INSPIRE: InP on SiN photonic integrated circuits realized through wafer-scale micro-transfer printing[1]

M. J. R. Heck
Eindhoven University of Technology, Eindhoven Hendrik Casimir Institute, the Netherlands
*email: m.heck@tue.nl

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ABSTRACT

INSPIRE will sustain Europe's industrial leadership in photonics by combining the generic integrated foundry technology at the pioneering pure-play foundry SMART Photonics, and the silicon photonics pioneer imec, with the micro-transfer printing technology developed at X-Celeprint. This will be a world-first platform combining the strengths to create best-in-class photonic integrated circuit (PIC) manufacturing. Furthermore, INSPIRE will strengthen the European manufacturing base by developing and implementing processing steps that are key to removing expensive assembly steps in PIC-based product realization. The methods will be developed for silicon nitride – indium phosphide integration. Since the optical coupling happens through a silicon intermediate layer the developed technology can be further ported to silicon, CMOS-compatible, photonics as well. INSPIRE will connect state-of-the-art manufacturing capability to leading-edge applications, and also to industry clusters through JePPIX, ePIXfab and the EC manufacturing pilot lines.

Keywords: integrated photonics, laser diodes, microwave photonics, micro-transfer printing

1. RATIONALE

The impact of photonic integration is currently exponentially increasing. Communication is the field that traditionally drives photonic integration, starting from the 1990s. Where arrayed waveguide gratings and discrete laser diodes initially enabled our long-distance fiber-optic communication links, we have seen in the decades thereafter an increased penetration of this technology into the shorter link lengths, such as fiber to the home and within datacenters. At the same time, we have seen an increasing amount of integration of lasers, photodiodes, modulators and multiplexers on a single chip, to enable the increasing demand for bandwidth.

This increased integration goes hand in hand with the maturing of a few platforms for photonic integration. A higher integration density requires platforms that are more robust, in terms of yield, reproducibility, and electro-optic performance. Since these demands increase, vice versa a more focused effort is needed to sustain these platforms. Given the diversity of needs, the field has not yet converged on a single main platform. In Table 1 the three main platforms are shown, each with their strengths and weaknesses.

The indium phosphide (InP) based platform has the most complete set of building blocks, including laser sources, optical amplifiers, high-bandwidth modulators and photodetectors, and a complete set of passive blocks, such as waveguides, splitters and multiplexers [1]. The manufacturing processes suffer from using an InP substrate, though. This limits scaling in volume, due to smaller wafer size than competing technologies, and limits packaging approaches, as wafer-level assembly techniques are typically optimized for silicon substrates. Silicon nitride (SiN) based platforms are manufactured using semiconductor (CMOS) compatible wafers, materials and tools, and can thus benefit from that infrastructure. Their low material loss makes them ultimately useful for applications that required low insertion loss or

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long delay lines [2]. The functionality, however, is limited to passive operation, as active blocks, such as lasers, modulators, and photodetectors are not native in this platform. Using silicon as a waveguide layer partially solves this, and diode-based modulators can be realized by doping the waveguides, using well-known techniques from the electronic semiconductor manufacturing. Adding germanium to the process flow gives access to detectors [3].

All of these platforms are now commercially available, either directly from foundries, as custom runs, or through so-called multi-project wafer runs, offered by both industry and institutes. The European Union and many of its member states have pioneered these, through coordinated efforts like JePPIX and ePIXfab. The EU's commitment to continuing development and the emphasis on their importance is now subject of various broad investments in the field of semiconductors, e.g., through the European Chips Act.

Referring to Table 1 again, it can be seen that there is no platform that excels in all key metrics. Although this might not matter for many applications in communications, as shown by the market uptake of these technologies, it does prevent the use of photonic integration in some more high-end applications. Specifically, as key topics of the INSPIRE project, applications in microwave photonics and fiber sensing require the low-loss passives, to ensure low-noise operation [4]. Also, high-port-count switches require such low loss and energy-efficient switching [5]. There is thus a clear market for a PIC platform that combines the best of all these three platforms. The question is how this can be done in the best way.

Table 1. Qualitative overview of key strengths and weaknesses of the main PIC technology platforms, compared to the INSPIRE approach.

PIC platform attributes	Indium phosphide	Silicon Nitride	Silicon (CMOS) photonics	INSPIRE
Light sources and amplifiers	✓✓✓	✗	✗	✓✓✓
Electrical energy efficiency	✓✓	✗	✓✓	✓✓
Electro-optic speed	✓✓	✗	✓✓	✓✓✓
Optical connect efficiency	✓	✓✓✓	✓	✓✓✓
Optical signal integrity	✓✓	✓✓✓	✓	✓✓✓
Robustness	✗	✓✓	✓✓	✓✓
Production scalability	✓	✓✓	✓✓✓	✓✓✓
Active device scaling	✓	✗	✗	✓✓
Passive device scaling	✓	✓	✓✓✓	✓✓
Hosting exotic materials	✓	✓✓✓	✗	✓✓✓
Route to 3D integration	✓	✓✓	✓✓✓	✓✓✓

2. INSPIRE APPROACH

The INSPIRE consortium assessed that micro-transfer printing is the most promising way to combine III-V materials, in our case InP, with silicon-substrate photonics, in our case SiN. In micro-transfer printing, different materials are heterogeneously combined by transferring coupons of one material to a wafer of another material, as shown in Figure 1. Very promising results have already been obtained, for example as detailed in [6].

The advantages of micro-transfer printing are outlined in Table 2. The approach is compared to various other techniques, that are often used. Laser micro-packages (LaMP) are traditionally used in silicon photonics, and give the industry the choice of a variety of off-the-shelf laser diodes to integrate into a package, that can further include an isolator and collimation optics. This package is then placed on a silicon-photonic wafer, coupled through a grating coupler, for example. Mature lasers can be used, but this technique does not scale well to higher integration densities. Flip-chip bonding of laser dies is typically done using solder pads and etched features in the target wafer, which limits the integration density somewhat. Wafer and die bond approaches, i.e., processing the III-V after layer transfer to the silicon-substrate wafer, scale very well, but are practically limited by the requirement of a single process flow, which is then unique for the technology. Micro-transfer printing offers advantages in all metrics of interest, in principle. Most importantly, it allows for the combination of mature process flows, in our case the InP process of SMART Photonics and the SiN process of imec. This gives the flexibility and modularity that will eventually be required by the industry.

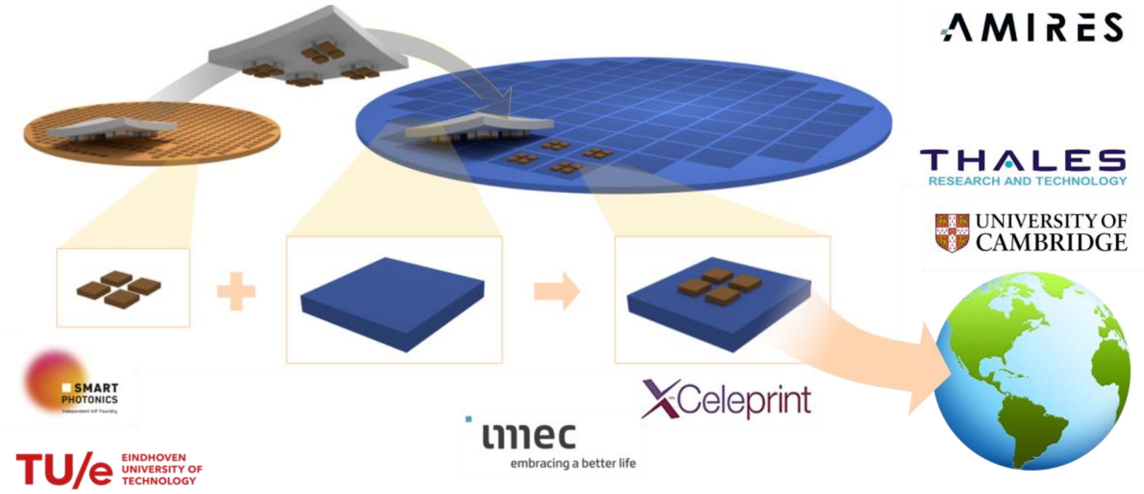

Figure 1. Schematic of the micro-transfer-printing process. InP actives are fabricated on their native substrate, and then etched into a membrane, supported only by small tethers. SiN passives are fabricated on a silicon substrate. The InP coupons are then picked up by a stamp, and transferred to the SiN wafer. The coupons are aligned with sub-µm precision, to allow efficient light transfer from InP to SiN and vice versa, through inverse taper couplers. Demonstrators will show the feasibility and viability of this approach.

Table 2. Qualitative overview of the key strengths and weaknesses of various techniques to combine silicon and silicon nitride photonics with III-V based photonics.

	LaMP	Flip-chip	Wafer-bond	Micro-TP
InP PIC maturity	✔	✔	On target wafer	✔
Optical coupling efficiency	✔	✔	✔	✔
Waveguide in-out devices	None	✔	✔	✔
Wafer level test and assembly	✔	✔	On target wafer	✔
Burn in	✔	✔	On target wafer	✔
Population of InP devices	Sequential	Sequential	✔	✔
Laser performance	✔	✔	✔	✔
Back end process integration	✔	✔	Substrate removal	✔
Density and volume	Micro-optics	Solder pad limit	✔	✔
Reduced barriers for new PICs	✔	✔	✔	✔

3. INSPIRE OBJECTIVES

INSPIRE has three key objectives. Firstly, it will expand the set of building blocks available in the micro-transfer printing platform. This includes the development of gain block arrays, for a tenfold higher integration density, and high-bandwidth modulators and photodiodes, at 4-5 times higher integration density. These will be integrated with SiN waveguides, which will have a reduced loss of about 5 dB/m, to allow for ultra-low noise PICs.

A second objective is to realize three validation demonstrators. The INSPIRE project aims to show beyond-state-of-the-art noise performance in a microwave photonics engine and a distributed fiber sensor, at a decreased size of the full system. The micro-transfer printing approach is a critical enabler for actually integrating such systems, while still having the required performance. Furthermore, an optical switch matrix will be realized, scaling to 32 input and output ports. The key enabling aspects of the INSPIRE platform will be the high integration density and the low-loss performance.

Finally, the third objective is to show the industrial viability, by laying out a clear route to a future Pilot Line based on mature foundries. This includes getting a grasp on yield, to increase process robustness. A first step will be taken to set up a process design kit, based on compact models.

4. IMPACT

The main impact of INSPIRE will be to establish a world-first platform that combines low-loss SiN waveguides with InP actives. By aligning this with mature foundry processes, our approach will sustain Europe's industrial leadership in photonics. This approach can, and will, be further extended to include micro-transfer printing on silicon photonics. This positions the platform, and thus Europe, well in the market, as such tight integration will be a critical requirement in the next decade, for example for chiplets that will be used for chip-to-chip communications.

To maximize this impact, and to smoothen the transition to the market, beyond the duration of the INSPIRE project itself, we have aligned ourselves with the main organizations in the field, such as JePPIX and ePIXfab, as lead coordinating entities for all the main technology platforms in Europe, and with the MICROPRINCE Pilot Line, for future scaling of volume of micro-transfer printing. The JePPIX Pilot Line is up and running for InP technology, and the imec 200-mm Pilot Line is running a SiN process for the 1.3 µm to 1.55 µm wavelength range. Figure 2 summarizes the envisioned impact of INSPIRE.

The Partners in the INSPIRE consortium are Eindhoven University of Technology, the Netherlands, imec, Belgium, SMART Photonics, the Netherlands, X-Celeprint, Ireland, THALES, France, University of Cambridge, UK, and AMIRES, Czech Republic.

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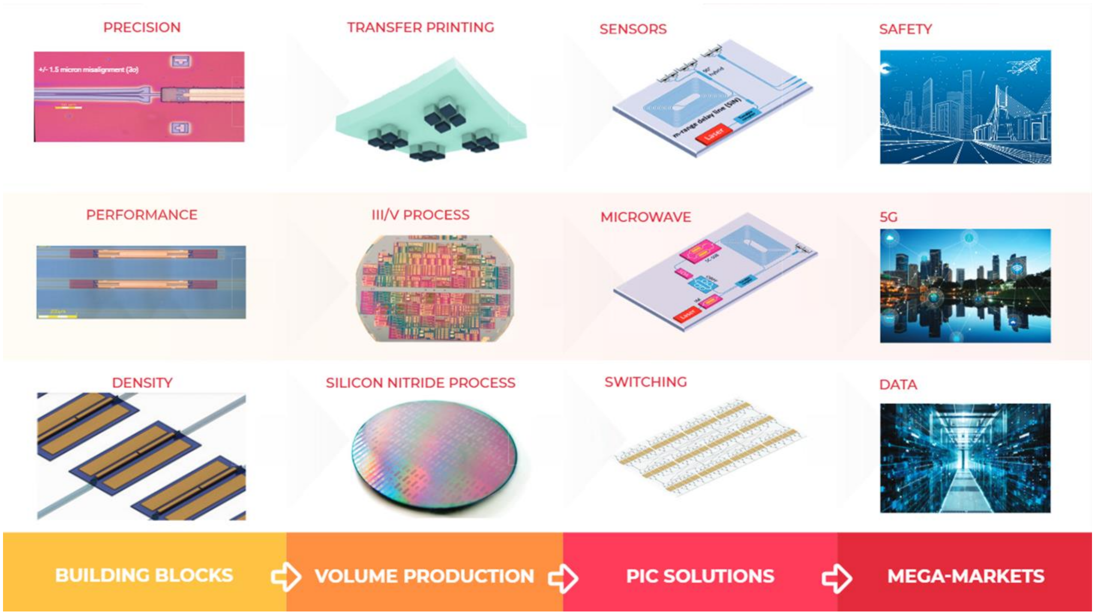

Figure 2. Schematic of the envisioned impact of INSPIRE. The competitiveness of the micro-transfer printing process will be increased by improving the precision of assembly, the performance of the building blocks, and the density of integration. Using mature transfer printing tools, applied to mature InP and SiN fabrication processes, we will then show the viability for applications in sensing, microwave technology and switching. These demonstrators are important for the broader fields of safety, 5G and data, highlighting the wider societal impact of INSPIRE.

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