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Foundry developments towards silicon nitride photonics from visible to the mid-infrared

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Abstract

Photonic integration technologies have spread in the past decade by means of foundry models that mirror the electronic integrated circuit industry developments of the past century. Several monolithic technologies exist, based on silicon and III-V semiconductors. In this paper, we discuss the current state and forthcoming developments of open access photonic foundries whose technology platforms are based on silicon nitride material. The paper presents various silicon nitride technologies and foundries, alongside with access models supported by generic integration and process design kits. Technical features, enabled by different micro-fabrication processes and tools are summarized. Application examples and developments of forthcoming incorporation into these platforms are outlined.

Index Terms

photonic integration, silicon nitride, generic technology, foundry model, open access, silicon photonics, multi-project wafer, visible light, near-infrared, mid-infrared, tele/data-com, bio/life sciences, environmental sensing, automotive.

I. INTRODUCTION

Photonic integration technologies have become central for a large number of incumbent and niche applications, in similar way as micro-electronics developed a few decades before [1]. With photonics as a key enabling technology [2], integration is the natural path towards cost-effectively populating application markets with stable, portable and low power consumption devices, analog to the spread of electronic integrated circuits. Whilst the main application drivers for photonic integration technologies developments are in the field of tele/datacom [3, 4], these are progressively entering other domains such as civil engineering [5], bio and life sciences [6], environmental sensing [7–10] and automotive [11], among many other.

In a natural way, the initial efforts in the development of photonic integration technologies were devoted to monolithic integration, so as to establish stable and accesible individual platforms. A key factor was the incorporation of generic technology philosophy [12, 13]. These early activities resulted into three mainstream technologies, based on Silicon (Si), Indium Phosphide (InP) and Silicon Nitride (SiN) materials [14–17]. Nonetheless, current reviews and roadmaps [18–20] advocate for hybrid and heterogeneous integration [21, 22], acknowledging the use of a single material platforms cannot encompass all the existing applications. The monolithic combination of Si and SiN films has been also subject of research [23, 24].

While undoubtedly, efficient light generation and amplification is brought by III-V semiconductors, with detection and modulation, also present in Si photonics, the very basic function of guiding light is the key advantage of SiN photonics, both in the linear and non-linear regimes, supported by the inherent optical broadband of Si_3N_4, from visible (VIS) well into mid-infrared (MIR) wavelengths [25, 26]. With respect to the purely passive function, as compared to Si guiding based and Silica platforms (so called planar lightwave circuits, PLC [27]), SiN photonics combines good features of both. Compared to PLC, it provides reduced footprint, due to higher index contrast and hence confinement of the optical mode, but with comparable propagation losses. The latter is an advantage when compared to Si nanowire photonics [14], but not to thick Si photonics [17]. Hence, SiN can be broadly speaking a platform that combines good propagation loss figures and footprint, with the added value of covering the VIS wavelength range as well.

Despite SiN material is widely used in the fabrication of microelectronic circuits as a support material [28], its use in photonics was not reported until 1977, with the first fabrication of SiN films on a SiO_2 buffer on Silicon wafers, for light

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propagation in the red visible wavelength (632 nm) [29]. This was followed by a series of works in the 1980s using visible light. Nonetheless, the application of this material to a functional device was demonstrated in 1993 [30], where the arms of a Mach-Zehnder Interferometer (MZI) for immunosensing assays were SiN/SiO_2 waveguides, while the optical couplers for the interferometer were external bulk optics. A fully photonic integrated circuit (PIC) incorporating a MZI sensor was reported a few years later [31], and with the beginning of the new century, works on this material in the near infrared (NIR) start to appear [32–37]. At the start of the present decade, there is a regained interest in visible light applications [38–40], but furthermore, demonstrations of SiN PICs for the long NIR wavelength band [41–44], with more and more SiN PICs and platforms being developed [45–47]. A detailed review can be found in [26]. Among other, a key aspect in these technology developments has been the aim at reducing propagation loss. Firstly, with the aim of reducing the effect of sidewall roughness, two opposite approaches can be found. On one hand, resorting to very low confinement waveguides, in which the optical field is majorly outside the (thin) nitride guiding layer, and thus propagating through the SiO_2, resulting in world-record values down to 0.001 dB/m [36], at the expense of circuit footprint. On the other, resorting to strong confinement (thick) waveguides, with values as low as 0.067 dB/cm [48, 49]. For medium confinement platforms, processing techniques so as to alleviate etch induced roughness have been applied [26, 50, 51].

TABLE I

Open foundry silicon nitride generic technologies and process design kits (abbreviations explained in the text). Technologies are from LioniX international (LX), Ligentec (LGT), Instituto Nacional de Micro-electrónica CNM-CSIC (CNM) and imec.

			BBs in	**Couplers**			**Optical I/O**			**Tuning**	**Trench**		**Filter**			**Time (months)**
Technology	**Broker**	**Direct**	**PDK for**	**DC**	**MMI**	**Y-b**	**GC**	**SSC**	**INVT**	**Thermo**	**Well**	**Deep**	**RR**	**AWG**	**DBR**	**GDS to chip**
LX-SS	-	Yes	Syn	✓	✓	✓		✓	✓	✓			✓			<3
LX-ADS HIC	JePPIX	Yes	Syn/VPI	✓	✓	✓		✓	✓	✓			✓	✓		
LX-ADS LIC	JePPIX	Yes	Syn/VPI	✓	✓	✓		✓	✓	✓			✓			
LX-SS-VIS	PIX4life	Yes	Syn	✓	✓	✓		✓		✓	✓	✓				
LX-DS-VIS	PIX4life	Yes	Syn	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		
LX-SS-NIR	-	Yes	Syn	✓			✓	✓		✓	✓	✓	✓			
LX-box HIC	JePPIX	Yes	Syn	✓	✓	✓		✓		✓			✓	✓		
LX-box LIC	JePPIX	Yes	Syn	✓	✓	✓		✓	✓	✓			✓			
LX-Buried	-	Yes	Syn	✓					✓	✓			✓			
LGT-AN150	VLC	Yes	Syn/Luc	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	2019	2 +0.75(TO) +0.75(WELL)
LGT-AN800	VLC	Yes	Syn/Luc	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	2019	
CNM-MINI	VLC	-	Syn						✓		✓	✓				<3
CNM-RIB	VLC	-	Syn	✓	✓		✓			✓	✓	✓	✓	✓	✓	
CNM-STRIP	VLC	-	Syn		✓					✓	✓	✓	✓	✓	✓	
CNM-VIS	-	Yes	2019	✓		✓	✓		✓		✓	✓				2
BIOPIX300	PIX4life	Yes	Syn/Luc	✓	✓	✓	✓	✓		in dev.	in dev.	in dev.	✓	✓		4
BIOPIX150	PIX4life	Yes	Syn/Luc	✓	✓	✓	✓	✓		in dev.	in dev.	in dev.	✓	✓		

Among all the above, several have embraced the generic integration open-access foundry model allowing for fabless photonic integration [13]. This paper presents their foundry offering, from technology, through applications, access models and forthcoming developments. The manuscript starts with section II, where the foundry access models for the different generic silicon nitride technologies and availability of process design kits and building blocks, are presented. Next, in section III a detailed summary of the different technology modules available is given, together with some detail on the manufacturing capabilities, so as to provide to the interested reader insight on the micro-fabrication tools and techniques that are available in these platforms. This is followed by section IV, where selected examples of the most relevant applications demonstrated are given. Section V shows an outline of the planned future developments, and the conclusion section VI closes this paper.

II. Foundry and access

The foundry models for PICs can be compared to the previously established for electronic integrated circuits, which have evolved into a market place where merchant foundries manufacture the devices (provide chip processing on wafers) under contract by other companies, without designing them. This is a business model that differentiates itself from the vertical integrated vendors, or integrated device manufactures (IDM), who provide services from design-to-packaged device [1].

The chip processing (front-end only) foundry activity in the microelectronics industry is dominated by Taiwan Semiconductor Manufacturing Corporation (TSMC), with a market share of more than 50% with an annual turnover (2017) of more than US$ 32B, largely driven by the production of devices for the leading edge 10 nm node [52]. Moreover, foundries are taking active part in development of the 3rd-generation semiconductor materials such as SiC and GaN, which will bring more changes in industry chain where TSMC provides a GaN foundry service and X-Fab provides SiC foundry services. Manufacturers have been providing foundry services of SiC and GaN devices, cutting into the supply chain where IDMs like Cree, Infineon, Qorvo, etc. used to dominate. Recent publication from TrendForce states that *"the development of foundry services will drive the growth* *of third-generation semiconductor materials market beyond the revenues over 2018 which are US$ 180M"* [53]. With regards to photonics, the market study by Photonics 21 in 2017 [54] claims that the photonics industry grew from €228 Billion in 2005 to €447 billion in 2015. The share for PICs is further detailed for the different integration technologies in the market research by [55], where the Global Photonic IC market for Monolithic, hybrid and module integration will reach US$ 1,338M in 2022. The Global market for Silicon-Nitride PICs will reach around US$ 130M in 2022, compared to InP PIC estimate of US$ 470M, Si is US$ 170M and SOI US$ 350M, all with CAGR around 25-30%.

The pure play foundry model puts the processing and fabrication of the wafer in the hands of the foundry which provides design kits, that include the design rules and the qualified design blocks and exports the chip-design in a digital format, commonly referred to as GDSII file format (Graphic Database System). The foundry commits a lead time for the wafers, and fabricates the wafer lots for different customers in its proprietary manufacturing process, using efficient parallel shuttle runs and in-line process control and yield monitoring. The pure play foundry model offers several advantages to fabless companies, such as confidentiality and unique capability, time to market advantage, and skipping lead-time for process development, by entering efficient production through standardized/qualified design blocks, with the delivery of the GDS files and the reception of wafers back. However, these foundries aim at high volumes, and there is therefore a request off set on the number of wafers to be processed. On the other hand, photonic open foundries exist [56] offering standardized processes via Multi-Project Wafer (MPW) shuttle runs, with predictable lead time, which favors quick turn around for test and rapid prototyping, and shared manufacturing costs. Moreover, training and support is offered (together with other applicants), and they constitute an excellent low-barrier entry point to the manufacturing eco-system. Furthermore, they supply process capability beyond MPW offering, with additional services 'a la carte' for development and modification over existing processes, entering dedicated runs, and still offering scale-up for volumes. The open foundry model entails a division of the overall risk from a business perspective, where qualified processes with process design kit (PDK) libraries [57], that enforce design integrity and intellectual property (IP) handling, guarantee, from a chip manufacturing (not functional) perspective, close to first time right manufacturable devices. Finally, and from a user perspective, the continued provision of foundry services in photonic integration technologies is a concern, and in that sense, open access shared infrastructures facilitate as well the acquisition, installation and servicing of dedicated equipment at the location, whereas supporting collaboration with the researchers to further strengthen the photonics ecosystem at large.

Several companies and research institutions offer silicon nitride platforms in open access scheme, as previously described, with remarks on the availability of generic technologies implementing different building blocks (BBs), supported by PDKs [57]. These are compiled in Table I for foundries LioniX international (LX), LIGENTEC (LGT), Instituto Nacional de Micro-electrónica CNM-CSIC (CNM) and imec. The entries in the first column correspond to the available technologies (see section III ahead), while the second and the third columns detail the access mode, either through brokering parties, such as JePPIX, PIX4life or VLC Photonics, and the possibility of direct access to the foundry. The rest of the columns provide firstly technical information on which BBs and IP blocks are available ('✓'), or in development ('in dev.') for different optical functions, such as couplers (directional -DC-, multi-mode interference -MMI- and Y branch), optical input/output (grating coupler -GC-, spot-size converter -SSC-, inverted taper -INVT-), thermal tuners, additional selective area etching (shallow cladding etch -well- or a deep trench etch) and filters (ring resonators -RR-, arrayed waveguide grating -AWG- and distributed Bragg reflector -DBR-). For most of the technologies, a PDK [57] library exist in some software packages, such as Synopsis/PhoeniX Optodesigner (Syn), Virtual Photonics Inc. (VPI) and Luceda Photonics (Luc). Last but not least, and estimated turnaround time from GDS delivered to fab by designers, to chips shipping back is given in the last column. Note that some cells include a year number, indicating forthcoming additions to the technologies.

So far the table reflects part of the supply chain activity, including micro-fabrication front end of the line (FEOL) and metal deposition and pattering, back end of the line (BEOL), see Table III ahead, as part of the PIC production steps: from concept, through design, manufacturing, packaging, assembly and test. For these steps taking place either in a horizontal or vertical business model [56], is in general a matter the particular requirements of a given application domain (see section IV). Further engineering BEOL activities are being conducted in order to facilitate access to these technologies, for which several road-blocks exist [58], that could be addressed through homogenization across foundries and technologies, at some or all the production steps, potentially resulting into increased access opportunities.

Hence, actors in the field (foundries and brokers) must therefore not only offer the silicon-nitride PIC, but provide a vertically integrated offering. This ensures the SiN PIC fits seamlessly as a part of larger final system for which it is designed for. Therefore, foundry and brokers activities are encompassing BEOL steps such as packaging, assembly and test. For example as shown in [67], for visible light applications of silicon-nitride integrated photonics, multiple interfaces are common. Interfaces other than the fiber connection, common in telecom, are free-space interfaces (with or without an end cap), either to air or to other optical elements like lenses. Direct connection of other chips (hybrid assembly of semiconductor based PICs for example [21, 22]), grating or 45 degree mirrors to couple out the light at places other than the edge of the chip as well as interaction regions where (part of) the PIC is interacting with the environment are all examples of uses of the SiN PICs. An example that shows non-standard assembly necessity from, in this case a life science application is given in Fig. 1.

As a particular mention to the technologies in Table I, LX is offering hybridization with InP, called 'chiplet' approach [68], within MPW runs and their PDKs, with a standard tunable narrow line-width laser offered as BB in the PDK. In dedicated

TABLE II
TECHNOLOGIES, WAVELENGTH RANGE, CROSS-SECTIONS AND FIGURES OF MERIT.

	Spectral region		**POL**	**Layer-stack (Substrate, Core, Cladding)**			**Cross-section**		**Loss**	**Dispersion**		
Technology	Range	λ [nm]	mode	h [µm]	h(-e) [µm]	h [µm]	w [µm]	R [µm]	α [dB/cm]	n_g	GVD	**Ref(s).**
LX-SS	NIR	1550	TE	SiO2 / 8.0	0.065	SiO2 / 5	4.2	2000	<0.03	1.5	-	[59, 60]
					0.05	bonded SiO2	5.3	∞	<0.007	-	-	[61]
					0.05		6.5	∞	<0.001	-	-	
					0.04		13	∞	<0.001	-	-	[36]
LX-SDS-HIC					0.170/0.500/0.170		1.2	100	<0.1	1.72	-	[62]
LX-SDS-LIC					0.035/0.5/0.035		1	∞	<0.1	1.46	-	
LX-ADS HIC					0.075/0.100/0.175	SiO2 / 5	1.1	100	<0.1	1.77	-	[59, 60]
LX-ADS LIC					0.075/0.100/0		0.8	∞	0.015 - 0.2	1.46	-	
LX-SS-VIS	VIS	405-700	TM		0.03	SiO2 / 5 & air	0.8	2000	<0.1	1.46	-	[63, 64]
LX-DS-VIS	VIS+NIR	405-1000	TE		0.03/0.35/0.03		0.8	200	<0.1	1.48	-	
LX-SS-NIR	NIR	850	TE		0.1		1	50	<0.1	1.52	-	[65]
LX-Box HIC		1550	TE+TM		0.17	SiO2 / 5	0.84	150	0.2	1.76	-	[59, 60]
LX-Box LIC					0.05		1.1	500	0.06	1.49	-	
LX-Buried			TE		0.8-1.2		0.8-1.0	12.5	<0.01	1.79	-	
LGT-AN800	NIR	1550	TE+TM	SiO2 / 4.0	Si3N4 / 0.8	SiO2 / 2.8	0.2-4.0	10	0.067	-	-	[48, 49]
LGT-AN150	VIS+NIR	405-1000			Si3N4 / 0.15		0.2-4.0	50	0.1	-	-	
CNM-MINI	NIR	1550	TE+TM	SiO2 / 2.5	Si3N4 / 0.15	SiO2 / 1.5	-	-	-	-	-	[26, 50, 51]
CNM-RIB					Si3N4 / 0.3	SiO2 / 1.5	1	150	0.99-2.2	1.71-1.93	-0.88,-1.14	
CNM-STRIP			TE		Si3N4 / 0.3-0.15	SiO2 / 1.5	1	350	1.35-2.0	1.94-1.96	-0.87,-2.14	
CNM-VIS	VIS	633	TE	SiO2 / 2.0	Si3N4 / 0.24-0.16	SiO2 / 1.5 & Air	2	0	0.2	-	-	[66]
BIOPIX300	VIS	650-1000	TE	SiO2 / 3.3	SiN / 0.3	SiO2 / 2 & Air	0.3-1	20-50	0.45	-	-	[40]
BIOPIX150	VIS	450-700	TE	SiO2 / 2.3	SiN / 0.15		0.15-1	20-50	0.6-2.1	-	-	

TABLE III
TECHNOLOGY MODULES AND MANUFACTURING PROCESS STEPS.

Technology	**Wafer**	**Process**	**Step 1**	**Step 2**	**Step 3**	**Step 4**	**Step 5**	**Step 6**	**Step 7**	**Step 8**
LX-SS	4”-8”	Subtractive	SiO2 wet ox	LPCVD Si3N4	Dry etch of stack	TEOS LPCVD SiO2	PECVD SiO2	-	-	-
LX-(A)DS	4”-8”				TEOS LPCVD SiO2	LPCVD Si3N4	Dry etch of stack	TEOS LPCVD SiO2	PECVD SiO2	
LX-Box	4”					Dry etch of stack	LPCVD Si3N4	Local removal Si3N4	TEOS LPCVD SiO2	PECVD SiO2
LX-Buried	4”	n.d.	SiO2 wet ox	Dry etch	LPCVD Si3N4	Planarization	TEOS LPCVD SiO2	PECVD SiO2	-	
LGT-AN800	4”-8”	n.d.	SiO2 - BOX	LPCVD Si3N4	Si3N4 - Patterning	SiO2 - ILD	Metal - PVD	Metal - patterning (ICP)	Pad open	Chip release
LGT-AN150		n.d.								
CNM-MINI	4”-6”	Subtractive	SiO2 wet ox	LPCVD Si3N4	RIE Si3N4	PECVD SiO2	(metal) Lift-off	(well) RIE SiOx	-	-
CNM-RIB									-	-
CNM-STRIP									-	-
CNM-VIS	4”-6”	Subtractive	SiO2 wet ox	LPCVD Si3N4	RIE Si3N4	PECVD SiO2		(well) RIE SiOx	-	-
BIOPIX300	8”	Subtractive	PECVD SiN	PECVD SiO2	PECVD SiN	Dry etch of SiN	PECVD SiO2	Local removal of SiO2	-	-
BIOPIX150	8”								-	-

projects, InP chips with any functionality are allowed. Hybrid InP integration is a subject of active development at LGT as well. PDK containing dedicated assembly features are in place for LX, LGT and CNM, including assembly and packaging design rules. LX offers a full assembly with fiber arrays, within the characterization package service (CPS) in the MPWs. The chip can be assembled with input and output fiber arrays including strain reliefs, fanout PCB for wire-bonds and a metal base for heatsink and easy mounting. The approach allows to characterize a chip, without the need for alignment stages or knowledge. LGT do also offer fiber attachment as part of their service. Common die size among CNM and LGT foundries may help assembly, packaging and test engineers, since thermal tuner contact positions and hence wire-bonding, is the same for both platforms. However, the use of different fabrication tools and processes, among other, still makes the transition from one fab to other not an straightforward task [58]. For use with MPW offering in SiN for instance it is possible to use a design template, included in the PDK offered by the foundries, to finally be assembled into a package with the main purpose being to measure the silicon nitride PIC. This avoids the need of owning, maintaining and operating alignment equipment and procedures.

III. TECHNOLOGIES AND MANUFACTURING

The technical features and figures for the open foundry silicon nitride technologies are summarized in Table II. For complementariness, refer to Table 1 in ref. [26], where similar information is compiled for an extensive list of SiN publications.

From Table II the technology portfolio features span from VIS to NIR wavelengths, where only the absorption of SiO_2 above approximately a wavelength of 3.7 µm precludes their use up to the transparency limit of Si_3N_4 close to 6.7 µm [25] as discussed in [26], and outlined later in section V. Rib (single-stripe, SS for LX) waveguides are available in all the foundries,

Fig. 1. LX assembly of three fiber arrays to a triangular shaped SiN PIC and a PCB for electrical interfacing. 45 degree on-chip mirrors are used to exit the visible light from the centre of the chip into free space.

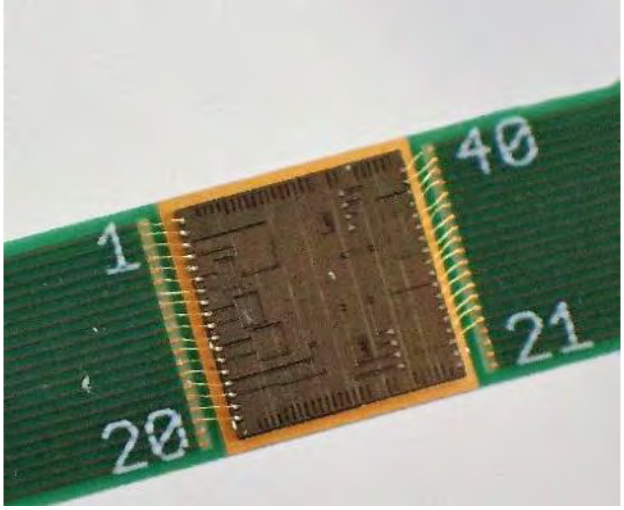

Fig. 2. Silicon nitride (LGT-AN800, nitride thickness 0.8 μm) 5x5 mm^2 chip with efficient heaters for tuning high FSR resonators and MZIs.

while strip and more complex structures such as double-stripe (DS), in its asymmetric (ADS) and symmetric (SDS) version, and box for low and high index contrasts (LIC/HIC) [60] are supplied by LX. These waveguides sit on top of a SiO_2 substrate, where the height is adapted to the designed guiding conditions for each platform, to minimize substrate leakage loss among other, with thicker substrates requiring in general longer deposition / oxidation times. A wide variety of SiN thicknesses are also available, from a few tens of nanometers (starting at 30 nm) to several hundred (0.8-1.2 μm). While very thin waveguides are used in the VIS, e.g. Fig 1, for single-mode condition, they are also employed in the NIR surrounded by sufficient SiO_2 so as to enable very low-confinement, yet very low loss propagation. Thick SiN waveguides are usually employed for strong confinement, e.g. Fig 2 presents a PIC manufactured on nitride films of thickness 0.8 μm, in LGT-AN800 (Table II) technology. Thicknesses of few hundreds of nm serve to multiple purposes [26]. The interested reader can find drawings for the different cross-sections in the references provided in the table and along the text.

The technologies have been developed and incorporated to the open access portfolio progressively. Firstly, LX technologies follow developments aimed at producing a controlled index contrast, with different approaches for the core, such from single stripes, to double stripes (symmetric and asymmetric, and for NIR and VIS wavelengths, for linear applications. Overall, and as shown in Table II, there is trade-off between propagation loss and device footprint (bending radius). The CNM techs for NIR aim at providing a moderate confinement technology for linear applications with modest propagation loss, whereas the VIS technology is exclusively targeting bio-photonics and sensing applications using the bimodal interferometric waveguide. LGT technology for NIR originated mainly from the non-linear integrated photonics applications using silicon nitride, and LX does also provide similar technology, where the common denominator is a thick guiding layer for strong confinement. Finally, BIOPIX technology is an emerging platform for VIS light life science applications. Consequently, all the platforms allow for selective cladding oxide removal.

With respect to the manufacturing steps, they are detailed in Table III. Silicon wafers of diameters from 4” to 8” are employed, in a processing approach which in most of the cases is additive, except for thick Si_3N_4 where different micro-

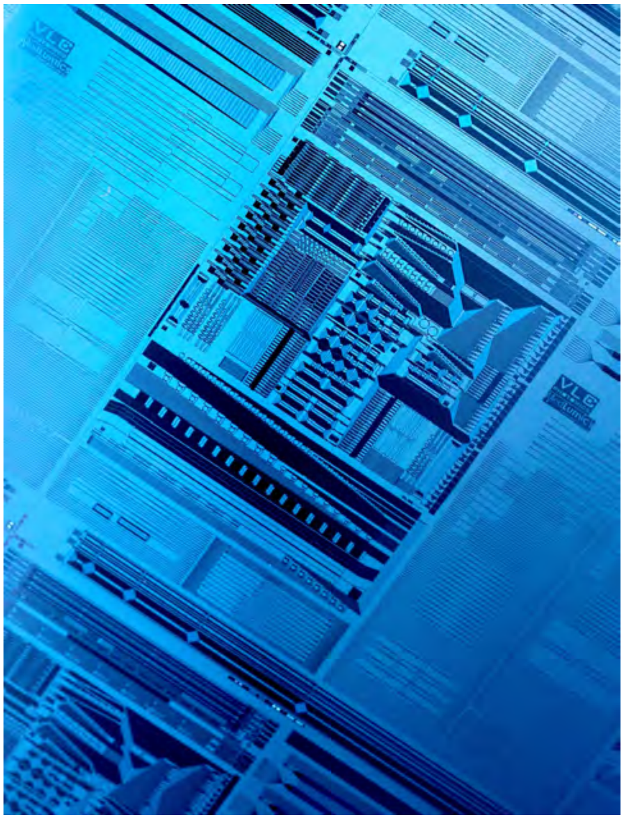

Fig. 3. Silicon nitride chip from imec BIOPIX300 MPW run.

fabrication approaches are used, to circumvent material stress [69] resulting from low-pressure chemical vapor deposition (LPCVD). Most use as first step the oxidation of the Si wafer, except imec BIOPIX, Fig. 3, that makes use of a thin SiN layer as anti-reflective coating below the substrate oxide (100nm and 70 nm thick for BIOPIX300 and BIOPIX150 respectively). The nitride layer is etched using dry techniques, such as reactive-ion etching (RIE) and the SiO_2 cladding deposited by several means (plasma enhanced CVD, PECVD or thermal oxide LPCVD). The choice of one or other deposition method is related to the targeted properties of the material (not only the thickness), but this is out of the scope of this paper, and information can be found spread in the references. Additional process modules such as metals for thermal tuners (via physical vapor deposition, PVD+RIE or lift-off techniques) as well as selective area openings, i.e. cladding removal to expose the nitride guiding layer (typically through RIE) are the latest steps, prior to subsequent BEOL steps such as wafer dicing. Despite the material quality advantages of LPCVD, technologies using PECVD such as BIOPIX allow monolithic integration of the PICs on CMOS imager wafers, due to the lower temperature deposition of the stack compared to LPCVD and wet oxidation based processes, which offers complementary application capabilities.

Finally, in terms of tools employed in the manufacturing, different foundries use different tools. LX technologies are produced either by mask or stepper lithography, imec and LGT employ deep-UV steppers with a resolution in 150-200 nm, and CNM uses either i-line steppers and mask aligners, with resolutions 600 nm and below 1 µm respectively.

IV. APPLICATIONS

Silicon nitride PICs have been reported so far for very different applications, where photonics mates with other disciplines such as bio/life science, tele and datacom, and sensing. These applications benefit from the propagation loss and confinement features of SiN, both in the linear and non-linear regimes. In this section, selected applications demonstrated in the technologies previously discussed, are collected with references for the interested reader. The order in which they are presented is related to the wavelength of the application, starting from visible wavelengths, despite some encompass more than one, i.e. those based on non-linear effects.

The VIS wavelength range is mainly devoted to bio-photonic applications due to non-ionizing interaction of light with live bodies [6, 70]. One salient application is Optical Coherence Tomography (OCT) [71] for which several have demonstrated systems with partially integrated parts [72–74]. Among the different approaches, a PIC in LX-SS waveguide stripe of thickness 75 nm, comprising several Arrayed Waveguide Grating (AWG) devices in cascade configuraiton, was demonstrated in [75] for hyper-spectral OCT. A picture of the fabricated PIC, splitting the VIS range in several bands, with an image of it mounted and wire-bonded are shown in Fig. 4.

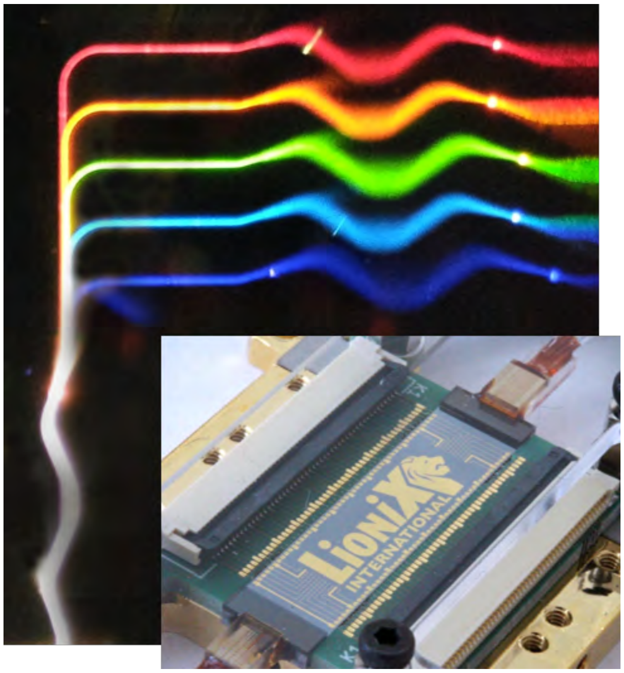

Fig. 4. Silicon nitride (LX-SS 75 nm thick) PIC for hyper-spectral optical coherent tomography on a handheld device [75]. The background image is a top view picture of the PIC with white light injected fromt the bottom, and the different colors separated on chip (horizontal color paths), while the foreground picture gives a view of the PIC mounted and wire-bonded onto a board and with fibers attached.

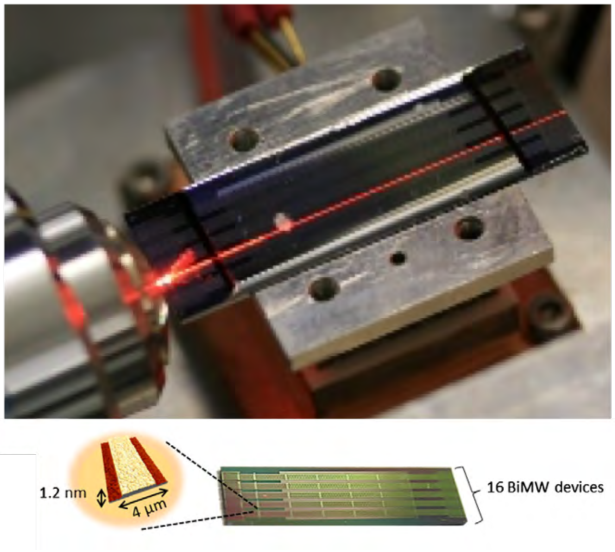

Fig. 5. Silicon nitride (CNM-VIS) PIC for evanescent field interferometric sensing [66]. (top) Red light injected with a microscope objective, and propagation through the different sections of the PIC. A two sector photo-detector is employed at the other end of the PIC (not present in the picture). (bottom) The PIC starts with a waveguide of thickness 0.16 µm, with a single mode supported, and it's followed by a section with nitride thickness 0.34 µm, that supports two vertical modes. The cladding oxide is selectively etched way on the latter, that is functionalized with specific chemistry targeted at the label-free detection of a particular analyte.

Using the evanescent nature of the guide mode in an optical waveguide, the CNM-VIS, Fig. 5 has been used for label-free detection [66] of different analytes, such as diagnosis of bacterial infections [76] or growth hormone in urine [77], based on Bi-modal Waveguide (BiMW) interferometers. These are comprised by a single straight bimodal waveguide that supports the zero- and first-order transversal modes, which propagate with different velocities depending, among other factors, on the refractive index of the cladding layer. The interference pattern formed at the exit of the waveguide changes if the refractive index varies due to interaction with the surrounding media. An emerging application of PICs is in the fluorescence microscopy of living cells, for which a slight modified CNM-VIS waveguide structure was used in [78, 79]. All in all, the use of analytic instruments enabled by a photonic chip core (cost-effective, label-free, very sensitive, disposable, using low volumes of analyte), is aimed at unattended rapid first screening diagnosis at the point-of-care [80].

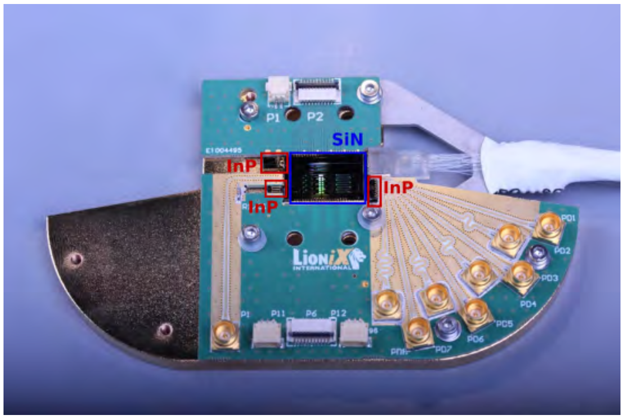

Fig. 6. Hybrid InP-TriPleX™ integrated MWP optical beamformer [86]. The red and blue rectangles enclose the InP and TriPleX™ PICs respectively in the picture.

The main use of the NIR wavelength range is related to tele and datacom, owing to the transparency of silica optical fibers, the light conduit per excellence for optical communications. Nonetheless, non-guided signal transmission at high frequencies using photonics assisted approaches is key, where in many situations a pure radio-frequency solution is not possible. Several sources detail the importance of integrated photonics for the future evolution of high frequency microwave signal processing [81, 82]. However, radio-frequency link gain is dominated by both modulator and propagation loss (c.f. [83], and hence it's key to employ integration technologies for partly or fully integrating microwave photonics functionalities. Among them, true time delay (TTD) beamforming for phased array antenna based on radio frequency (RF) technology suffer from electrical cross-talk, still rather limited bandwidth, and large foot-print, resulting in high propagation losses. In recent years, it has been shown that by harnessing microwave photonics (MWP) [84] the generation, distribution, and processing of RF signals can be done with a number of advantages. The main advantages of MWP over pure RF systems is a reduction of size and weight, extreme low and frequency independent propagation losses (e.g. 0.2 dB/km in fibers), no EMI, extreme high capacity by using broadband signals, very wide RF frequency range (from DC to hundreds of GHz), and low power consumption. Specially the use of photonic integrated circuit (PIC) technology in MWP comes with enhanced functionalities and robustness as well as a reduction of size, weight, cost, and power consumption [85]. An Optical Beamforming Network (or OBFN) is an implementation of several types of Analog Photonic links (APLs) where signals are split, combined or modified using several building blocks such as Mach-Zehnder Modulator (MZM), intensity modulation direct detection (IMDD) or Phase Modulator (PM). The example in Fig. 6 shows the state of the art technology demonstrator manufactured as a hybrid InP-TriPleX™ module where the laser, the modulator array, and the photodetector arrays are manufactured on 3 separate InP chips which interface with the, relatively big, TriPleX™ chip where signal processing and filtering takes place. The manufacturing considerations and introduction of the different integrated photonic functions in the OBFN are related to the required performance of the modules, to mention: RF input average power, the input resistance, the envisioned field of view of the array antenna, the required instantaneous bandwidth, tuning and settling speed, link gain, signal to noise ratio (SNR), the third-order intermodulation distortion and the Spurious-Free Dynamic Range (SFDR) [86]. The building blocks at hand are the (1) laser, operating at a certain wavelength (range) providing certain guaranteed optical power, line-width(or frequency noise), relative intensity noise (RIN), stability; (2) the modulator(array), its bandwidth of operation, modulation sensitivity V_π and insertion loss, (3) the detector responsivity, (reverse) bias and detection bandwidth, and (4) the complex OBFN processor, located between the laser and detector, and the photonic interconnects which add inevitable signal loss. The architecture of the OBFN and the used modulation schemes define the actual RF Gain factor.

With more and more PICs being produced world-wide, there is an immediate need in changing the paradigm under which these are qualified. For single device photonic integrated circuits (e.g. a laser) methods exist that can be found elsewhere for wafer scale device testing and qualification, therefore preventing late detection of faulty devices (i.e. after dicing, bonding etc). Nonetheless, the complexity of PICs is increasing, with more and more structures combined on a densely integrated circuit. For those, techniques and on-chip engines able to deliver as much information as possible on the internal structure of the chip, are sought. Traditionally, optical frequency domain reflectometry (OFDR) [87, 88] has been used in several approaches, some of them resulting into commercial instruments. In [89] an integrated OFDR engine is presented on a silicon nitride chip using a CNM-RIB waveguide cross-section, Fig. 7, in the optical telecom C-band. The device allows retrieving the internal amplitude and phase response of the chip, while de-embedding the waveguide dispersion. Waveguide dispersion in silicon nitride may be large, depending on the cross-section and technology, and to gain proper insight through full-field measurements, on-chip structures with dispersion de-embedding are key. Despite the demonstration is in the NIR, the concept can be translated to other wavelength ranges, provided a tunable laser technology is available. Furthermore, a low loss platform such as silicon

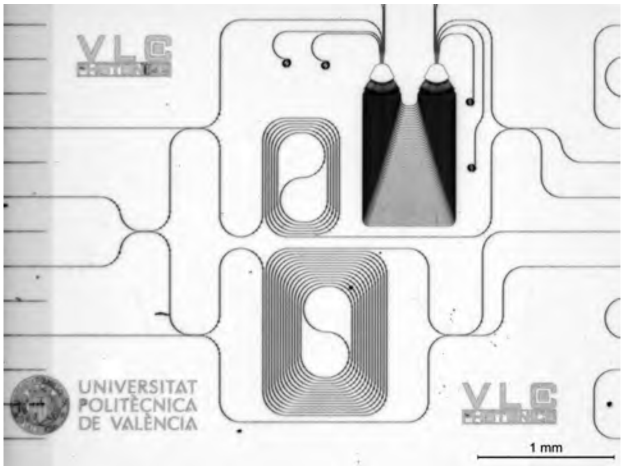

Fig. 7. Silicon nitride CNM-RIB integrated optical frequency domain reflectometry chip [89].

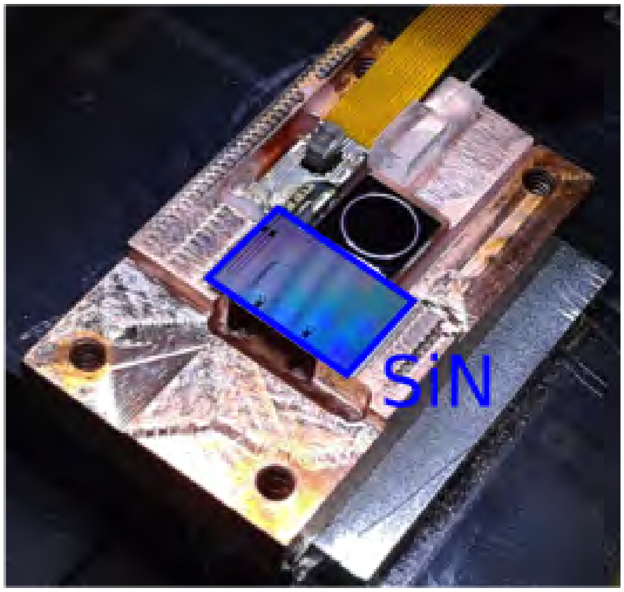

Fig. 8. Picture of the Chip-scale Optical Resonator Enabled Synthesizer (CORES) developed under DARPA MTO DODOS program [93]. LGT silicon nitride interposer chip connects multiple PIC components including a III-V laser, a SiO2 resonator and ultrafast detectors. The blue box encloses the silicon nitride chip.

nitride enables working interferometers, as those in Fig. 7, with large path length imbalance.

Silicon nitride also offers a plethora of application areas for nonlinear integrated photonics, which combined with the very low loss properties, result into high performing PICs. When compared to other integration technologies such as Si photonics, SiN has comparatively lower two-photon absorption, and this has enabled SiN as key platform for non-linear applications, such as supercontinuum and frequency comb generation [90, 91], albeit the Kerr nonlinear coefficient is comparatively small [92]. For example, as a result of non-linear interaction and low-loss propagation, an integrated laser and photo detectors recently showed on chip frequency synthesis [93], Fig. 8. This resulted into a tunable laser set to a certain optical frequency by the precision of sub-Hz accuracy. Dispersion engineering and height control of the silicon nitride is of utmost importance in this case. Thick film silicon nitride above 700 nm shows anomalous dispersion and shows frequency comb generation over large spectral bandwidth [94]. Here a CW laser is tuned in a high-Q resonator and with a four wave missing process additional frequency lines are created. Related to the above, supercontinuum generation is an effective method to generate a large bandwidth spectrum with a pulsed laser source, typically in the femto-second range. Supercontinuum generation is widely used with high nonlinear fibers for sensing applications as well as stabilizing femto-second laser sources [95, 96]. Due to its high Kerr nonlinearity and tight confinement of the optical mode, thick film silicon nitride waveguides can lower the optical pump pulse power significantly. Supercontinuum generation in silicon nitride was used to stabilize an optical frequency comb lowering the power consumption down to 5 W [97, 98]. Furthermore it was shown that the supercontinuum can cover a spectral range from the visible up to the mid-IR, which gives access to the molecular fingerprint region for sensing applications [99].

V. OUTLOOK

As shown along the previous sections, silicon nitride offers the possibility to have very low propagation losses and enhanced non-linear interactions over a broad optical bandwidth, thus covering a wide range of applications. The applications reviewed in this paper included hyperspectral optical coherence tomography and label free detection of analytes in the VIS, NIR telecom/datacom true-time delay beamforming and analog photonic links, as well as frequency comb and supercontinuum generation over a wide wavelength range. The differentiators and advantages for them were: i) the inherent SiN low propagation loss, which for telecom wavelengths, combined with high integration density, allows complex functions; ii) the broad spectral range of operation can be leveraged into photonic chips for new applications, with proper hybrid integration of lasers, modulators and detectors and iii) the absence of two photon absorption combined with low propagation loss, enables high power applications, with affordable set-on thresholds, in the non-linear regime.

Hence, silicon nitride can be considered a key candidate in solving technical challenges, while improving performance and capturing share in application markets where some of the following are required: a) more complex pics, b) dense integration, c) reconfiguration based on efficient thermal or advance stress-based tuners, for reduced power consumption and cross-talk -impacts on dense integration too-, d) heterogeneous and monolithic integration with active materials such as lithium niobate and InP to obtain more functionality in the chips, e) make membrane based SiN waveguides to address a suite of NIR applications and f) further reduce optical losses of transmission lines and optical interconnects through use of bidirectional on-chip-tapers and interposers. Hence, to further embrace novel and emerging opportunities, research is on-going to complement several aspects of the technology.

Firstly, more complex PICs are being designed and manufactured, with a general trend in densely integrating reconfigurable chips. Tuning elements which are conventionally implemented as thermal-optic heaters that require several hundreds of mW, require novel approaches so as to minimize overall PIC electrical power consumption, as well as to alleviate unwanted thermal cross-talk effects. Hence, novel developments at LX encompass lead zirconate titanate (PZT) based tuners [100–102], for which the power consumption is calculated to be less than 4 mW per actuator. This makes the PZT stress-optic actuator at least 100 times more power efficient than thermo-optic tuners. Despite the current versions of the PZT actuators are rather long (15 mm) compared to their thermal heater counter parts (2 mm), they can be packed closer to one another, whereas the thermal actuators need a separation of more than 250 μm to prevent thermal crosstalk. The denser packing for PZT-tuning can therefore be provided at similar footprint of the thermal tuning, which eventually makes the PZT tuning equally efficient, much faster and more power efficient. LGT, approach is to use optimized heater geometry and combine it with their arbitrary facet definition technology, in oder to create more compact and power efficient heaters, operating within 3V envelope. LGT approach allows for power consumption in the order of 120 mW, with 0.5 mm long waveguides packed in less than 40 μm distance. The higher power efficiency results from putting the heater structure closer to the Si_3N_4 waveguide, capitalizing on the strong confinement of light in the LGT-AN800 platform..

Secondly, heterogeneous and monolithic integration with active materials is pursued to extend the functionalities of the PICs. LGT has demonstrated a heterogeneous lithium niobate integration [103] and is actively working in monolithic InP integration under publicly funded research programs. Such approach can create more efficient, compact and increased functionality PICs.

Thirdly, Si_3N_4 is shown to be transparent in the range of 0.4-6.7 μm, but so far all the foundry offering using this material as guiding layer, Tables I, II and III, make use of SiO_2 as substrate and/or cladding material. Silica transmission starts at visible as well as for silicon nitride, but has a strong absorption around 2.7 μm, despite with some processing it may allow transmission up to close 4 μm, using high confinement waveguides, which minimizes the interaction of the mode with the cladding material [99]. Hence, their combination is usually quoted as the broadband in photonics terms. Nonetheless, applications such as trace gas analysis, chemical-biological sensing, environmental sensing, industrial process control, medical diagnostics, communications, defense and security and astronomy[104], among many other, find room in wavelengths starting in the long NIR and above. Since the usual combination of SiO_2 with SiN is limited by SiO_2 absorption [105], efforts are in progress at CNM so as to create membrane[106] based integrated optical waveguides. Several approaches may exist to manufacture a silicon nitride membrane [26]. The current developments in CNM are in implementing a process flow with double side wafer processing, including pattering and etch [50]. This would ultimately create a supporting silicon nitride light guiding platform that can be hybridized with laser, detector and modulator PICs of different type for specific wavelength ranges.

Finally, co-integration of SiN photonic devices and microelectronics circuits is considered of great interest, so as to have full functional opto-electronic devices on a chip. For instance, the monolithic integration of source, waveguide and detector in the visible range was reported for the first time in [107].

VI. CONCLUSION

In this paper, we have presented the current state of open access silicon nitride photonic foundries, their technologies and activities from micro-fabrication to complementary activities in assembly and hybridization aimed at lowering the entry barrier of technology users. Detailed technical and operational information for four open foundry suppliers, with a wide technology catalog, covering applications from visible to mid-infrared wavelengths, have been supplied. Examples of applications for bio/life sciences, tele/data com and sensing among other, have been given. The incorporation of the novel and other developments outlined into the open foundry generic technology based platforms presented in this paper, should ultimately result into agile fabless business operation on niche markets, that build upon tools, techniques and infrastructures capable of volume manufacturing.

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