speed metal connections, GSG contacts, routing of metal contacts above waveguide circuits, thermal tuning of passives and heatsinking to the silicon carrier wafer.

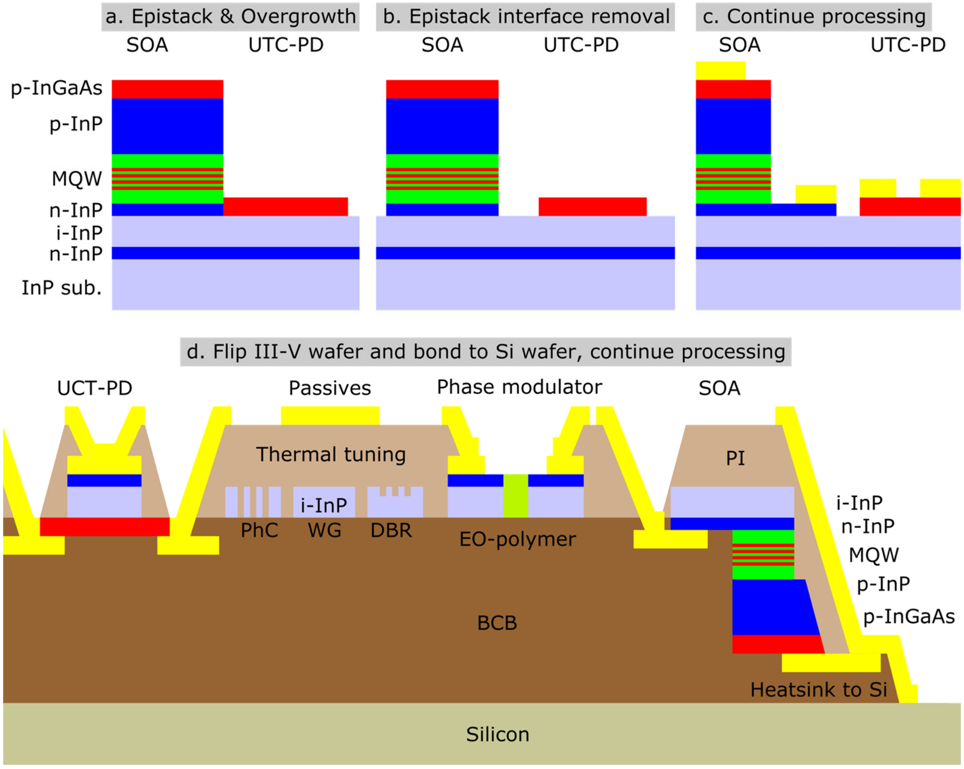

Fig. 5: Cross-section and process flow of the proposed IMOS platform that integrates a high-speed UTC-PD, EOPM, SOA as well as tunable passives.

Conclusion

In this paper a fully integrated membrane photonics platform on silicon is proposed that integrates an SOA, UTC-PD and EOPPM with thermally tunable passives and heatsinking capabilities to the silicon carrier. By combining layer reuse, double sided processing and overgrowth maximum flexibility is obtained while keeping fabrication complexity limited.

References

[1] J.J.G.M. van der Tol et al., “Photonic integration in Indium-Phosphide Membranes on Silicon (IMOS)”, Proceedings of SPIE, Vol. 8988, 2014.
[2] V.G. Pogoretskiy et al., “An Integrated SOA-building block in a InP-membrane platform”, JW4A.1, Advanced Optics Conference: OSA Optics & Photonics Congress (IPR), 2017.
[3] L. Shen et al., “High-bandwidth uni-traveling carrier waveguide photodetector on an InP-membrane-on-silicon platform”, Optics Express, Vol. 8290, 2016.
[4] A.J. Millan Mejia et al., “Fabrication technology of a slot waveguide modulator in InP Membranes on Silicon (IMOS)”, 18th European Conference on Integrated Optics (ECIO 2016), Warsaw.
[5] D. Inoue et al., “Integrated Optical Link on Si Substrate Using Membrane Distributed-Feedback Laser and p-i-n Photodiode”, IEEE Journal of Selected Topics in Quantum Electronics, Vol. 23, No. 6, 2017.
[6] T. Sato et al., “Photonic Crystal Lasers for Chip-to-Chip and On-Chip Optical Interconnects”, IEEE Journal of Selected Topics in Quantum Electronics, Vol. 21, No. 6, 2015.
[7] L. Shen et al. “Double sided processing for membrane-based photonic integration”, 18th European Conference on Integrated Optics (ECIO 2016), Warsaw.
[8] A. Millan-Mejia, “Design and simulation of a high bandwidth optical modulator for IMOS technology based on slot-waveguide with electro-optical polymer”, Proceedings of the 18th Annual Symposium of the IEEE Photonics Benelux Chapter, 2013.