InP membrane on silicon (IMOS) photonics

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Jos van der Tol, Yuqing Jiao, Jorn van Engelen, Vadim Pogoretskiy, Amir Abbas Kashi, Kevin Williams

***Abstract*—InP membranes have appeared in the last decade as a viable integrated photonics platform, suitable for adding photonic functions to silicon electronics. It combines the strengths of silicon photonics (high index contrasts and therefore small footprint devices) with those of generic InP-platforms (monolithic integration of active and passive devices). A range of functionalities has been developed on this platform, which goes by the name of IMOS (Indium phosphide Membrane on Silicon). Competitive performances have been demonstrated for lasers, fast detectors, waveguides, filters, couplers, modulators and more. Here we provide an overview of IMOS and describe recent developments regarding technology and devices. This includes record low propagation losses, plasmonic waveguides, a variety of laser structures and improved wavelength demuliplexers. These developments demonstrate that IMOS has potential to deliver photonic integrated circuits to a wide variety of application fields, e.g. telecom, datacom, sensing, terahertz and many others.**

***Index Terms*— Indium Phosphide, Membranes, Lasers, Photonic integration, Waveguides**

I. Introduction

Higher integration densities in silicon electronics lead to an impeding communications bottleneck [1]. Optical interconnects are therefore proposed, to be combined with electronic chips. This has given rise to SOI (silicon-on-insulator) photonics. However, within SOI-platforms light sources are not available, hence solutions based on heterogeneous integration with III-V semiconductor are developed [2]. Alternatively, it is possible to create a III-V photonic layer separate from the silicon, as a thin membrane on top of the CMOS-chip [3]. This technique, InP-Membrane On Silicon (IMOS), avoids the need for photonic waveguides in the silicon. It provides a full set of photonic functions and is implemented with a flexible bonding technique that provides thermal isolation. IMOS allows small footprint and low power consuming devices. The technique does not interfere with standard processing of electronic circuits. Here we will present an overview and describe the recent developments of IMOS. In particular new and not previously published results will be reported on improvements from wafer scanning technology, plasmonic waveguides and new laser structures. Finally, we will discuss the perspectives of the IMOS-platform.

II. IMOS Concept

The basic idea of the IMOS platform is depicted in Figure 1. Using post-processing techniques a thin membrane of InP is bonded with a benzocyclobutene polymer (BCB) to a CMOS wafer. The membrane photonic layer contains both active (lasers, detectors, modulators) and passive (waveguides, filters, couplers, demultiplexers) devices. Only electrical contacts are needed between the electronic and photonic layers, which substantially reduces alignment requirements as compared to optical couplings. The integration with CMOS is a longer term perspective of IMOS, and is so-far not yet demonstrated. The technology developed to realize the photonic membrane circuits is described in [4,5]. Using optimized E-beam lithography and plasma etching, processing of both sides of the membrane and careful bonding to silicon carrier wafers, high quality waveguides and a range of well-performing photonic devices are demonstrated. Here we will present some of our latest results on active and passive devices.

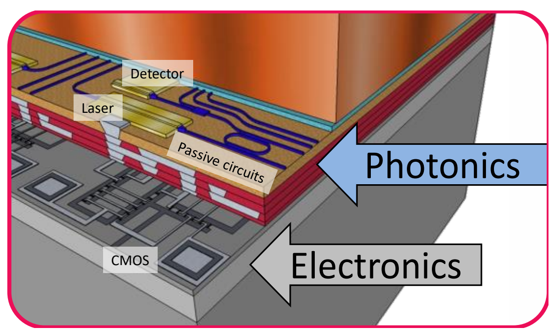

Fig. 1. Artists' impression of the InP membrane platform, with high-confinement active and passive photonic components in the InP membrane circuit, and in close connection with CMOS electronics [3].

III. Earlier Results

Table I reports on a number of devices that have been realized before in the IMOS-platform. These show several record performances for InP-based membrane photonics [3].

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General characteristics are the small footprints, as a consequence of the high index contrast in the membrane, large electrical bandwidth and reproducibility in the realizations, demonstrating the high quality of the developed technology.

TABLE I
REALIZED IMOS DEVICES [3]

Device	Dimensions	Main performance parameters	Remarks
UTC-Photodiode [6]	10×3 μm^2	0.7 A/W responsivity >67 GHz bandwidth	3 dB bandwidth extrapolated to 110 GHz
90° bend [7]	0.96 μm radius	0.13 dB/90°	Low loss and reflection
Arrayed Waveguide Grating [8]	0.2 mm^2	10 dB loss	10 dB crosstalk
Planar Concave grating [9]	400x600 μm^2	4 dB loss	25 dB crosstalk Thermal tuning over 3.7 nm
Polarization converter [10]	5 μm long	<1 dB loss	Conversion 99%
Ring resonator [11]	7 μm radius		Q-factor 62000
1x2 MMI coupler	2×3 μm	0.6 dB loss	

IV. NEW DEVELOPMENTS

IMOS technology has improved to allow a wider range of devices, and better performance parameters. Furthermore also the yield of the processing is improved, especially by introducing state-of the art techniques for BCB-bonding of the membranes. Here we will highlight some of the latest achievements.

A. *Wafer scanner technology*

The propagation loss of high contrast waveguide devices is critically dependent on the lithography, because of the high modal overlap with the sidewall roughness. Using special E-beam resists [4] low losses were obtained. Now we have realized devices with even better performances, using an ASML PAS5500/1100B scanner lithography tool [11].

The propagation loss was measured with a ring resonator (fig. 2, left), by analyzing its spectral response (Fig. 2, right). Record low values for InP-membrane waveguides of 1.8±0.1 dB/cm were found, which is significantly below the previously obtained lowest values [4]. This indicates a much reduced sidewall roughness.

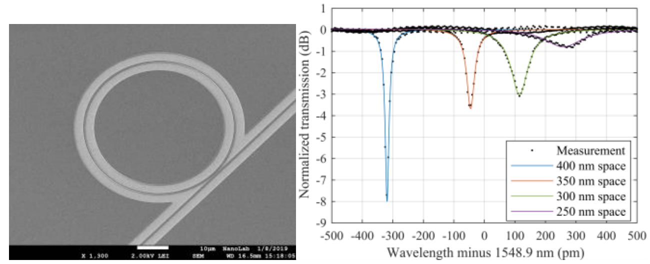

Fig. 2. Results from wafer scanner lithography. Left: SEM-picture of a ring resonator, Right: transmission spectra for four identical rings with different coupling gaps to the straight waveguide.

B. *Arrayed Waveguide Grating (AWG)*

Wavelength demultiplexers using the AWG-principle are challenging for membrane platforms. This is because the phase noise in the high contrast waveguides of the array can be large, due to sidewall roughness. Also a phase error can occur due to poor definition of the array arms. Using the wafer scanner lithography it is however possible to reduce the roughness and improve feature size control, resulting in better performance. Figure 3 at the top shows a realized AWG with this technique, while at the bottom the measured spectral response is given. Losses of 3.5 dB and crosstalk levels of better than 20 dB are obtained; much improved w.r.t. the device reported in Table 1.

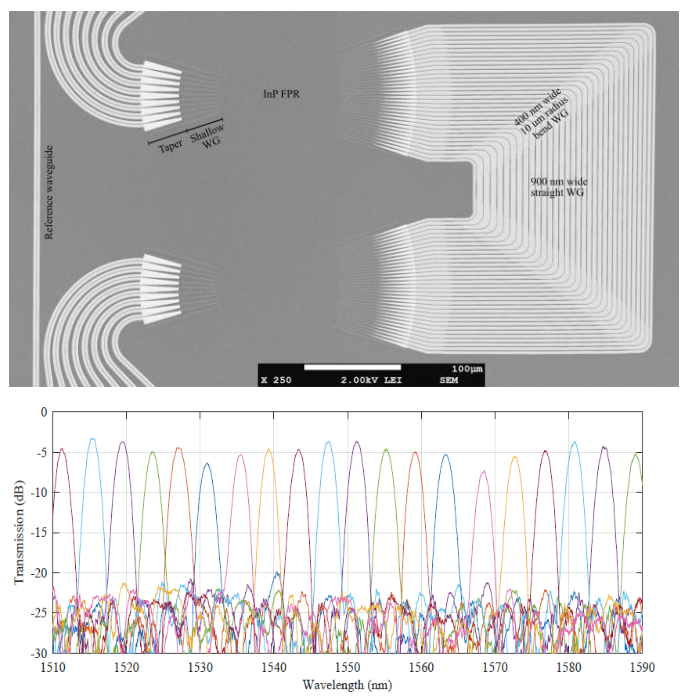

Fig. 3. Top: The AWG realized with wafer scanner. Bottom: spectral response of the AWG.

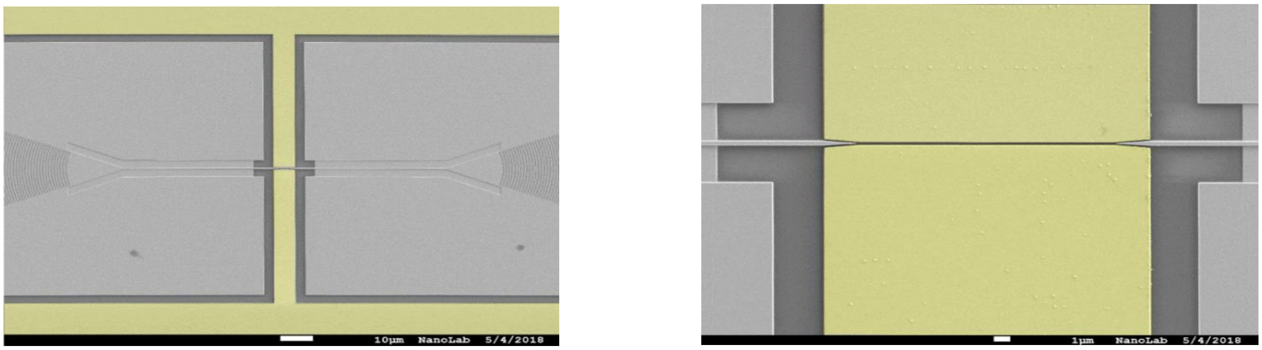

Fig. 4. Left: overview of the plasmonic measurement structure, connected with waveguides to gratings for input and output coupling. Right: Slot in the metal sheet to form the plasmonic waveguide, coupled with tapers to the dielectric waveguides.

C. Plasmonic waveguides.

Plasmonic based components have been proposed as an alternative for conventional approaches to high speed modulators, with low-energy drivers and small footprint [12,][13]. Recent advances in plasmonic modulators have shown the potential of these structures to reach modulation bandwidths beyond 170 GHz [14],[15]. Among all plasmonic modulators, the plasmonic-organic hybrid (POH) approach allows the highest modulation bandwidth, thanks to the combination of the metal slot waveguide with the fast electro-optic (EO) polymers. The slot provides a very high overlap of the optical field of the surface plasmon polariton (SPP) mode with the polymer.

Here, we demonstrate a plasmonic slot waveguide for the first time on a InP membrane. The slot of this structure is filled with an EO polymer and can be used as a high speed phase shifter in a Mach-Zehnder modulator.

The plasmonic slot waveguide is composed of a metal-insulator-metal (MIM) structure coupled with conventional InP membrane waveguides, as depicted in Figure 4.

Light from a fiber couples into the conventional membrane waveguide with a surface grating coupler. A taper converts the waveguide mode to the SPP mode in a 200 nm wide slot. The SPP mode propagates through the slot and couples back to the waveguide mode through a second taper, and couples out with another surface grating coupler.

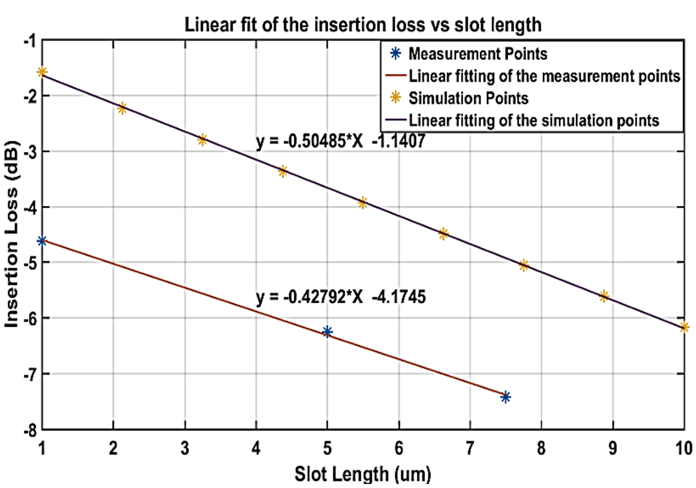

Figure 5. Linear fit of the measured and simulated insertion loss versus metal slot length.

A lift-off process is used to create the plasmonic metal slots in the metal layer, which consists of three sublayers, 30 nm Ni, 50 nm Ge and 250 nm Au, respectively. These metals are not optimal for low loss plasmonics, but they are convenient in the context of IMOS because the same metal layer stack is used for contacts in the active devices.

In Figure 5, a linear fit of the insertion loss versus the metal slot length is shown. The propagation loss in the metal slot and the coupling loss between the semiconductor taper and metal slot are determined from this graph

A propagation loss in the plasmonic slot as low as 0.43 dB/µm is achieved which is comparable to the state of the art achievements for plasmonic waveguides [14]-[16].

D. Lasers

Based on processing both sides of the membrane a SOA structure was developed, using a twin-guide approach (fig.6) [17]. This SOA was used in various laser structures, the performances of which are given in Table 2.

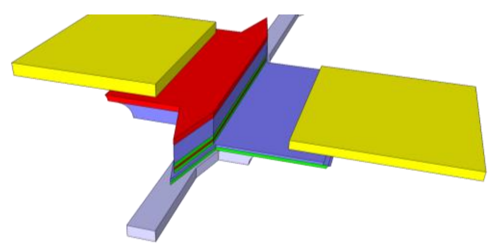

Fig. 6. Twin-guide amplifier structure used for various IMOS laser demonstrations. The gray line is the passive waveguide, on top of which the active layer stack, based on quantum wells, is placed. Tapers couple light between the active and the passive layers. An S-shaped design is used, with the p-side contact on top and to the left, while the n-side contact is below and to the right [17].

One of the lasers incorporates two ring resonator filters (see Fig. 7), which can be thermally tuned [18]. The laser cavity is only closed when the resonances of the two rings align, which gives a Vernier effect. Therefore, with relatively minor tuning of one ring, substantial wavelength shifts from the laser can be obtained. Fig.8. shows the spectra from the laser under various tuning conditions, by adjusting the current through one of the

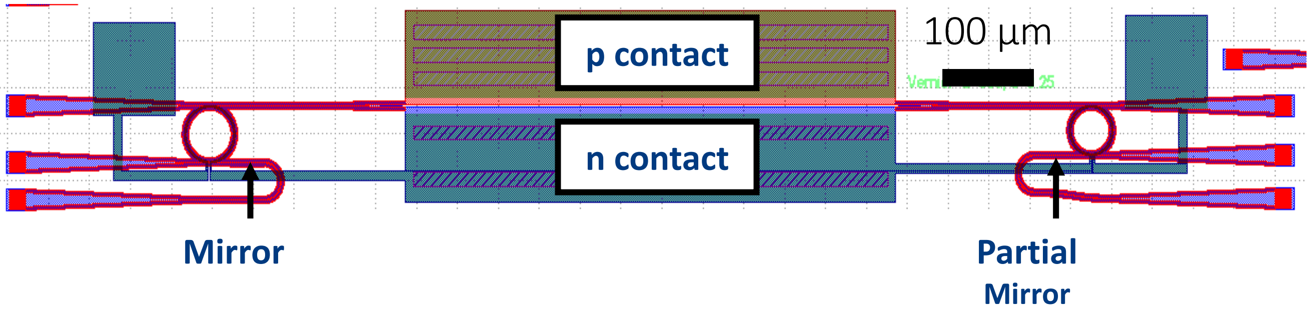

Fig. 7. Schematic representation of the tunable laser. The laser cavity runs through the two ring resonators. Only if the resonances of them are aligned a closed cavity appears. Both rings can be thermally tuned with a heater. [17].

rings. The results indicate that 25 nm of wavelength tuning is achieved.

TABLE II
DEMONSTRATED LASERS IN IMOS

	Threshold current density	Output power	SMSR	Tunability
DBR laser	2 kA/cm^2	1 mW	30 dB	/
DFB laser	2.5 kA/cm^2	10 mW	60 dB	/
Tunable laser	2.4 kA/cm^2	0.44 mW	>30 dB (45 dB highest)	25 nm

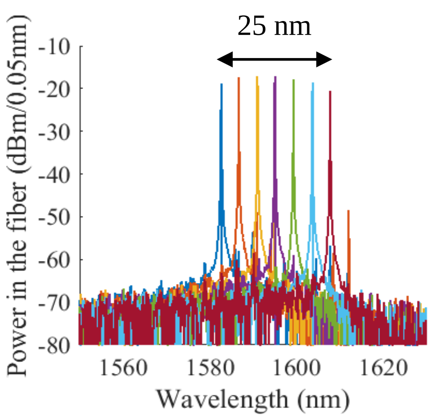

Fig. 8. Spectra of the tunable laser, for different heater current through one of the ring resonators [17].

V. PERSPECTIVES

The IMOS platform is maturing, as is illustrated by the results reported here. There are still some major steps that needs be taken. The integration of the full set of photonic functions and devices as yet has to be demonstrated. One crucial aspect for this is flexibility in material bandgaps. With the twin-guide concept, which aims at a single growth process, we can have two different active layer stacks, one on each side of the passive waveguide layer (Fig. 9) [19]. In this way we can e.g. combine passive functions with a laser and a UTC-PD.

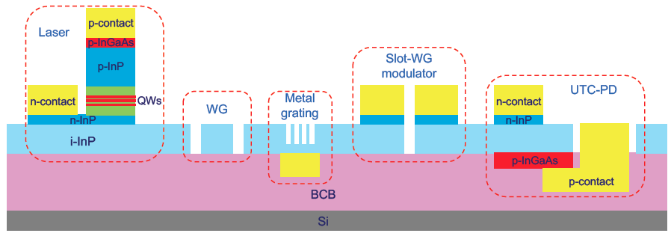

Fig. 9. Integration platform concept based on the twin-guide approach. All devices are linked by the central, light-blue, passive layer. Using double-side processing, with a single epitaxial growth two active layer stacks can be added, in this case one for the amplifier/laser structure (left side) and one for the UTC-PD (right side) [19].

However, if more active functions are required, like an electro-absorption modulator (EAM), or lasers covering different wavelengths, this approach will be too limiting. Therefore a redesign of the platform is considered, in which regrowth techniques are used, similar to the approach used in generic integration on InP [20]. Not only does this allow a broader range of active functions, but, since the active and passive functions will now be in the same membrane layer, it also avoids the use of tapers for coupling between different layers. This leads to a further reduction in device sizes, and thus to higher integration density. Moreover, it opens up the path to optimization of layer stacks for other functions, like a band-filling based EAM [21]. It even will allow a flexible, application oriented, use of the platform; for example including different active materials suitable for other wavelength ranges, that are relevant for sensing. Fig.10 depicts how this architecture can look like.

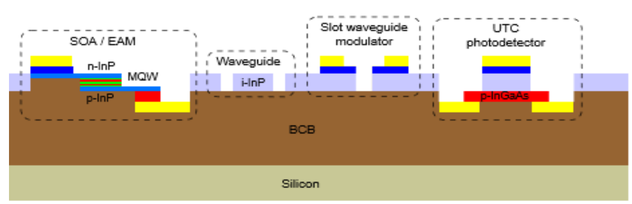

Fig. 10. Integration platform concept based on the active-passive regrowth approach. All devices are aligned to the central layer. With multiple epitaxial growths various active layer stacks can be added, in this case one for the amplifier/laser structure (left side) and one for the UTC-PD (right side).

To finally demonstrate the full potential of the IMOS platform the hybrid integration with electronics will be developed. Here the platform has the major advantage that it allows photonic membranes to be added to an electronic circuit in a post-processing step. This avoids any interference with highly standardized production processes in the electronics industry, and moreover provides the opportunity to combine IMOS with any sort of circuitry, even non-silicon based ones like InP or GaAs electronics. To realize functioning photonic-electronic circuits in this way it becomes essential to use a co-design approach. This will lead to optimized combined structures, reducing power consumption and increasing frequencies. This is very similar to the path explored in the European project WIPE [22]. The electrical connections between the electronics and the photonic devices is achieved there with vias through the BCB bonding layer. A similar concept will work for IMOS as well.

VI. Conclusions

The latest developments of IMOS, a membrane based photonic integration platform, are presented. Waveguide loss as low as 1.8 dB/cm is obtained as well as improved performance on demultiplexers and plasmonic waveguides. Furthermore the integration of SOAs into various laser cavities is shown, with good results.

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Yuqing Jiao was born in Hangzhou, China. He obtained PhD degrees from both Eindhoven University of Technology, the Netherlands, and Zhejiang University in China in 2013. Since then he continued his research at Eindhoven University of Technology. Since 2016 he is appointed as an assistant professor at the Institute of Photonic Integration (IPI, former COBRA Research Institute) of the Eindhoven University of Technology. His research topic is focused on a novel III-V based nanophotonic platform. He is focusing on ultrafast and strong light-matter interactions in sub-micrometer optical confinement. Applications span from optical interconnects, ultrafast photonic devices, to optical beam steering and optical sensing. He has strong background and expertise in a wide range of photonic materials (from silicon to III-V) and nanotechnologies. He has (co-)authored more than 30 international journal publications and 70 conference papers. He is a member of the IEEE Photonics Society and the Optical Society of America. Currently he serves as a board member of IEEE Photonics Society Benelux Chapter.

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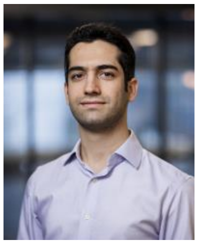

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