SILICON NITRIDE TWG

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EXECUTIVE SUMMARY

Introduction

The silicon nitride photonic platform is based on a combination of (stoichiometric) silicon nitride (SiN) Si_3N_4 as waveguide layers, filled by and encapsulated with silica (SiO_2) as cladding layers on a silicon wafer. Silicon nitride (SiN) waveguides have a number of advantages over alternative technologies, including low propagation loss, wide range of transparency from visible to the mid-infrared, low cost, good reliability for high power and industrial operating conditions, as well as good coupling to standard single-mode fiber.

The typical propagation loss of only 0.5dB/m allows to achieve filters with high finesse which are required in for example narrow line width external cavity laser but also for example to improve sensitivity of resonant micro optic gyroscopes. In sensor applications SiN has benefits in low loss over a wide range of wavelength from visible to the mid-infrared. For high-speed datacentre transceivers of 400Gb/s and beyond, loss has become even more critical as multi-bit amplitude modulation reduces the power level between the bits. So, in order to achieve the same signal to noise ratio, the power levels in the fiber and from the chip need to increase proportionally. Currently, the hypercloud datacenters experience a massive delay in the delivery of 400Gb/s transceivers due to the additional power requirements which existing suppliers cannot meet reliably. Low-loss SiN technology could meet the conflicting demands on small footprint and low loss that currently cannot be served with silicon photonics nor monolithic Indium Phosphide (InP), due to high loss for these platforms. The difficulty in making future transceivers using discrete optics lies in the challenge to fit in the small footprint, as a consequence of the larger size of the discrete optical lenses and filters, again favouring SiN as a more suitable technology platform.

For some applications it is also important to handle high power densities. This is for example the case in future 5G networks where optical mux and demux devices will be installed to connect antennas to the base station. For these applications the antennas may be at a short distance from the base station resulting in multiplexed powers of the order of Watts. These power levels can easily be handled by SiN waveguides.

All antennas in 5G networks, top of rack switches in data centers, and also many sensors, are connected by single-mode optical fibers. So for the optical chip, coupling loss to standard single-mode fiber should be better than 90%. This can be achieved by SiN technology. Using hybrid SiN technologies with joint Nitride Glass waveguides one can reach close to 99% coupling efficiency. So, for the roll-out of 5G networks, but also for future data center applications, and other products that require high power and low loss, SiN is an attractive technology. In particular, heterogeneous and hybrid integration techniques of SiN with more complex active subsystems have now been demonstrated, including stress-based modulation on the TriPleX platform of LioniX [32]. A recent comprehensive review of the latest progress on SiN technology platform and integration with active components can be found in reference [32].

Current status

SiN fabrication processes are already mature. SiN layers with uniform thicknesses, typically within 1 %, and reproducible refractive indices are deposited using both LPCVD and PECVD. For SiN waveguides both stepper lithography as well as contact lithography can be used, considering the relatively low effective index compared to Si, allowing relatively large waveguide widths while maintaining single mode characteristics. Using typical commercially available stepper lithography tools, lines/spaces of 250 nm can be fabricated. The width of 250 nm for the lines/spaces is sufficient for all applications in this platform at telecom wavelength.

Similar to silicon, the SiN platform is not efficient for lasing. LioniX International has solved this problem by hybrid integration of InP gain medium with tunable mirrors defined in their SiN platform. These hybrid lasers have high output power > 10 mW, very narrow laser linewidth and can be tuned over the whole C-band [39]. Hybrid integration has been used to integrate InP modulators and waveguide detectors with LioniX SiN plaform. With regards to switching and modulation, very reliable but rather slow modulation can be achieved through the well-known thermal phase modulation in case of SiN (limited to 1 kHz). Faster modulation up to the MHz and the GHz regimes has been achieved using PZT material [31,38]. In case of (quasi-) DC operation, these modulators furthermore reduce the required switching power to a few microWatts (μW) only.

Multi Project Wafer (MPW) runs operating in the C-band around1550 nm are available since 2011. For application in the VIS domain, MPW shuttles are provided since 2017, by both LioniX International as well as IMEC. In these MPW services, fundamental building blocks are available, including optical waveguides, thermo-optic phase tuning elements, Y-branches, micro ring resonators (MRR's), directional- and multi-mode interference (MMI) couplers.

ROADMAP OF QUANTIFIED KEY ATTRIBUTE NEEDS

TECHNOLOGY NEEDS

In the tables below the parameters' values of different SiN fabrication processes are given. The values of these parameters for the next 5 to 15 years are specified.

EPITAXIAL DEPOSITION

(Epitaxial) growth/layer deposition	[unit]	5 years	5-10 years	10-15 years
Layer thickness uniformity SiN	%	1	0.5	0.5
Layer thickness reproducibility SiN	%	2	1	0.5
Layer refractive index uniformity	RIU	5*10-3	2*10-3	1*10-3
Layer refr. index reproducibility	RIU	5*10-3	2*10-3	1*10-3
Layer thickness uniformity SiO2	%	2	1	0.5
Layer thickness reproducibility SiO2	%	3	2	1
Layer refr. index uniformity SiO2	RIU	1*10-2	5*10-3	2*10-3
Layer refr. index reproducib. SiO2	RIU	1*10-3	5*10-3	2*10-3

* defect in regrowth

DRY ETCHING

Dry etching	[unit]	5 years	5-10 years	10-15 years
Side wall roughness	[nm]	1	0.5	0.2
Side wall angle	°	2	1	0.5
Etch depth reproducibility	[nm]	50	25	10
Etch depth uniformity	[nm]	25	10	5
Selective etch masking layers	NA	2	3	4
Minimal linewidth	[µm]	0.5	0.2	0.1
Minimal reproducibility	[µm]	0.5	0.2	0.1
Waveguide width uniformity	[µm]	0.1	0.05	0.03
Minimum spacing	[µm]	0.5	0.2	0.1
Minimum grating pitch	[µm]	0.3	0.2	0.1
Grating etch step uniformity	[nm]	50	20	10

WET ETCHING

Wet etching	[unit]	5 years	5-10 years	10-15 years
Side wall roughness	[nm]	0.5	0.3	0.2
Etch depth reproducibility	[nm]	50	20	10
Etch depth uniformity	[nm]	50	20	10
Selective etch masking layers	NA	2	3	4
Minimal linewidth	[µm]	0.5	0.2	0.1
Minimal reproducibility	[µm]	0.5	0.2	0.1
Wave guide width uniformity	[µm]	0.1	0.05	0.03
Minimum spacing	[µm]	0.5	0.2	0.1
Minimum grating pitch	[µm]	0.3	0.2	0.1
Grating etch step uniformity	[nm]	30	20	10
Wet etch undercuts	[nm]	500	750	1000

LITHOGRAPHY

Contact Lithography	[unit]	5 years	5-10 years	10-15 years
Overlay accuracy	[µm]	1	0.8	0.5
Resolution	[µm]	0.8	0.6	0.5
Required Flatness requirements				

Stepper/scanner Lithography	[unit]	5 years	5-10 years	10-15 years
Overlay accuracy	[nm]	500	250	100
Resolution	[nm]	300	200	100
Required Flatness requirements	[nm]	300	200	100

Laser Lithography	[unit]	5 years	5-10 years	10-15 years
Overlay accuracy	NA			
Speed	NA			
Resolution	NA			
Required Flatness requirements	NA			

E-Beam Lithography	[unit]	5 years	5-10 years	10-15 years
Overlay accuracy	NA			
Speed	NA			
Resolution	NA			
Required Flatness requirements	NA			

ANNEALING

Annealing	[unit]	5 years	5-10 years	10-15 years
Temperature@time budget	[K]	1150	1150	1150

PLANARIZATION

Planarization	[unit]	5 years	5-10 years	10-15 years
Temperature@time budget	[K]	NA	NA	NA
Required flatness		300	200	100

PASSIVATION

Passivation	[unit]	5 years	5-10 years	10-15 years
Temperature@time budget	[K]	350 C	200 C	RT

DICING AND CLEAVING

Dicing and cleaving	[unit]	5 years	5-10 years	10-15 years
Position accuracy	[µm]	2	1	0.5

METAL DEPOSITION

Metal deposition	[unit]	5 years	5-10 years	10-15 years
Temperature budget	[C]	250 C	150	100

WAFER BONDING

Wafer bonding	[unit]	5 years	5-10 years	10-15 years
Temperature budget	[C]	500 C	500 C	500 C

CRITICAL (INFRASTRUCTURE) ISSUES

TECHNOLOGY NEEDS

Routes to extend the usability of these platforms should hence address:

1. Extension of the guiding range from 0.4-5 µm by means of Si_3N_4 membranes [28]
2. Adoption of mix & match lithography, combining stepper photo-lithography with wafer scale Electron-Beam Lithographies (EBL)
3. Further development of process allowing for scaling up of
    a. Power-efficient tuning mechanisms, such as piezo and MEMS actuators; and

   b. The co-integration with other CMOS compatible materials for high speed electro-optical modulation [29].

4. Development of transfer printing processes for the hybrid integration of sources and detectors, at the different wavelength ranges in 0.4-5 µm [20]
5. Increased level of integration: light sources, modulators and detectors need to be heterogeneously and monolithically integrated onto the SiN platform.
6. Investigation of maximum optical power that can be handled by SiN waveguides.
7. Smart integration of SiN platforms with microfluidics for life science applications

PRIORITIZED RESEARCH NEEDS (> 2025 YEARS RESULT)

Table X. Prioritized Research milestones (> 2025)	Relative priority
Further development of process	Critical
Extension of the guiding range	Regular
Investigation of maximum optical power	Desirable
Adoption of mix & match lithography	Regular

PRIORITIZED DEVELOPMENT & IMPLEMENTATION NEEDS (< 2025 YEARS RESULT)

Table X. Prioritized Development & Implementation milestones (≤ 2025)	Relative priority
Integration of SiN platforms with microfluidics	Desirable
Increased level of integration	Critical
Development of transfer printing processes	Critical
Non-linear interactions	Desirable
Quantum guided applications	Desirable
MPW standardization for different wavelengths ranges and applications	Regular

GAPS AND SHOWSTOPPERS

RECOMMENDATIONS ON POTENTIAL ALTERNATIVE TECHNOLOGIES

Appendix

INTRODUCTION

The silicon nitride photonic platform is based on a combination of (stoichiometric) silicon nitride (SiN) Si_3N_4 as waveguide layers, filled by and encapsulated with silica (SiO_2) as cladding layers on a silicon wafer. This waveguide technology started with the development of components in the visible wavelength range, applied to build optical sensors [1]. Stulius and Streifer reported in 1977 [3] the first fabrication of Si_3N_4 films on a SiO_2 buffer on Silicon wafers, for light propagation in the red visible wavelength (632 nm). After some works in the 1980s on the propagation of visible (VIS) light through straight channel Si_3N_4 waveguides, a seminal contribution on the application of this material in a functional device was made by Heideman et.al. [4], showing a partially integrated Mach-Zehnder Interferometer (MZI) for immunosening assays, where the two arms of the MZI were in fact Si_3N_4/SiO_2 waveguides, while the optical couplers for the MZI were external to the photonic chip.

Despite that a fully integrated MZI sensor was reported in the late 1990s [5], new interests in this material platform only started again in 2005, when Sandia Labs (USA) [6] and University of Trento (ITA) [7] developed processes and demonstrated applications in the near-infrared (NIR) frequency range. They were followed by silicon oxynitride (SiONx) waveguides [8] and Si3N4 waveguides [9,10,11] from 2008 to 2011.

Up to 2011 demonstrations by telecom related groups concerned the NIR C-Band at 1550 nm, and all the waveguide cross-sections were developed for moderate confinement (film heights > 100 nm), despite that some groups by 2011 reported about low confinement waveguides (film h < 100 nm) [22]. By 2013, researchers [12,13] set new paths of Si3N4 technology for applications in the visual (VIS) spectrum. Since 2011 there is a growing interest on high confinement (film h > 400 nm) waveguides for the long near-infrared (NIR) frequency range (NIR+, wavelength > 2000 nm) [14,15,16,17]. In 2015–2016, new players in moderate confinement technologies appear [18,19,20].

The operation wavelength range of SiN-technology spans from visible to the mid-infrared, with very low loss. However, the main disadvantage of this technology is that no optical sources, detectors, amplifiers and modulators are available in the generic MPW processes. Integration of light sources with the aforementioned active building blocks requires a hybrid or heterogeneous approach with separately fabricated InP or other active materials platform chips. Since 2018 LioniX international is offering integration of light sources, at 1550 nm, in their MPW processes.

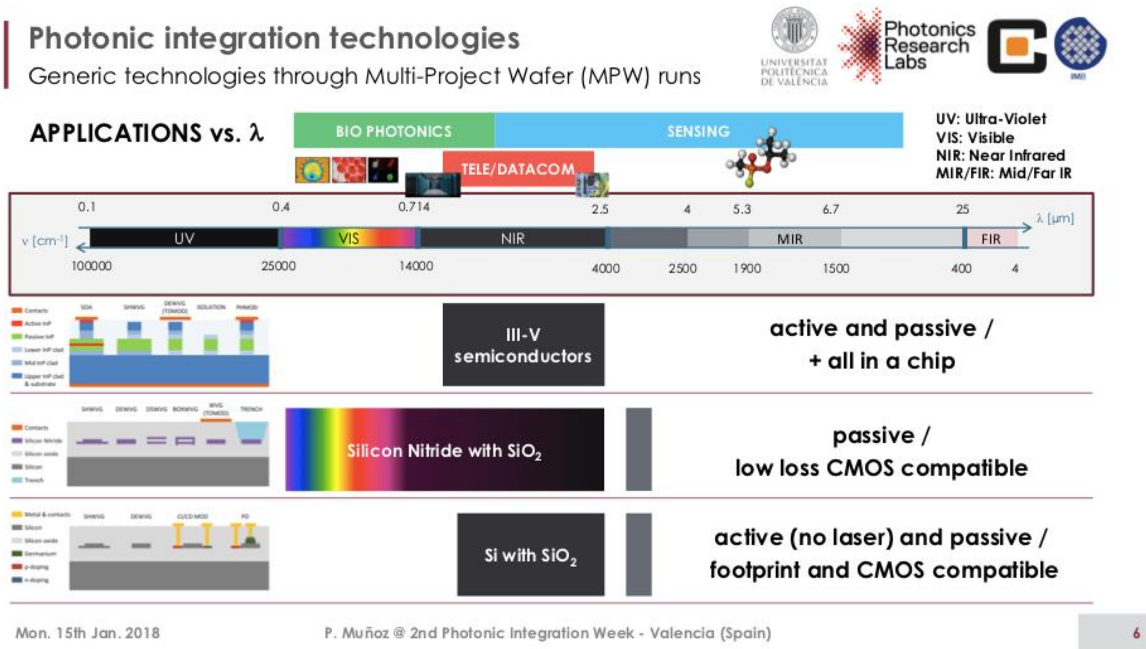

Figure 1. Comparison between InP, SiN and SOI technology platforms. Different waveguide structures in each platform are shown. The figure also mates the PIC applications to transparency range.

WAVEGUIDE PERFORMANCE RELATED TO VARIOUS SIN-PLATFORMS

In the following, the state of the art for strip waveguides as presented in Table 1 is discussed, grouping the platforms by wavelength range and optical confinement. Other types of waveguides, such as box waveguide and double strip waveguide, (Figure 1, top-right, BOXWVG and DSWVG respectively), have been reported [21, 22, 23] with propagation loss and bend radius as low as 0.1 dB/cm and 70 µm.

For use in the NIR, low confinement strip waveguides were demonstrated jointly by LioniX and UCSB, with guiding film heights ~100 nm, waveguide widths ~2800 nm and propagation loss as low as 0.09 dB/cm @ 1550 nm for 0.5 mm bend radius. The lowest loss reported by these groups is 0.001 dB/cm. The low propagation loss is due to the low confinement in the Si3N4, being most of the mode guided through the SiO2, enabled by huge layers of the buried oxide (BOX) and cladding (8 µm and 7.5 µm respectively). Still for the NIR, moderate confinement waveguides (nitride height in between 150–400 nm) have been demonstrated by several groups. Sandia (2005) [6] and UCD (2015) [19] reported LPCVD Si3N4 guiding film heights of ~150–200 nm, with waveguide widths ~800–2000 nm. The propagation loss reported is 0.11–1.45 dB/cm@1550 nm for BOX height up to 5.0 µm. Other groups such as IMEC and University of Toronto have reported 3D SiN on top of SOI in the NIR [24], employing LPCVD Si3N4 guiding film heights ~300–400 nm, with waveguide widths ~800–1000 nm, resulting in propagation loss of 1.30–2.10 dB/cm @ 1550 nm for BOX heights in between of 2.0 µm and 5.0 µm. Using similar film heights in the VIS and VIS+ wavelength ranges, Aachen University and Ghent University reported PECVD guiding film heights ~100–220 nm, waveguide widths ~300–800 nm PECVD guiding film loss 0.51–2.25 dB/cm @ 532–600 nm for BOX height ~2400 nm.

Finally, both for the NIR and NIR+ wavelength ranges, high confinement waveguides have been reported by Kippenberg (EPFL) [14], Lipson (Cornell, then Columbia) [15,17] and Agarwal (MIT) in 2013 [25], followed in 2015 by Torres (Chalmers) [16] and companies such as LioniX International [26] and LigenTec [27]. Guiding film heights ~700–2500 nm, with waveguide widths ~700–4000 nm and propagation loss of 0.04–1.37 dB/cm @ 1550 nm and 0.16–2.1 dB/cm @ 2600–3700 nm, for BOX heights in the range of 2.0–8.0 μm have been reported.

TECHNOLOGY AVAILABILITY

SiN fabrication processes are already mature. Both the IMEC SiN photonics platform (BioPIX) as well as LioniX International (TriPleX) offer the fabrication of PICs operating in visible and near-infrared wavelength range. The BioPIX technology dates back to 2012, when PECVD SiN material with low photonic losses and low autofluorescence in the visible range was developed at IMEC [13]. The TriPleX platform, based on ultra-low loss low pressure chemical vapor deposition (LPCVD) stacks, has been available for over a decade. Ligentec also uses LPCVD technology for their waveguide platform.

Since 2017, both the BioPIX platform and the TriPleX platform are offered as MPW runs for visible light through the EU project 'Pix4Life' pilot line initiative.

TriPleX

TriPleX chips are currently applied in visible light-based commercial products (Pacific Biosciences, Karl Zeiss, etc.). The TriPleX platform consists of alternating Si_3N_4 and SiO2 layers and is based on very high quality LPCVD batch processes, resulting in layers with very uniform thicknesses and very reproducible refractive indices.

To incorporate light generating properties, LioniX has developed a hybrid integration of InP gain medium with tunable mirrors defined in TriPleX. LioniX already commercializes hybrid lasers using this integration process. These hybrid lasers have high output power of typically several 10's of mW's (up to up to 100 mW), very narrow laser linewidth and can be tuned over the whole C-band. This type of hybrid on-chip lasers are also available through MPW services as of mid-2018 [30]. Furthermore, this hybrid assembly process can be scaled to other wavelength ranges as well. In case of 850 nm applications, LioniX has demonstrated integration of VCSELs operating at 850 nm onto SiN using flip-chip process and grating coupling a few years ago. In case of visible light applications, light sources can be coupled in multiple ways to the TriPleX platform, e.g. by grating coupling or butt-end coupling. LioniX also offers MPW services operating at 850 nm.

In the SiN platform, very reliable but rather slow modulation can be achieved by the well-known thermal phase modulation (limited to 1 kHz). In addition to that, in February 2018 LioniX has announced to also commercially supply piezo based stress-optical modulators on their TriPleX platform, based on PZT, which allow switching speeds up to the MHz regime [31]. Additionally, in the case of (quasi-) DC operation, these modulators reduce the required switching power to a few microWatts only. Even faster modulators operating in the GHz regime have been realized in 2018 by efficient edge coupling of InP modulators with TriPleX chips. LioniX is also able to connect InP based waveguide detectors to their platform using end-butt coupling.

Based on the TriPleX platform, a configurable interference pattern generator has been demonstrated by LioniX as well as a Multi-Color Laser Engine by RWTH Aachen University, TOPTICA Photonics, LioniX International and Miltenyi Biotec [37]

BioPIX

The BioPIX platform is based on PECVD SiN waveguides embedded in PECVD SiO_2 cladding. The low temperature deposition of the stack allows monolithic integration of the PICs on CMOS imager wafers, which offers novel application capabilities. For patterning of the SiN layer, 193nm DUV stepper lithography equipment has been employed, which allows to target a minimum feature size of 150 nm. Shallow and deep etching of the waveguide layers are done by fluorine-based plasma etching. In order to allow direct contact of liquid or gas medium with the waveguides for sensing applications, an additional so called "open clad" module has been developed by removing the oxide top cladding selective to the SiN core layer via successive dry and wet etching steps. Additional to the standard modules of shallow and deep patterning of the waveguide layer and the open clad module, metal heaters for thermo optic modulation, top metallization and edge coupling modules for light source integration are currently under development.

There are two flavors of the platform readily available for designers: BioPIX300 and BioPIX150. BioPIX300 is targeting wavelengths above 650nm with a SiN core thickness of 300nm whereas the BioPIX150 is meant for wavelengths between 450nm to 700nm with a SiN core thickness of 150nm, all fabricated on 8" wafers.

Component libraries for the BioPIX platform are still under development. Various building blocks based on the standard modules have been made available within the PDK libraries as part of the software packages offered by Luceda Photonics and Synopsis. Each run contains new library components, as well a set of standard process control monitoring structures, for which the light in and out coupling is achieved by grating couplers. Grating structures allow wafer scale probing of the dies for photonic validation after fabrication.

The platform mostly focusses on life science and med-tech industry applications. The BioPIX technology has been applied for PICs in applications such as fluorescence and label-free molecular sensing [33, 34], while also cytometry [35] and on-chip Raman spectroscopy [36] has been already demonstrated. In addition, within the Pix4Life project an on-chip OCT imager for ophtalmologic applications has been designed and fabricated by VLC Photonics (Valencia, Spain) and Medlumics (Madrid, Spain). A multi-degree freedom sensor for liquid / gas sensing by Gent University and Robert Bosch GmbH (Stuttgart, Germany) are using the BioPIX platform as well.

LASER INTEGRATION IN SILICON NITRIDE

Similar to the silicon photonics (SiPh) platform, the SiN platform has no laser generating capability. Lately, there has been a lot of progress in the field. In March 2018, LioniX International announced to incorporate lasers in their TriPleX based MPW-services, based on its hybrid InP-TriPleX approach.

SITUATION (INFRASTRUCTURE) ANALYSIS

MANUFACTURING EQUIPMENT

MANUFACTURING PROCESSES

SiO_2 and Si_3N_4 layers are fabricated with CMOS-compatible techniques like thermal oxidation and industrial standard low-pressure (LPCVD) and plasma enhanced (PECVD) chemical vapour deposition techniques equipment that enables cost-effective volume production. Several waveguide cross-sectional geometries are available (Figure 1). In general, the cross-sections shown perform at 1550 nm showing losses below 0.5 dB/cm and minimum bending radius typically around 50 μm. In/out-coupling is achieved by means of adiabatically tapered spot-size converters with <1 dB coupling loss to standard single mode fiber. A summary of the reported strip waveguide silicon nitride platforms is given in Table 1. The table collates information on the operation wavelength, layer stack, cross-section dimensions and, when available, cut-off wavelength, propagation loss and bend radius.

Mechanisms responsible for optical propagation loss in strip silicon nitride waveguides employing different fabrication recipes have been previously described and experimentally explored by Sandia Labs in [6]. In short, propagation losses are reduced by removal of impurities in the silicon nitride and silicon oxide layers (e.g. through annealing) and by reducing the surface roughness (film roughness and waveguide sidewall roughness) together with the mode confinement at the operation wavelength (given by the waveguide cross-section, width, height, as well by the substrate and cladding heights); those cross-sections for which the optical mode feels less side-wall roughness (either because of strong confinement, low roughness or both), will be subject to lower propagation losses.

To fabricate SiN waveguides both stepper lithography as well as contact lithography can be used, considering the relatively low effective index compared to Si, allowing relatively large waveguide widths while maintaining single mode characteristics. Using typical commercially available stepper lithography tools, lines/spaces of 250 nm can be fabricated. The width of 250 nm for the lines/spaces is sufficient for all applications in this platform.

TEST, INSPECTION, MEASUREMENT (TIM)

CONTRIBUTORS

Rene Heideman (LioniX International)

Pascual Munoz (Universitat Politècnica de València)

Sami Musa (VA-Photonics)

Andim Stassen (IMEC)

Henk Bulthuis (Kaiam)

Michael Geiselmann (Ligentec)

Serna Otalvaro (MIT)

Samuel (MIT)

Jerome Michon (MIT)

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Table 1: A summary of SiN waveguide technology platforms around the world. The table provide information on the operation wavelength, layers stack, cross-section, cut-off frequency and propagation losses.

Group	Range	l [nm]	Substrate	Core	Cladding	Confinement	Width [nm]	Height [nm]	Cut-off [nm]	Bend R [µm]	Straight [dB/cm]
Imec/ Severi	VIS	488-700	SiO2 (h=2.3µm) PECVD	SiN PECVD	SiO2 (h=2.0 µm)	High	300+	150		50	2.5@ 488 0.7@ 638
Gent/B aets	VIS	532	SiO2 (h=2.0 µm) HDP-CVD	SiN PECVD	SiO2 (h=2.0 µm)	Moderate	300 400 500	180	530 @ 532		7.00 @ 532 3.25 @ 532 2.25 @ 532
Imec/ Severi	VIS+	650-1000	SiO2 (h=3.3µm) PECVD	SiN PECVD	SiO2 (h=2.0 µm)	High	480+	300		50	0.5 @ 850
Aachen/ Witzens	VIS	660	SiO2 / 1.45 (h=?)	SiN / 1.87 PECVD	SiO2 (Water)	Moderate	700	100	580	35 (60)	0.51 @ 600 (0.71)
Gent/B aets	VIS+	780	SiO2 (h=2.4 µm) HDP-CVD	SiN PECVD 1.89@780	SiO2 (h=2.0 µm)	Moderate	500 600 700	220	900 @ 780		2.25 @ 780 1.50 @ 780 1.30 @ 780
Gent/B aets	VIS+	900	SiO2 (h=2.4 µm) HDP-CVD	SiN PECVD	SiO2 (h=2.0 µm)	Moderate	600 700 800	220	1100 @ 900		1.30 @ 900 0.90 @ 900 0.62 @ 900
IME/Lo	NIR	1270-1580	SiO2 (h=2.2 µm)	Si3N4 LPCVD	SiO2	Moderate	1000	400			0.32 @ 1270 1.30 @ 1550 0.40 @ 1580
IME/Lo	NIR	1270-1580	SiO2 (h=3.32 µm)	Si3N4 PECVD	SiO2	Moderate	1000	400			0.45 @ 1270 3.75 @ 1550 1.10 @ 1580
IME/Lo	NIR	1270-1580	SiO2 (h=3.32 µm)	Si3N4 PECVD	SiO2	Moderate	1000	600			0.24 @ 1270 3.50 @ 1550 0.80 @ 1580
Trento/ Pavesi	NIR	1550	SiO2 (h=2.5 µm)	Multi-layer	Air / SiO2	Moderate		100/50/200/50 /100 nm			1.50 @ 1550 nm
Sandia/ Sullivan	NIR	1550	SiO2 (h=5.0 µm)	Si3N4 LPCVD	SiO2 (h=4.0 µm) PECVD or HDP	Moderate	800	150		500	0.11-1.45 @ 1550

Group	Range	l [nm]	Substrate	Core	Cladding	Confinement	Width [nm]	Height [nm]	Cut-off [nm]	Bend R [µm]	Straight [dB/cm]
Twente/ Driesen	NIR	1550	SiO2 / 1.45 (h=?)	SiON PECVD	?	Moderate	2000-2500	140-190		25-50	0.20 @ 633 0.20 @ 1550
IME/Lo	NIR	1550	SiO2 (h=5.0 µm) PECVD	SiN / 2.03 (h=400nm) PECVD	SiO2 (h=2.0 µm) PECVD	Moderate	700	400			2.1 @ 1550
LioniX-UCSB	NIR	1550	SiO2 / 1.45 (h=8.0 µm)	Si3N4 LPCVD	SiO2 / 1.45 (h=7.5 µm)	Low	2800	100		500	0.09 @ 1550
LioniX-UCSB	NIR	1550	SiO2 / 1.45 (h=8.0 µm)	Si3N4 LPCVD	SiO2 / 1.45 (h=7.5 µm)	Low	2800	80		2000	0.02 @ 1550
Cornell/ Lipson	NIR	1550	SiO2 (h=?)	Si3N4 LPCVD	SiO2 (250nm+2µ m)	High	1800	910		115	0.04 @ 1550
LioniX	NIR	1550	SiO2 (h=8.0 µm)	Si3N4 LPCVD	SiO2 (h=8.0 µm)	High	700-900	800 1000 1200			0.37 @ 1550 0.45 @ 1550 1.37 @ 1550
Toronto - IME/Po on	NIR	1270- 1580	SiO2 (h=2.2 µm)	Si3N4 LPCVD	SiO2	Moderate	900	400			0.34 @ 1270 1.30 @ 1550 0.40 @ 1580
Toronto - IME/Po on	NIR	1270- 1580	SiO2 (h=3.32 µm)	SixNy PECVD	SiO2	Moderate	1000	600			0.24 @ 1270 3.50 @ 1550 0.80 @ 1580
CNM-VLC	NIR	1550	SiO2 (h=2.0 µm)	Si3N4 LPCVD	SiO2 (1.50µm)	Moderate	800	300		150	1.00 @ 1550
UCD/Y oo	NIR	1550	SiO2 (h=?)	Si3N4 LPCVD	SiO2 (h=2.0 µm)	Moderate	2000	200		50	0.30 @ 1550
LigenT ec	NIR	1550	SiO2 (0.13-3.5 µm) Thermal	Si3N4 LPCVD	SiO2	High	~2000	800		119	?
Chalme rs/Torr es	NIR	1550	SiO2 (h=2.0 µm)	Si rich SiNx LPCVD	SiO2 (h=2.0 µm)	High	1650	700		20	1.00 @ 1550

Group	Range	l [nm]	Substrate	Core	Cladding	Confinement	Width [nm]	Height [nm]	Cut-off [nm]	Bend R [µm]	Straight [dB/cm]
Ghuagzhou/Shao	NIR	1550-1600	SiO2 (h=2.0 µm)	SixNy ICP-CVD	?	Moderate	1400	600		40	0.79 @ 1575
Columbia/Lipson	NIR+	2300-3500	SiO2 (h=4.5 µm)	Si3N4 LPCVD	SiO2 (500nm+2µm)	High	2700	950	2500	230	0.60 @ 2600
MIT/Agarwal	NIR+	2400-3700	SiO2 / 1.45 (h=4 µm)	Si rich SiNx LPCVD	SiO2	High	4000	2500		200 @ 2650 200 @ 3700	0.16 @ 2650 2.10 @ 3700