Advances in Silicon Photonics targeting next generation transceiver PICs

Stéphane BERNABÉ
Project Leader – Photonic Circuits and Modules, CEA-Leti, France

online / October 5th – 8th / 2020
Photonics Days
Berlin Brandenburg
innovationconference

MASSTART

virtual conference session:
Data Center Interconnects – Towards Mass Manufacturing
online / October 6th 2020 / 4 – 7pm

leti
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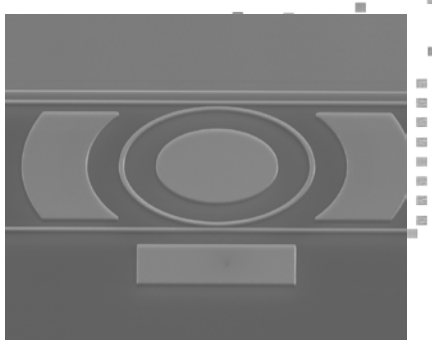
COSMIC
CmOs Solutions for Mid-board Integrated transceivers with breakthrough Connectivity & ultra low Cost (COSMICC)

MASSTART

NANOELEC.



ADVANCES IN SILICON PHOTONICS TARGETING NEXT GENERATION TRANSCEIVER PICS

Photonics Days Berlin Brandenburg| Stéphane Bernabé, Quentin Wilmart, Bertrand Szelag | 06.10.2020

OUTLINE

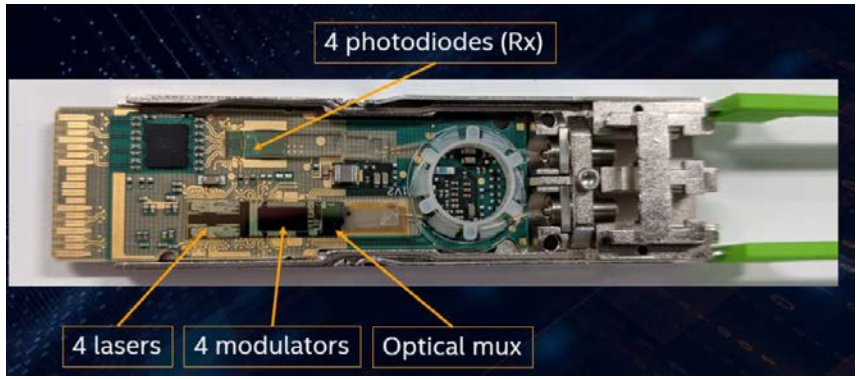
1 Today Status : SiPho platforms

2 New trends and requirements
- Ultra-low loss silicon waveguides
- 3D photonics : Si-SiN platform
- Laser integration
- Packaging

3 Conclusion

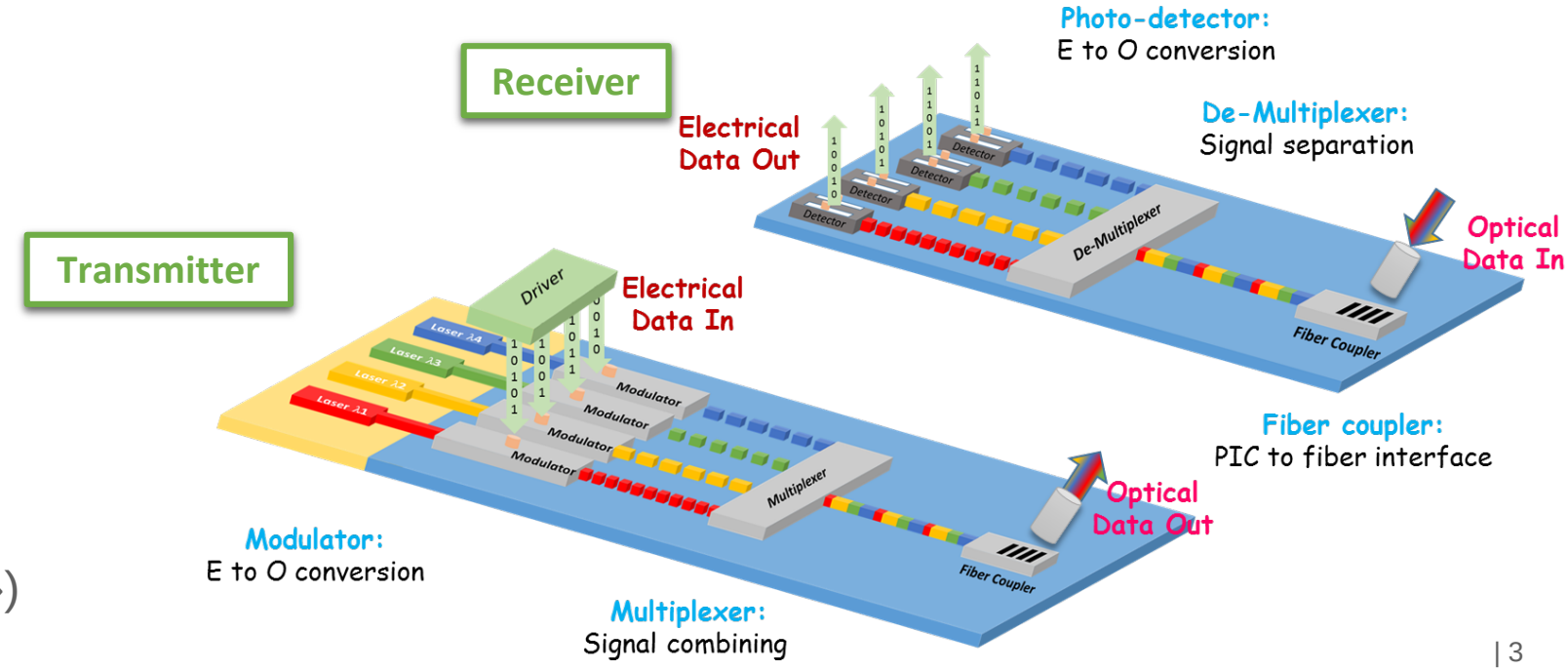
TODAY STATUS IN SILICON PHOTONIC TRANSCEIVERS

- **Two big players**
  - Intel (see pictures)
  - Cisco (Acacia/Luxtera/Lightwire)
- **Start-ups**
  - Ayar Labs
  - Rockley Photonics
- **Commercial foundries**
  - GlobalFoundries
  - TowerJazz
  - CompondTek
  - TSMC
  - IHP
  - AMF
- **R&D Organizations & pilot lines**
  - CEA-LETI, imec, VTT… (« RTOs »)
  - AIM



This image shows the optically connected FPGA board developed by Intel and Ayar Labs.
Source: Ayar Labs

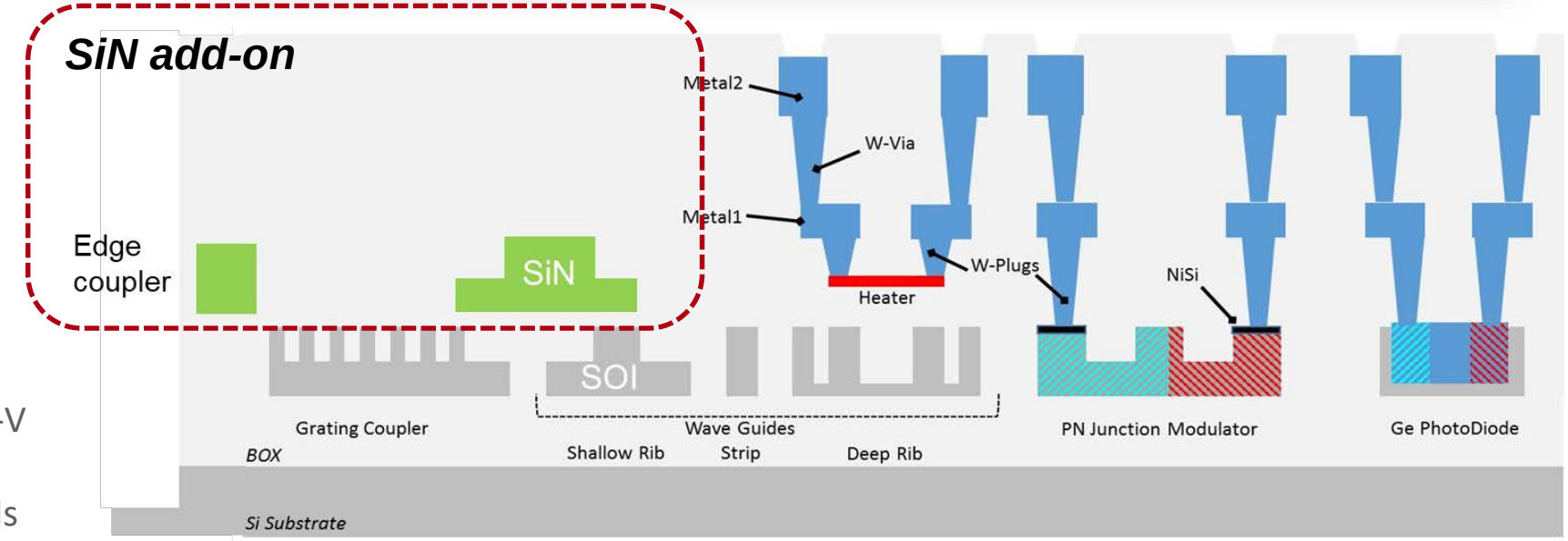
Silicon Photonic Links



TECHNOLOGY KEY PROCESS FEATURES

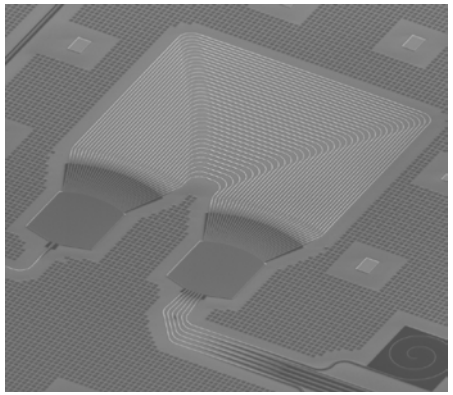
- **Si photonics platform**
  - Substrates : SOI 310nm
  - > 200 steps
  - 24 litho levels
  - 40 metro/control steps
  - Flexibility: possibility to integrate the SiN layer for thermal properties or III-V epitaxies for hybrid lasers

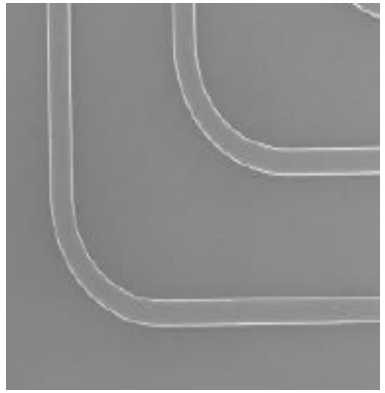
- **Process building blocks**
  - Multilevel silicon patterning
  - PN Silicon junctions
  - Germanium
  - SiN waveguides
  - Integrated resistance (heater)
  - Integrated laser (direct bonding of III-V wafers/dies)
  - Planarized BEOL : 2 AlCu routing levels

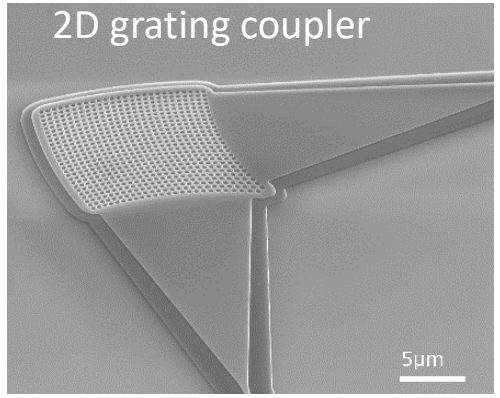


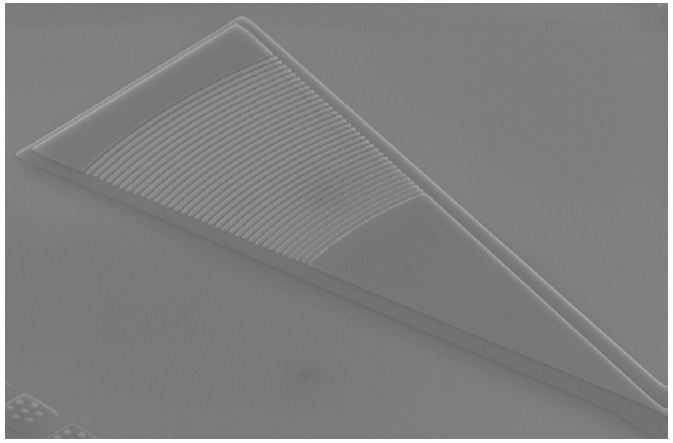
PASSIVE DEVICES

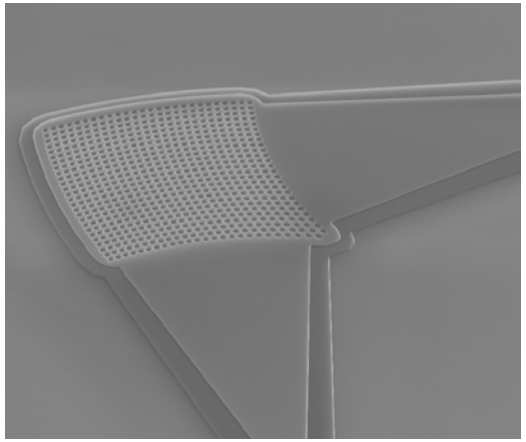
- Routing (waveguides, bends, crossings, splitters, MMI…)
- Wavelength Management
- Polarization Management
- Fiber Coupling
- DC phase shifter (with heater)

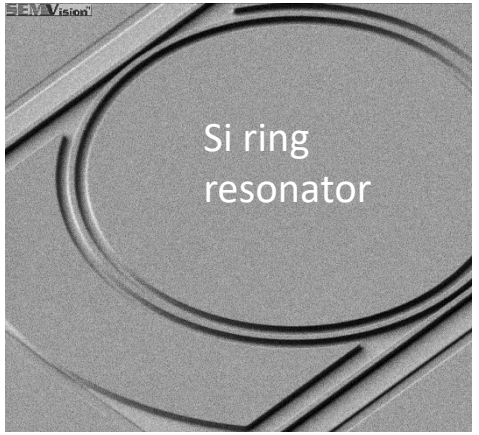


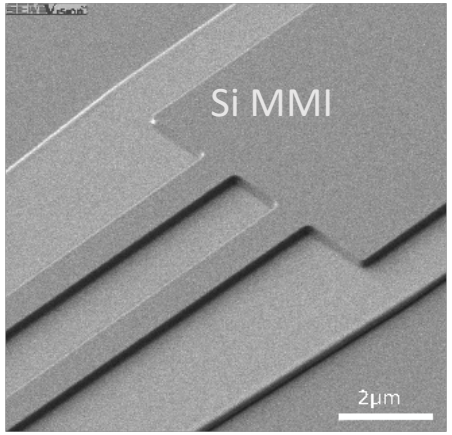






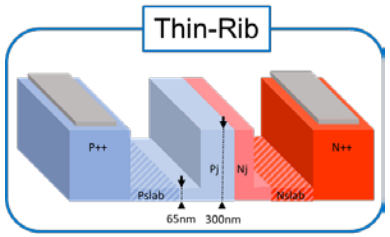




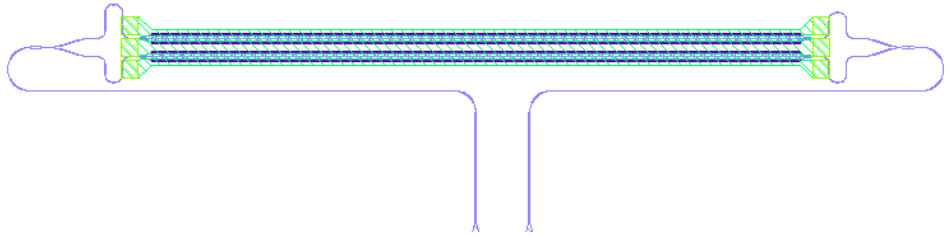


All these components available through Process Design Kits, as layout (p-cells) & models

ACTIVE DEVICES: P-N MODULATOR

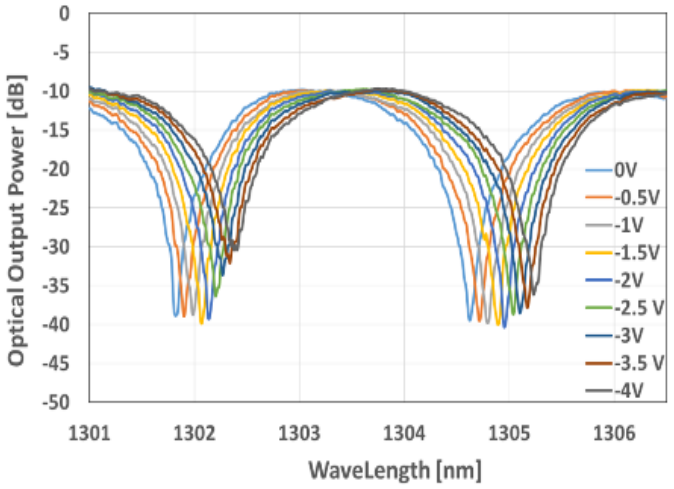


Mach-Zehnder modulator

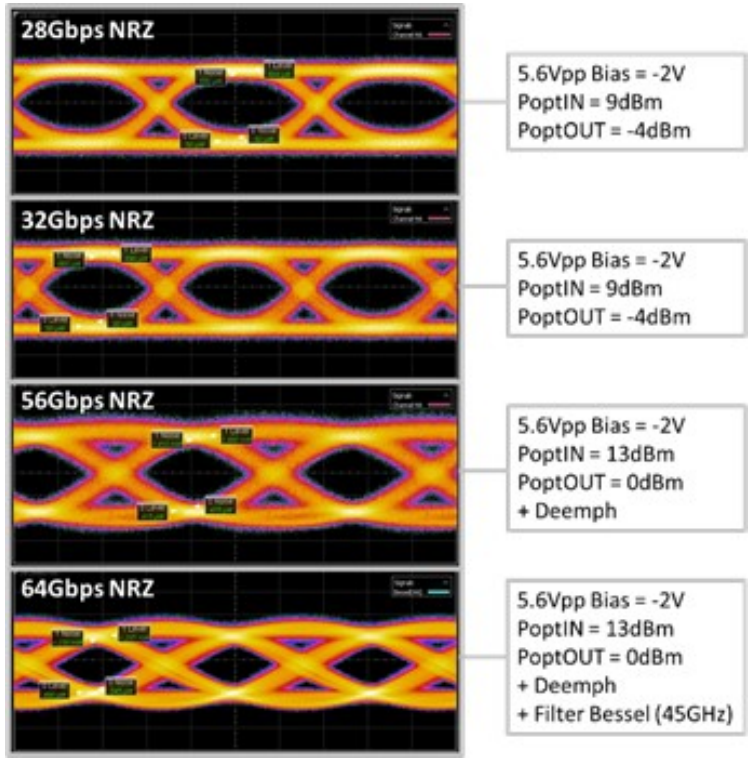


Electro-optical characteristics

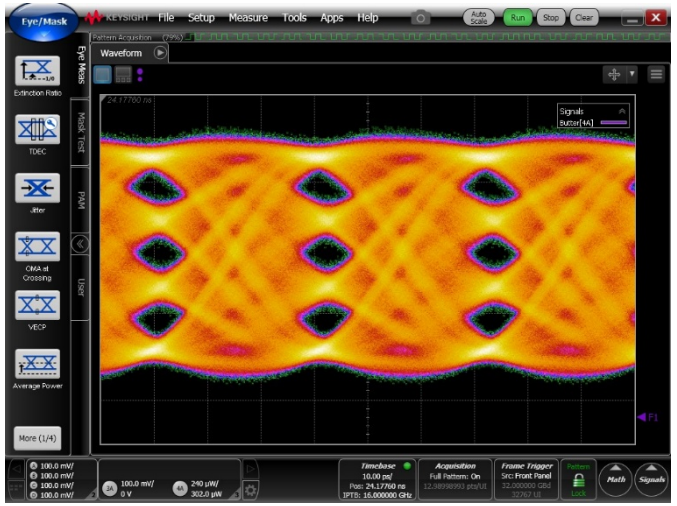
Parameters	Thin-rib
VpiLpi@-2V (V.cm)	1,5
Losses (dB/mm)	0,7
BW@-6dB (GHz)	25



Modulation characteristics



32GBaud PAM4
Bias PN : +4V
PDFA_IN = -10dBm
PDFA_OUT = 0dBm

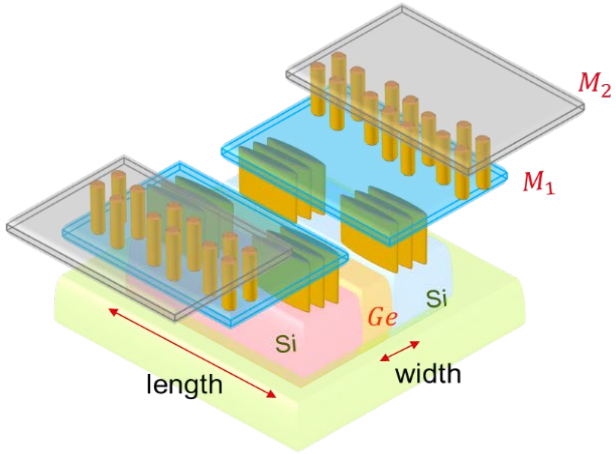


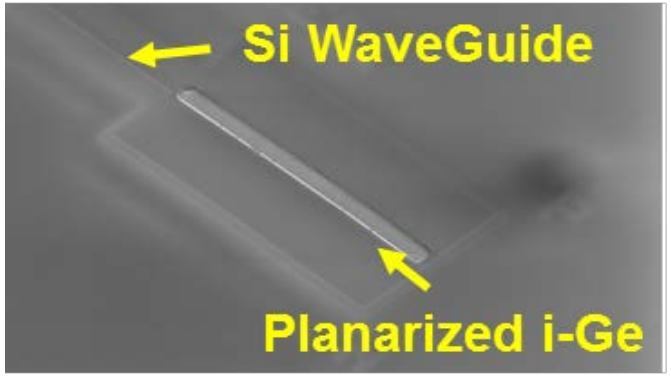
Szelag et al., "Optimization of a 64Gbps O-band Thin-Rib PN Junction Mach-Zehnder" SSDM, 2018

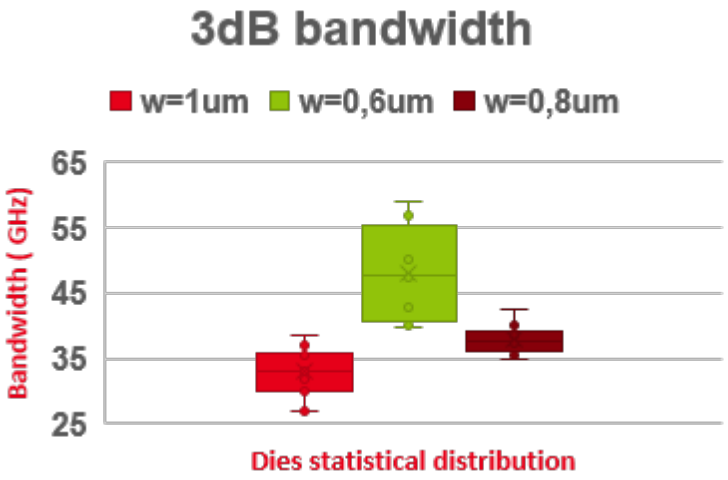
ACTIVE DEVICES: PHOTODIODE

High speed Si-Ge-Si photodiode

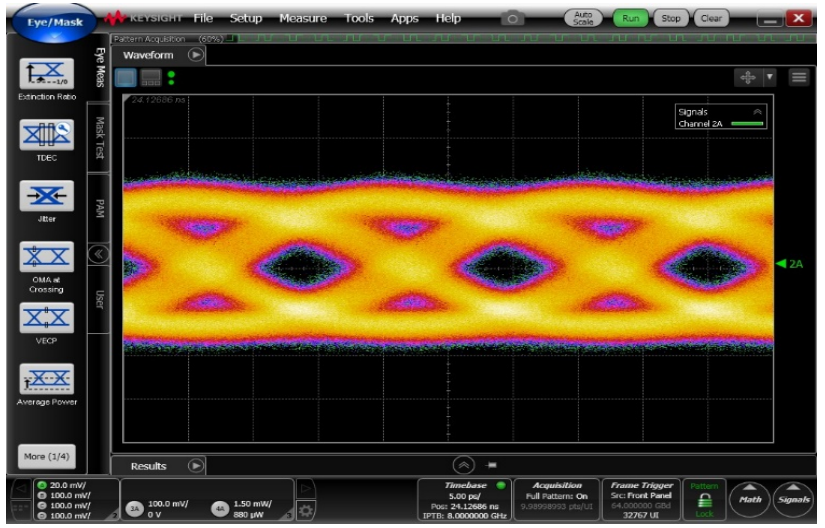
Width	0.8µm
Length	15µm
Responsivity	0.7 A/W
Dark current @ -2V	5 nA
BW @ -2V	> 35GHz







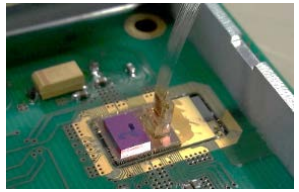
Eye diagram at 64Gbps NRZ:
BER=3 ∗ 10^{-5} (SNR=4)

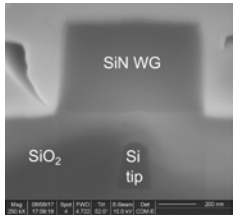


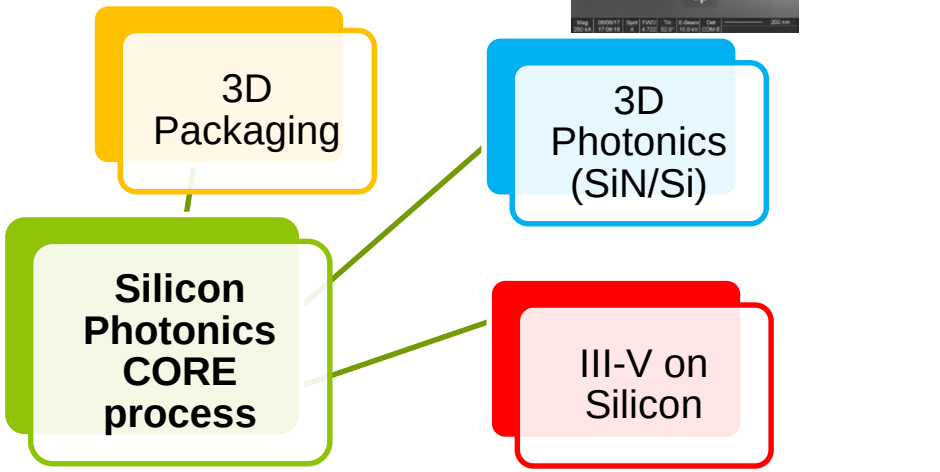
H. Zegmout et al., Photonics West 2020

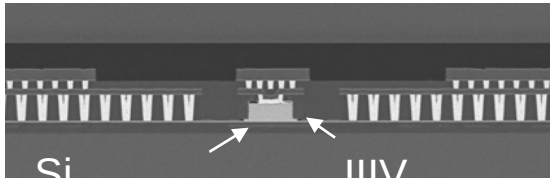
NEW TRENDS AND REQUIREMENTS

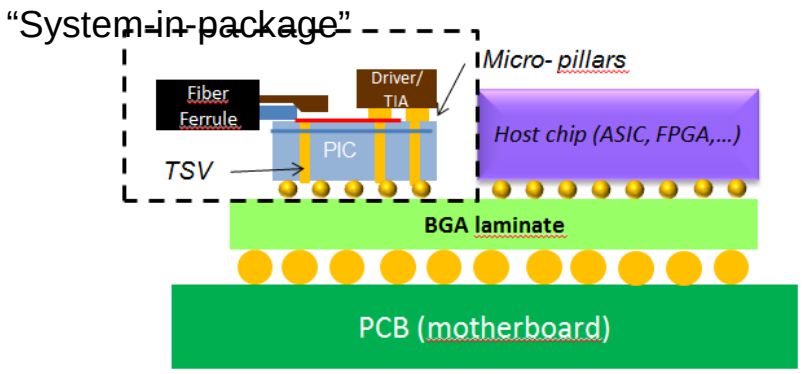
- **Increasing Data rate**
  - 800 Gbps and more
  - 25-50 GBd per channel
  - WDM, IQ modulation, PAM-4
- **Increasing density**
  - Tbps / mm2
  - Dense I/O connections
  - Co-packaging close to the host chip
- **Increasing Complexity**
  - Larger circuits
  - Increased number of I/Os
  - Complex routing
- **Laser source integration**

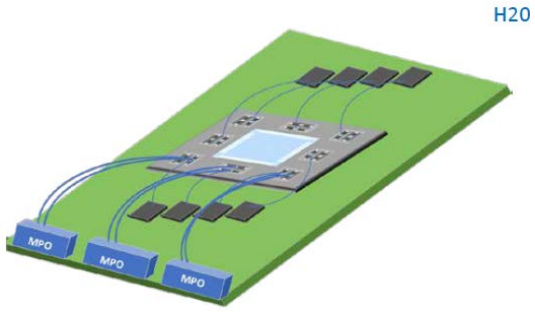




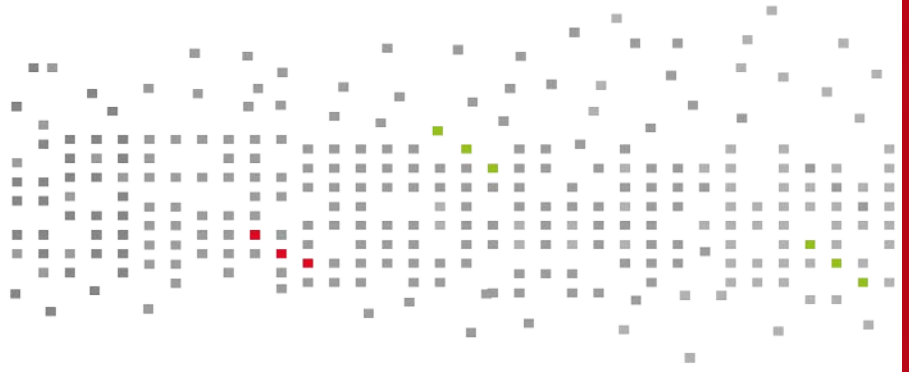


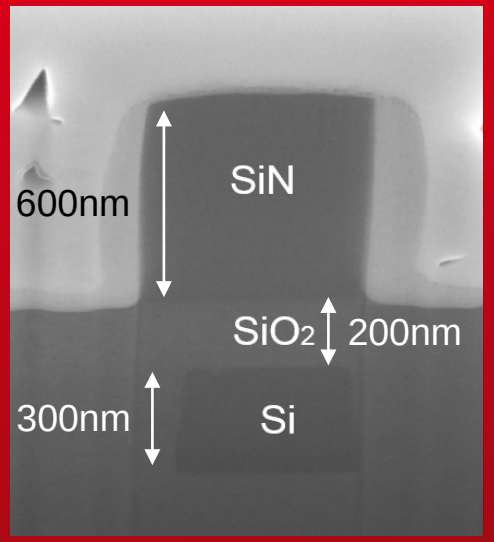






SILICON NITRIDE ADD-ON





ADD-ON: SILICON-NITRIDE AS A PHOTONIC LAYER

Why Silicon nitride:

- Low refractive index (n_{SiN} = 1.88)

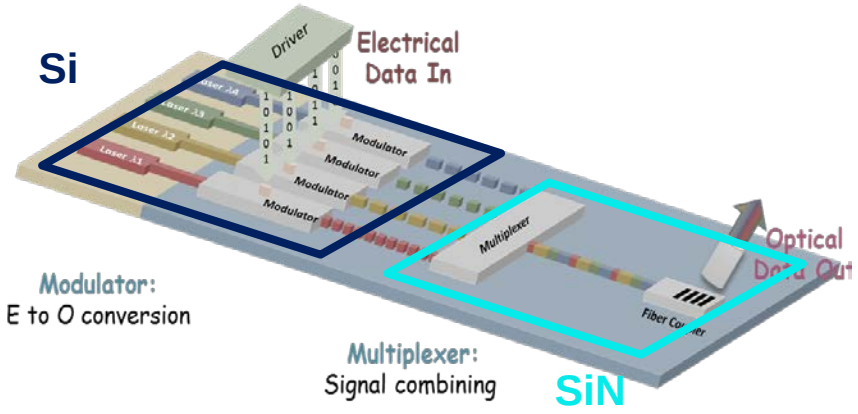
→ less sensitive to fabrication imperfections

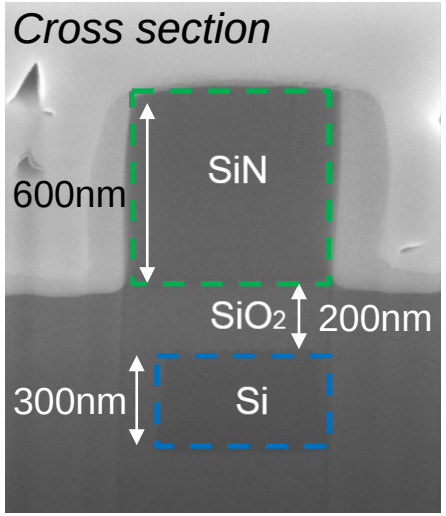
Waveguide: 0.6dB/cm

- Low thermo-optic coefficient (~$2x10^{-5}$ K^{-1})

→ Temperature quasi-insensitive **multiplexer**

- Broadband coupling scheme



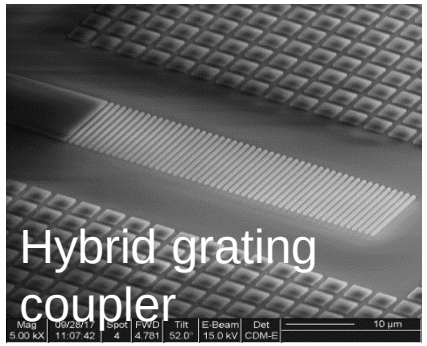


Q. Wilmart et al., Appl. Sci. (2019)

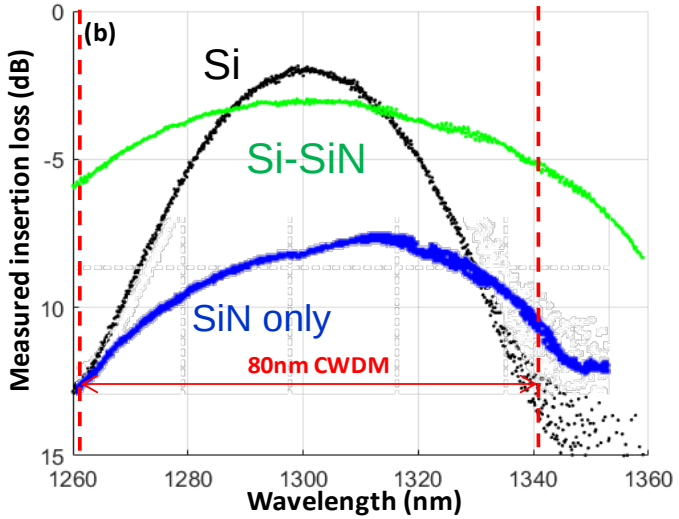
SIN BROADBAND FIBER COUPLERS

SiN-Si hybrid grating coupler
- 2-layers grating SiN-Si
- 2.8 dB insertion loss
- -1dB BW ~ 50nm

→ CWDM components wafer level testing (broadband)

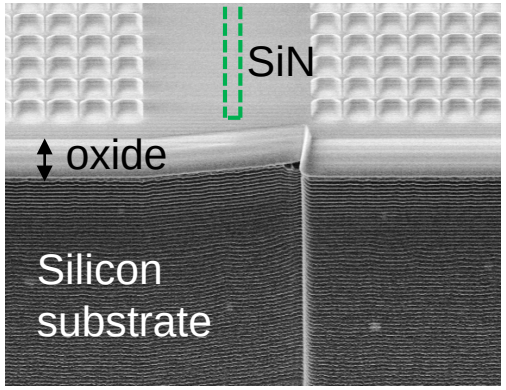


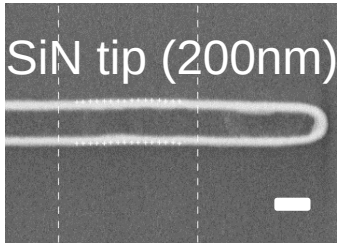
Grating couplers



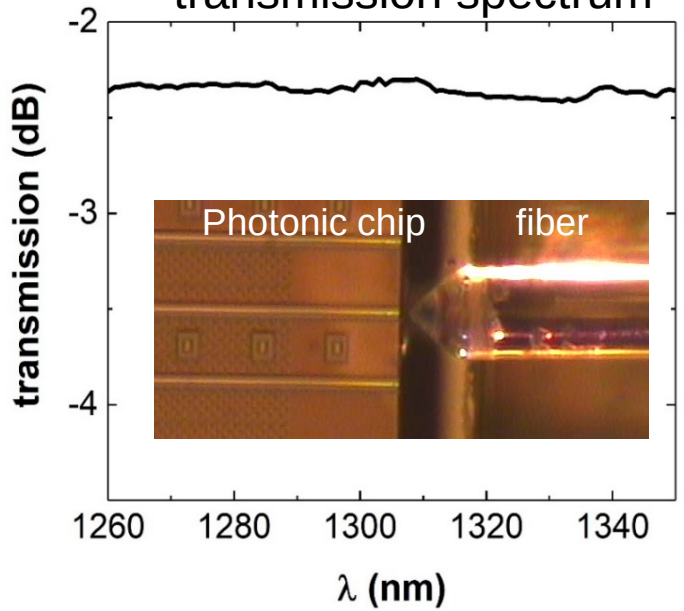
Q. Wilmart et al., Appl. Sci. (2019)

Edge coupler with SiN taper
- Lensed fiber : MFD = 2.5µm
- SiN inverse taper
- Deep trench by dry etching
- Coupler insertion loss : **< 2.4dB** (O-band)
- For CWDM modules

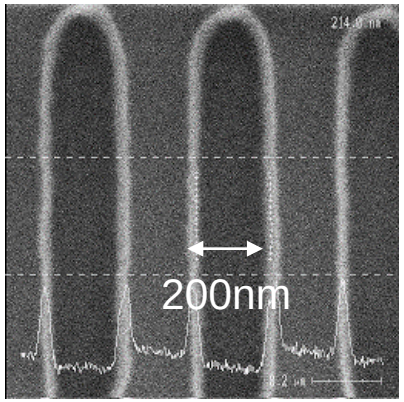




Edge coupler transmission spectrum



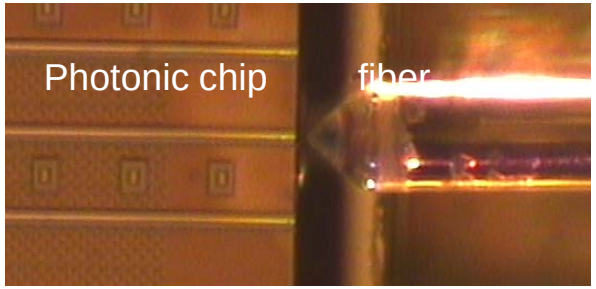
SIN CWDM MULTIPLEXER

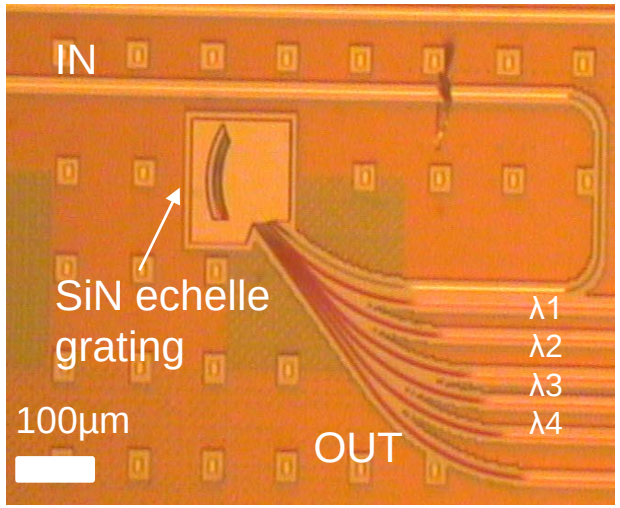


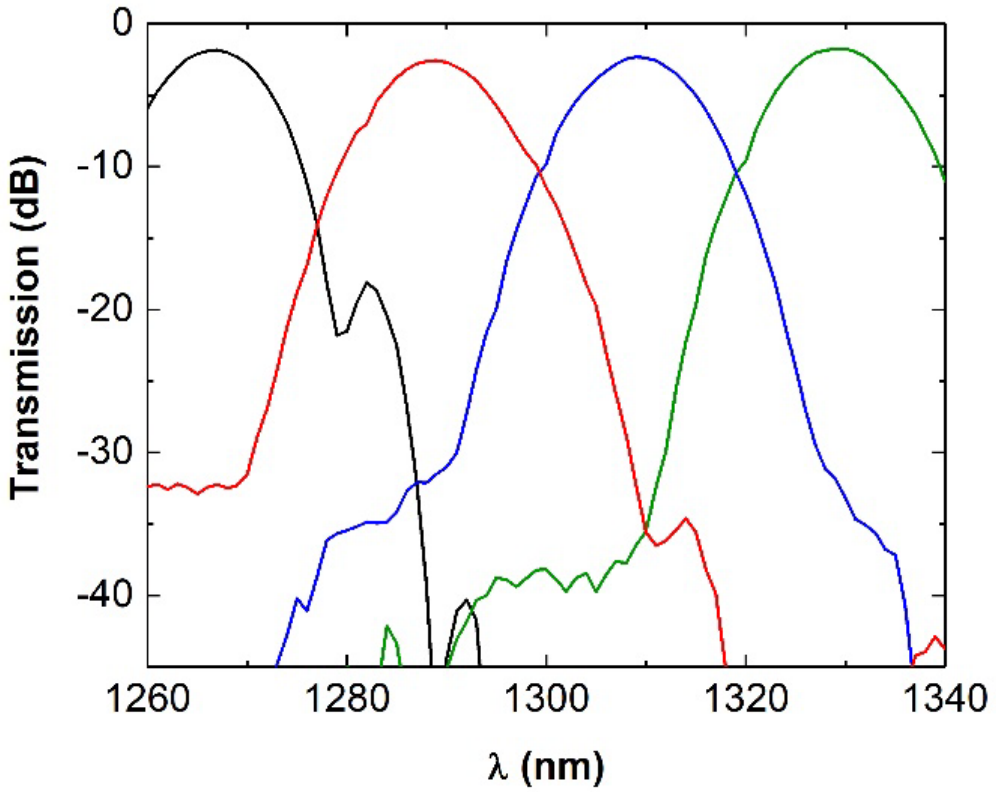
SiN Bragg grating

SiN Echelle grating MUX

- 4 channels CWDM (O-band)
- Edge coupling measurement
- 193nm DUV photolithography of the SiN bragg grating
- Insertion loss : < 2.5dB
- Crosstalk < -30dB
- -1dB bandwidth ~8nm
- Thermal sensitivity: 13pm/K

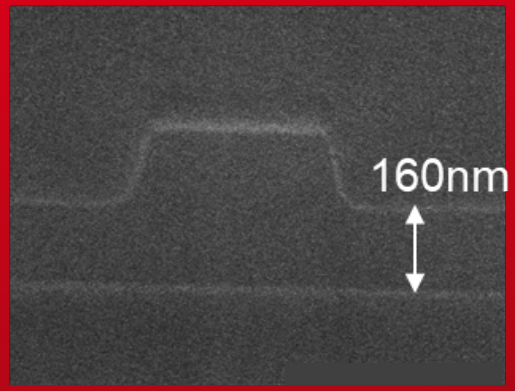






Q. Wilmart, Ph West (2020)

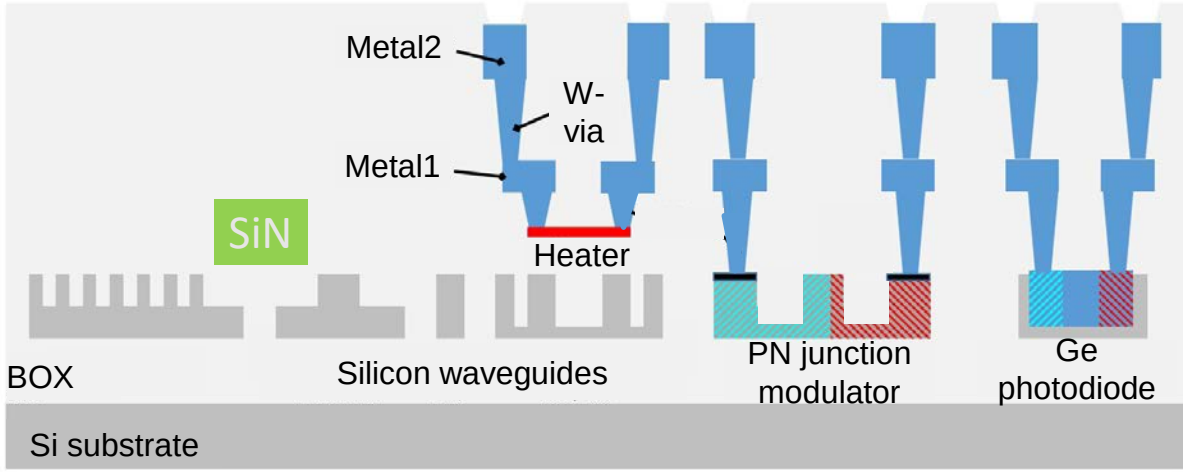
ULTRA LOW LOSS SILICON WAVEGUIDES

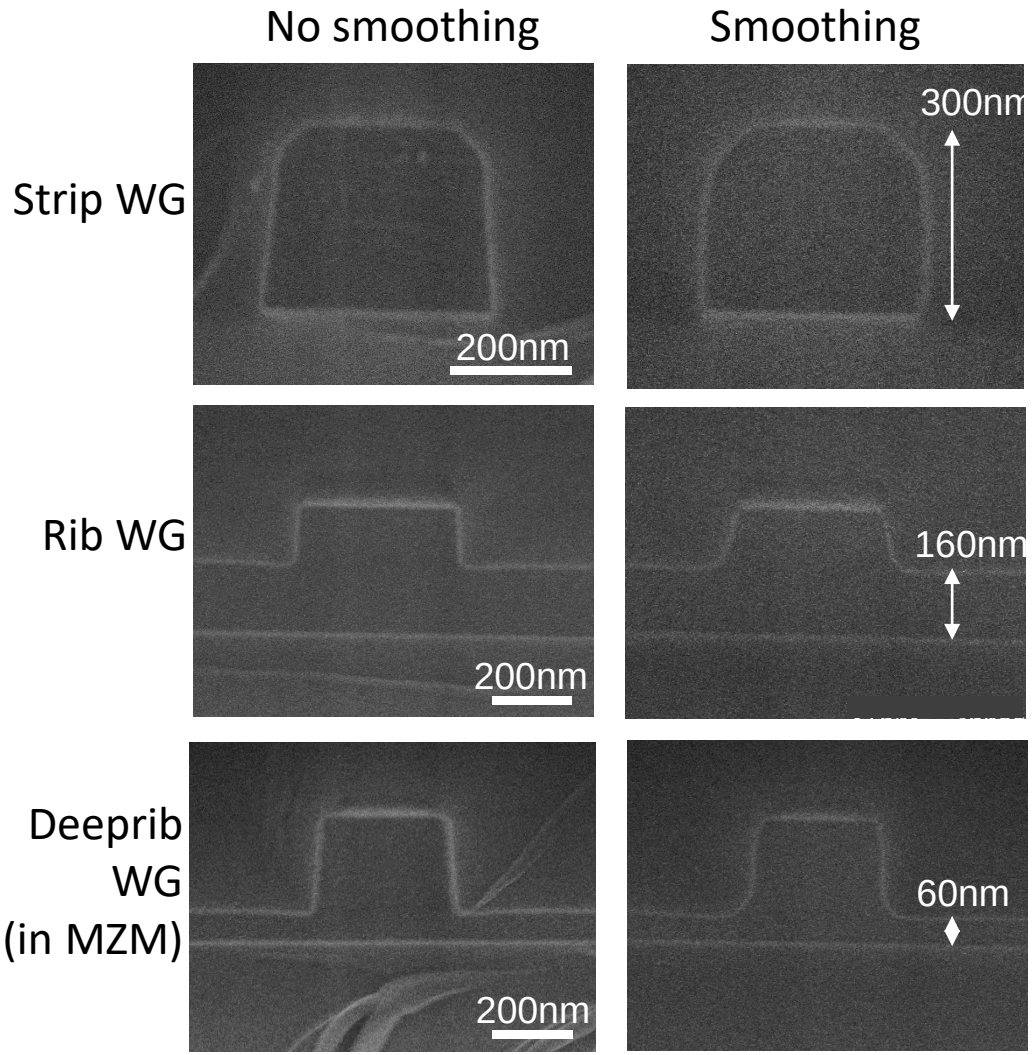


LOW LOSS SI WAVEGUIDES IN THE FULL PHOTONICS PLATFORM

Hydrogen smoothing annealing applied on the full silicon photonics platform

- H_2 annealing leads to Si atomic surface migration
- Significant roughness reduction observed (CNRS – LTM)
- Targeting ultra-low loss on 3 types of waveguide (strip, rib and deeprib)
- Si3N4 hard mask on top of Si

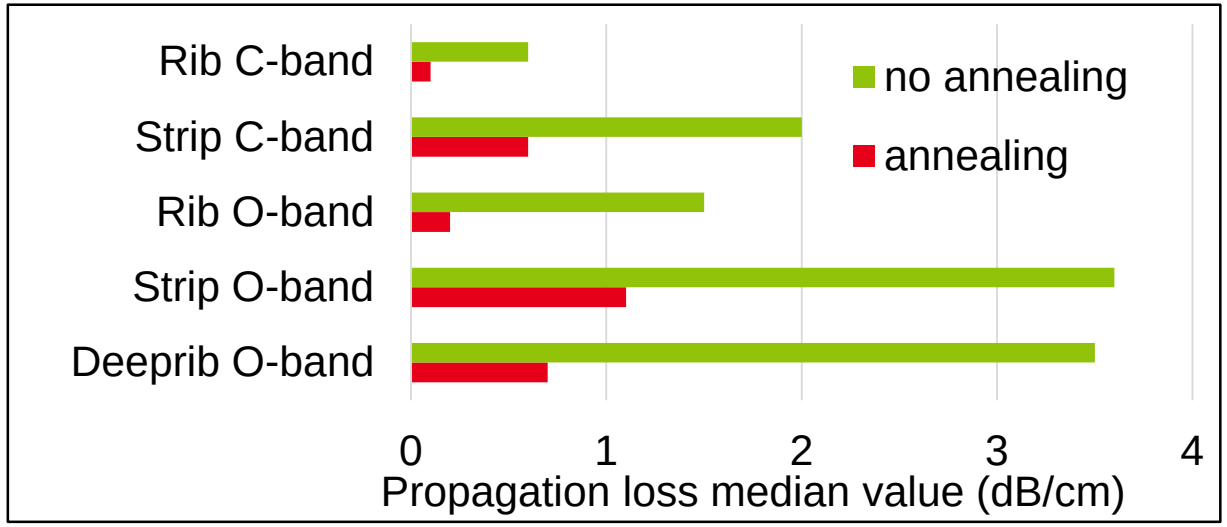




Q. Wilmart, GFP (2019)

LOW LOSS SI WAVEGUIDES IN THE FULL PHOTONICS PLATFORM

- **Propagation loss measurement**



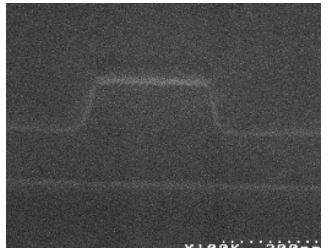
- Efficient sidewall smoothening
- Good wafer uniformity
- Outperform advanced immersion lithography waveguides

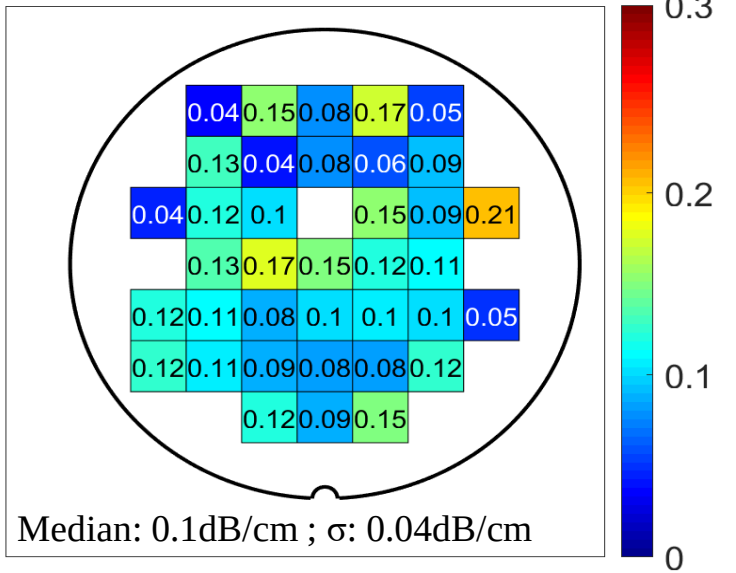
0.1dB/cm (rib) ; 1.1dB/cm (strip)
→ State-of-the-art!

Q. Wilmart et al., IEEE J. Lightwave Tech., to be published (2020)

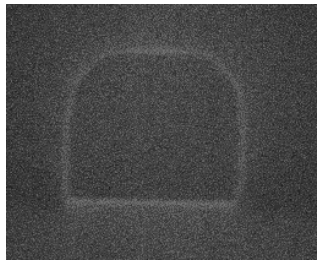
Propagation loss mapping (dB/cm)

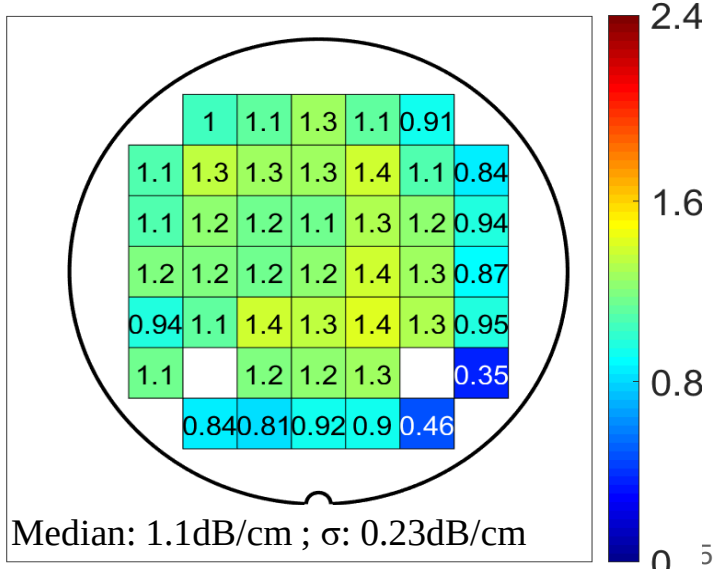
Rib
λ = 1550nm





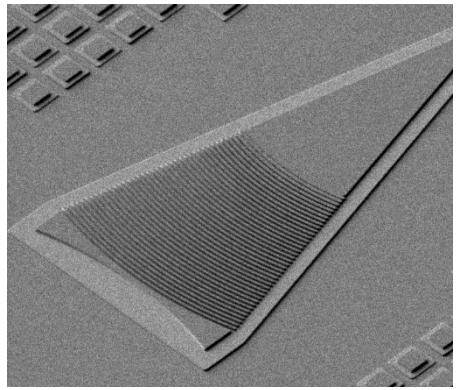
Strip
λ = 1310nm



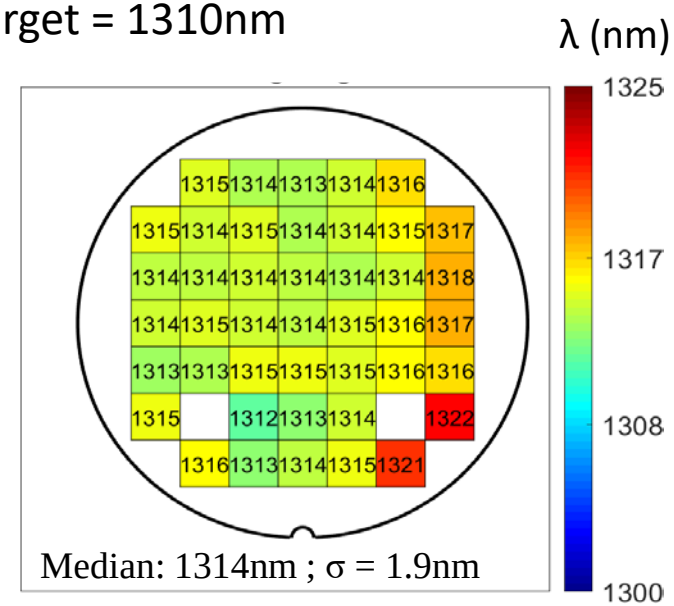


IMPACT OF ANNEALING PROCESS ON PASSIVE DEVICES

- Grating coupler central wavelength. Target = 1310nm



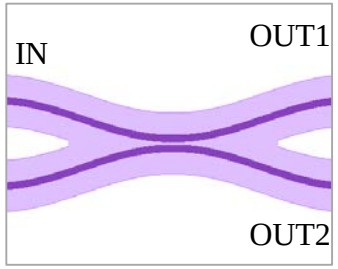
2-silicon levels apodized grating fiber coupler

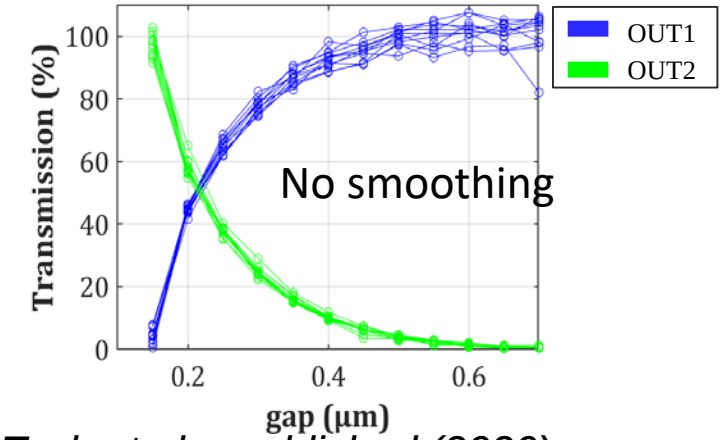


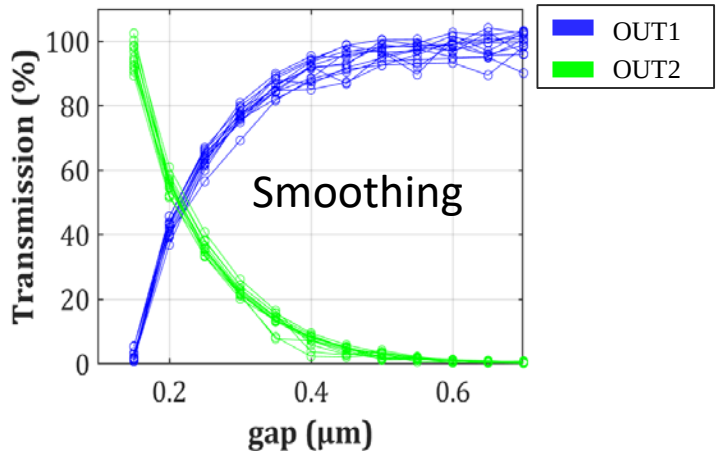
- ✓ Central wavelength
- ✓ Grating coupler insertion loss = **2dB / grating**

~ no impact of annealing

- Directional coupler transmission @1310nm

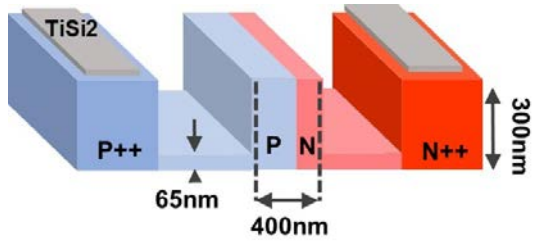


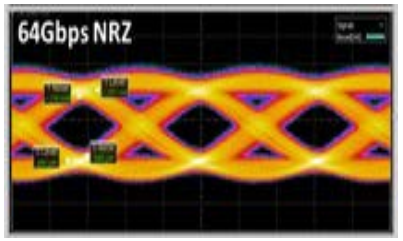




Q. Wilmart et al., IEEE J. Lightwave Tech., to be published (2020)

IMPACT ON MACH ZEHNDER MODULATORS (MZM)



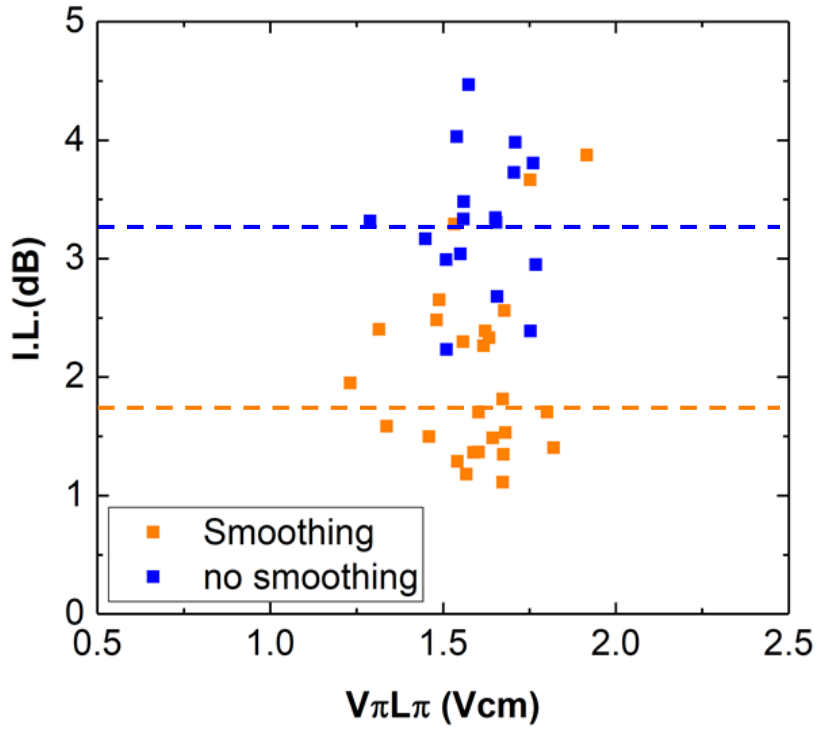


Smoothing annealing on modulators:

- No effect of the smoothing annealing (>800°C) on the P-N junction
- Efficiency preserved ($V_\pi L_\pi$ = 1.6 V.cm with or without annealing)

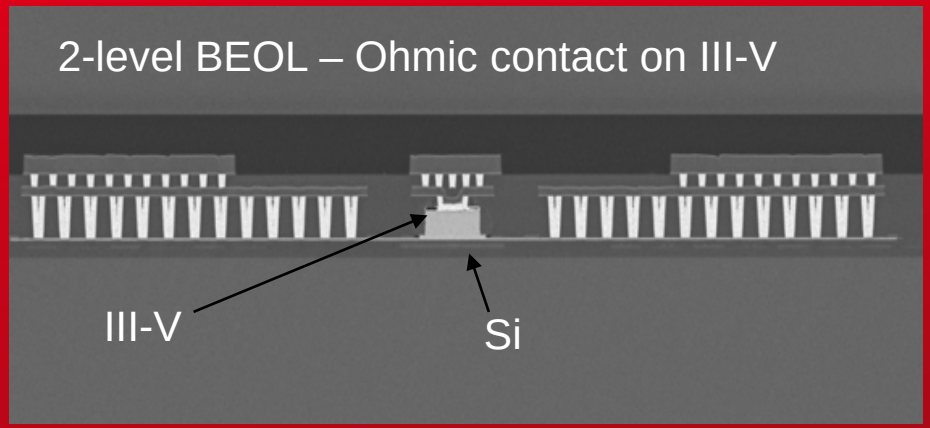
- **Total loss of MZM reduced by several dBs**

(1.5dB gain with 1mm-long MZM)



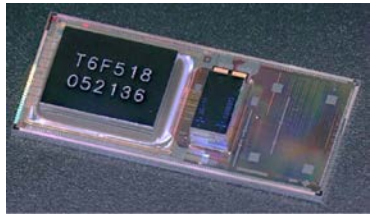
Q. Wilmart et al., IEEE J. Lightwave Tech., to be published (2020)

III-V LASER DIRECT BONDING INTEGRATION



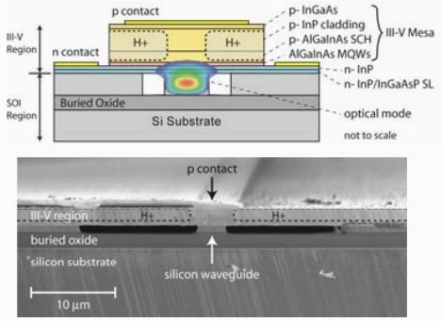
WHICH LIGHT SOURCE ON SILICON ?

Assembly of already processed III-V laser



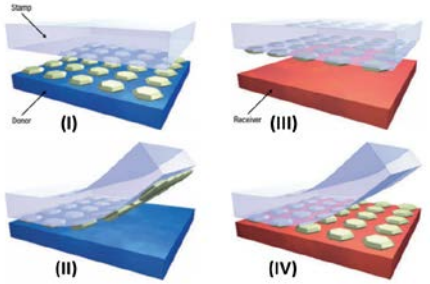
Luxtera's
silicon photonics Optical Engine (100G TX+RX PSM-4)

III-V/Si Bonding



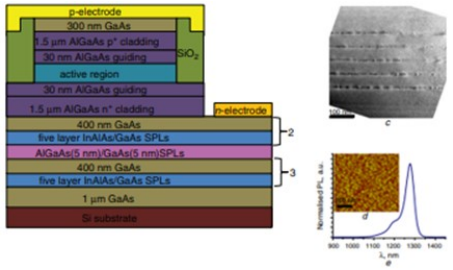
J.E. Bowers, et al., *Hybrid Silicon Evanescent Laser in a Silicon-onInsulator Waveguide, OFC (2007)*

Transfer printing



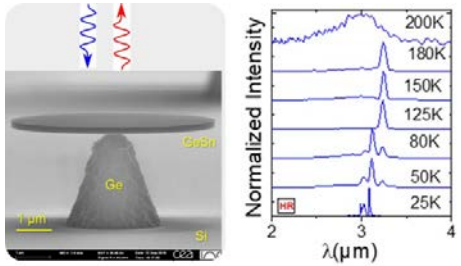
M. A. Meitl, et al, *Transfer printing by kinetic control of adhesion to an elastomeric stamp, Nature Materials **5**, 33–38 (2006)*

Direct epitaxy of III-V on Si



S.M. Chen, et al, *1.3 µm InAs/GaAs quantum-dot laser monolithically grown on Si substrates operating over 100°C, Electronics letters,* Vol. 50 No. 20 pp. 1467–1468 (2014)

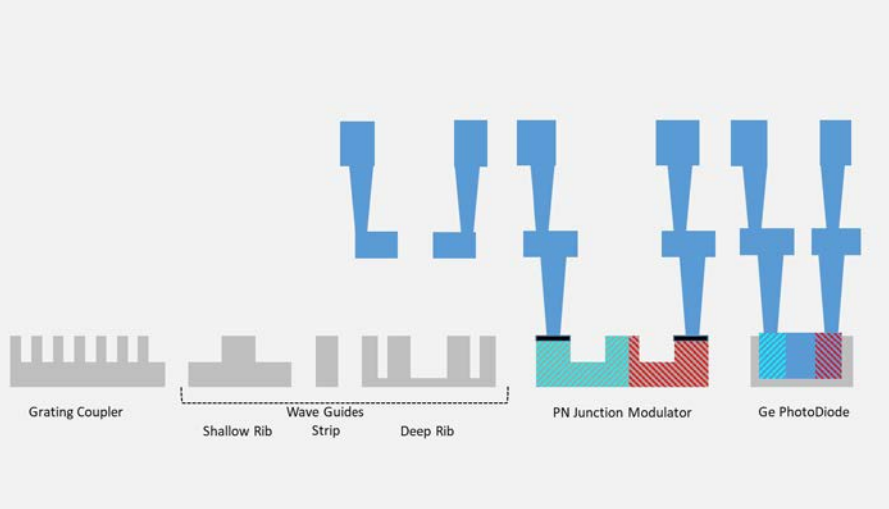
Ge(Sn) laser on Si



V. Reboud et al., *Optically pumped GeSn micro-disks with 16% Sn lasing at 3.1 µm up to 180 K, Appl. Phys. Lett. 111, 092101 (2017).*

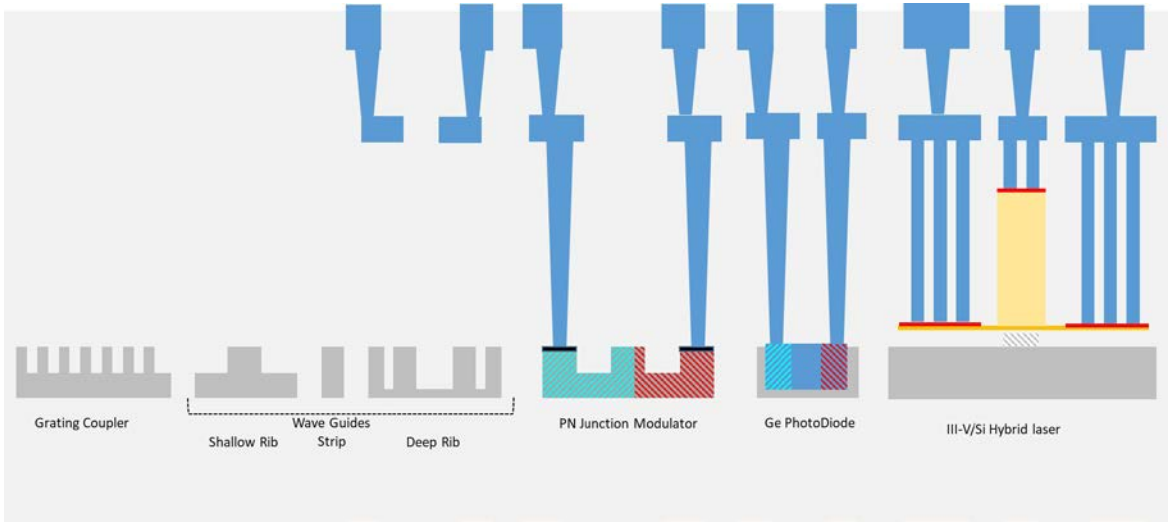
TECHNOLOGY– LASER INTEGRATION IMPACT

Si Photonic Plateform Core Process



- 310nm SOI – 2µm BOX
- 193nm DUV lithography
- Multilevel silicon patterning
- 8 Implantations levels
- Selective Germanium epitaxy
- Silicide
- Metal heater
- Planarized BEOL
- 2 AlCu routing levels
- UBM for Cu pillar assembly

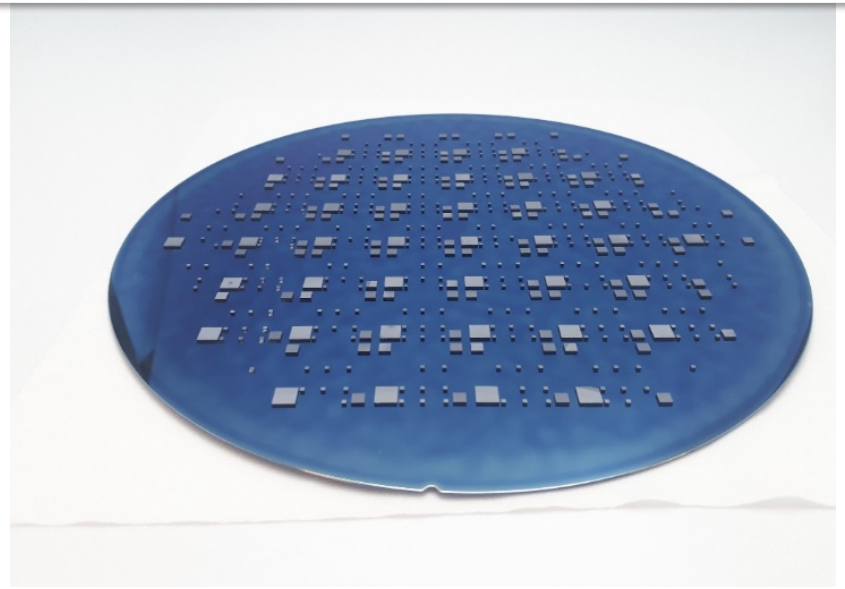
CMOS Compatible III-V/Si Integrated Laser



- Collective die bonding
- Additional Laser process steps cmos compatible:
  - No noble metals for III-V contacts
  - Conventional patterning steps (no lift-off)
- Thick M1 to Silicium contact module
- Localized Si thickening on 310nm SOI:
  - Damascene process with Si-Amo or selective Si-epi
- Planarized multi-metal level BEOL
- Additional thermal budget due to laser integration < 600°C

LASER ON SI LARGE SCALE INTEGRATION: DIE BONDING

Development of automated die bonding of III-V/SOI

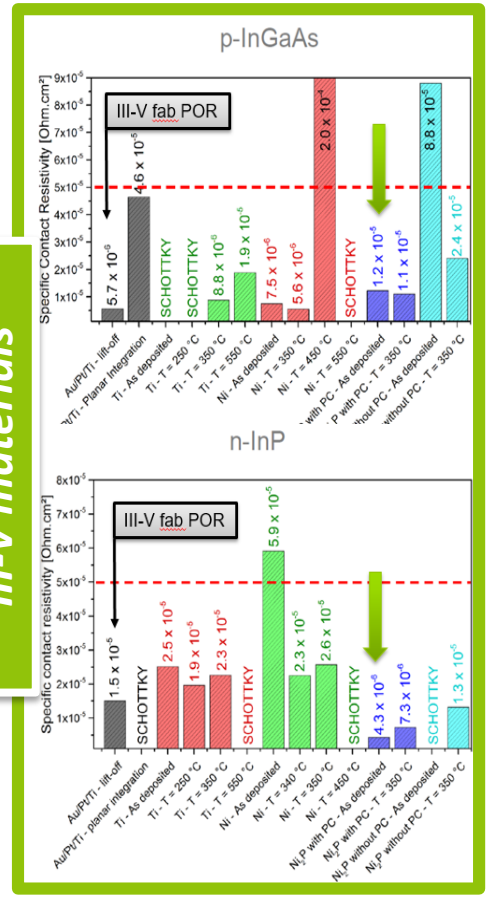


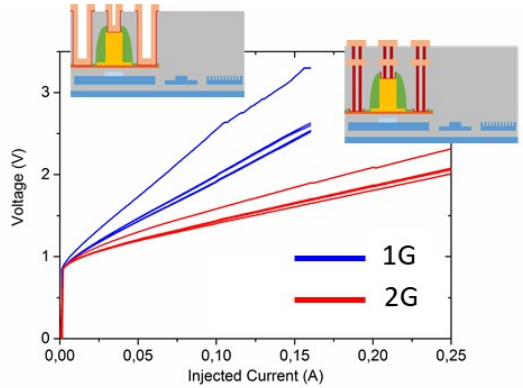
Collective die Bonding with adhesive film

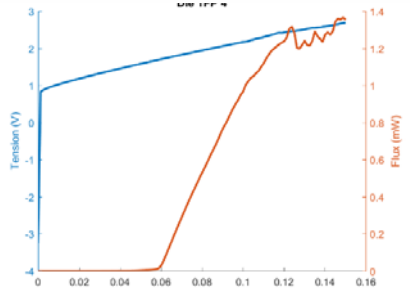
- + Process validated for InP die
- + Process compatible with die thickness variations up to 50 µm
- + Compatible with multidie bonding
- + Minimum Die Size 1x1mm²
- + Die spacing 400µm
- + Scalable to 300mm wafers

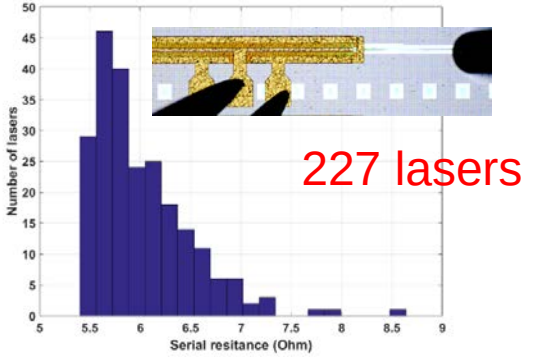
Development of efficient CMOS friendly BEOL / III-V

Ohmic contacts on III-V materials





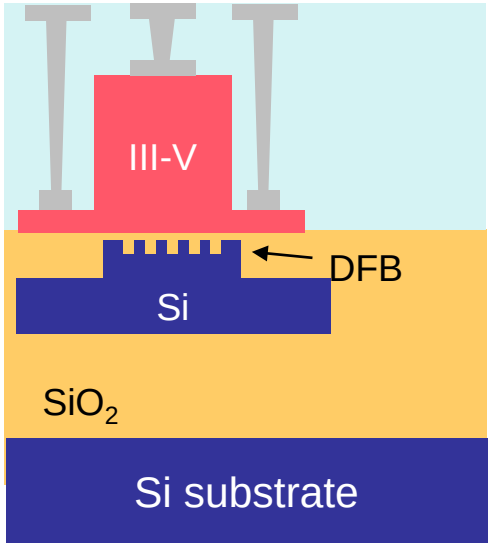




K. Hassan et al., Photonics Europe (2020)
P. Rodriguez et al., Jpn. J. Appl. Phys. 59, (2020)

III-V INTEGRATION ON THE SI/SIN PLATFORM

Si/III-V integrated platform

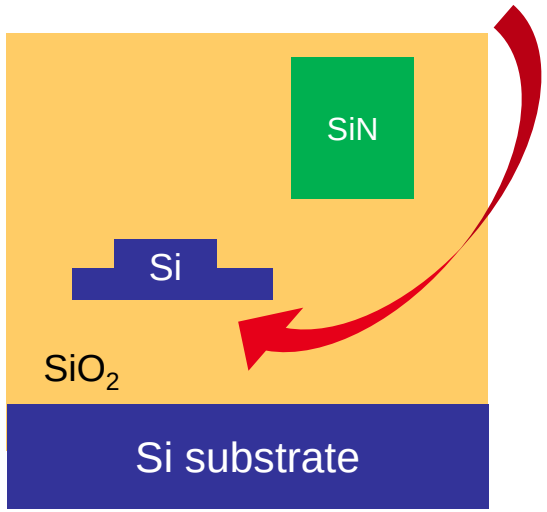


- III-V 100nm on top of Si
- Si is 500nm thick

➢ Si/III-V coupling

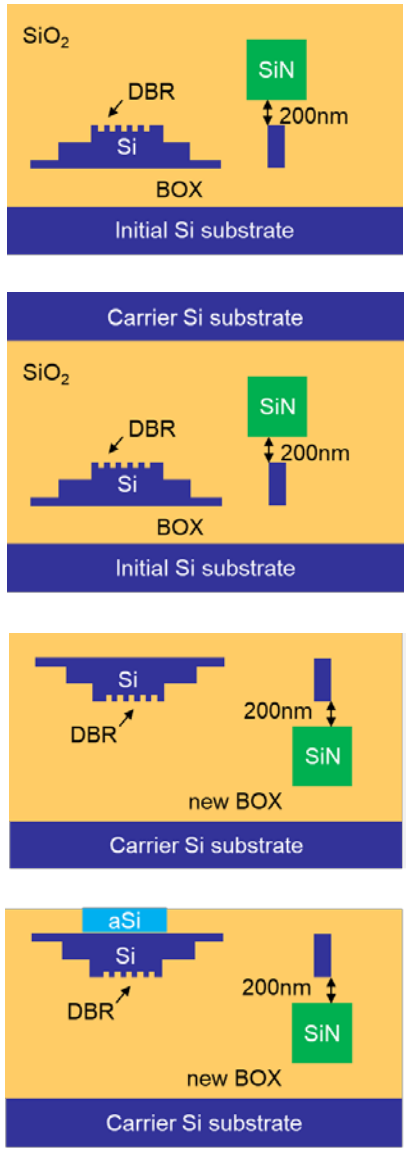
Si/SiN platform

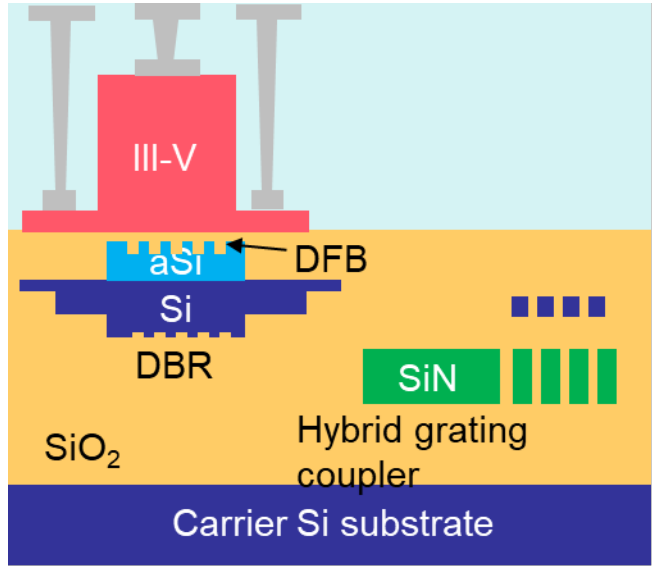
Solution: III-V in the backside



- SiN is 200nm on top of Si
- Si is 300nm thick

➢ Si/SiN coupling





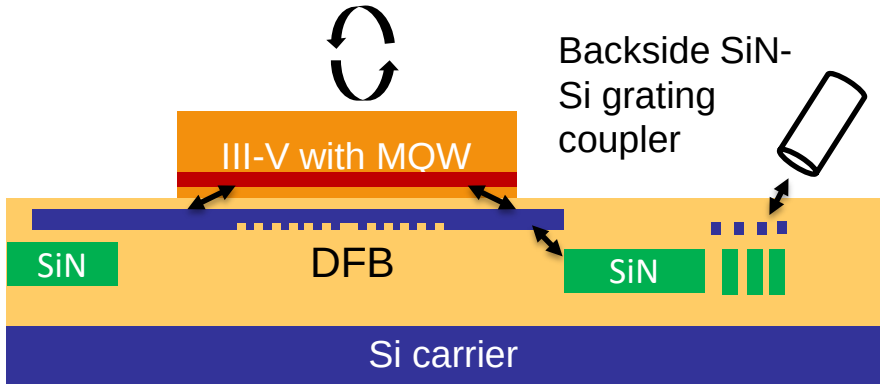
Backside integration of III-V epitaxy on the backside of the Si/SiN platform

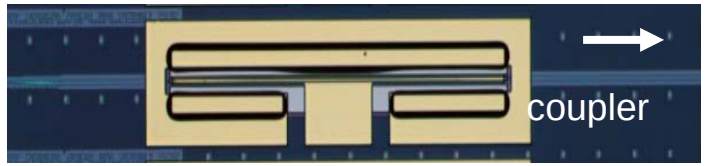
SCINTIL spin-off

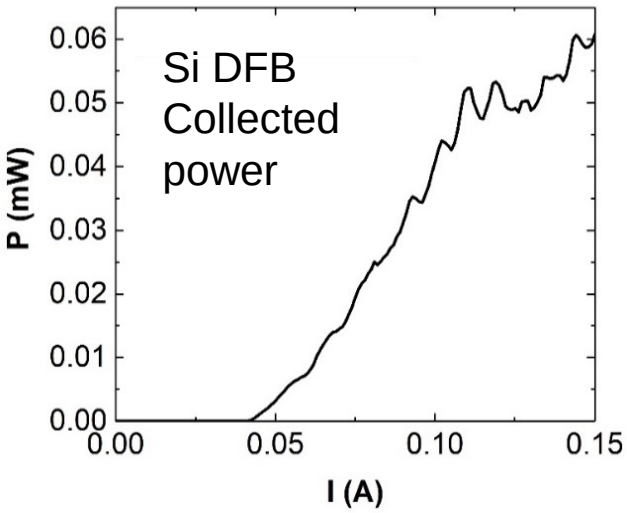
Q. Wilmart, SSDM (2020)

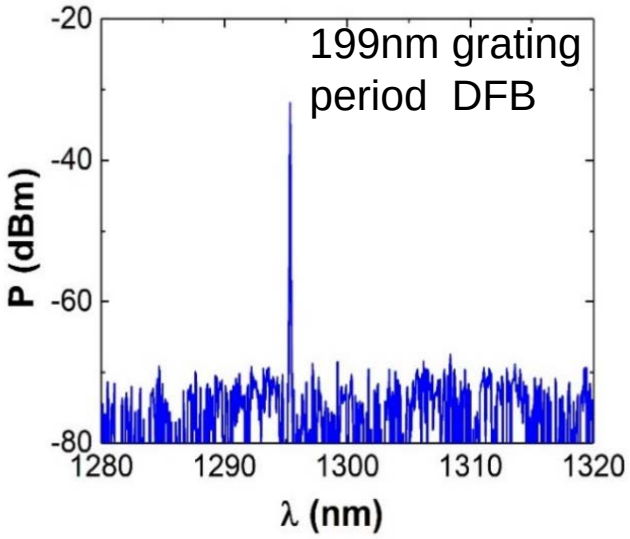
III-V/SI LASER ON THE SI/SIN PLATFORM

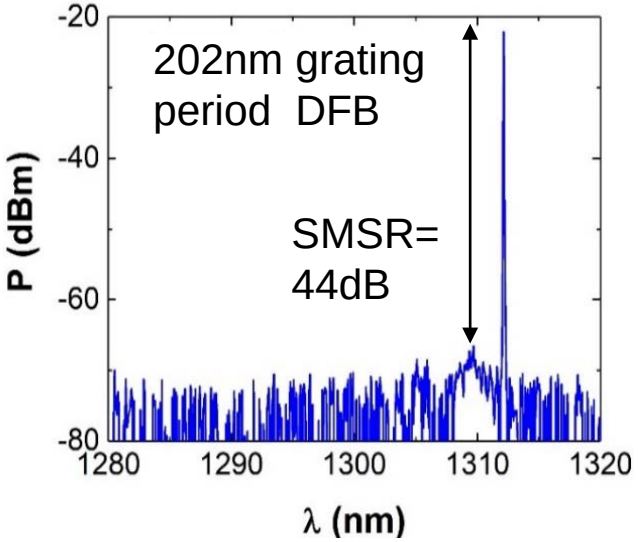
- III-V/Si hybrid laser with backside integration
- DFB type laser (DFB grating in Si)
- Gain length = 400µm
- Off-chip coupling with SiN/Si grating coupler







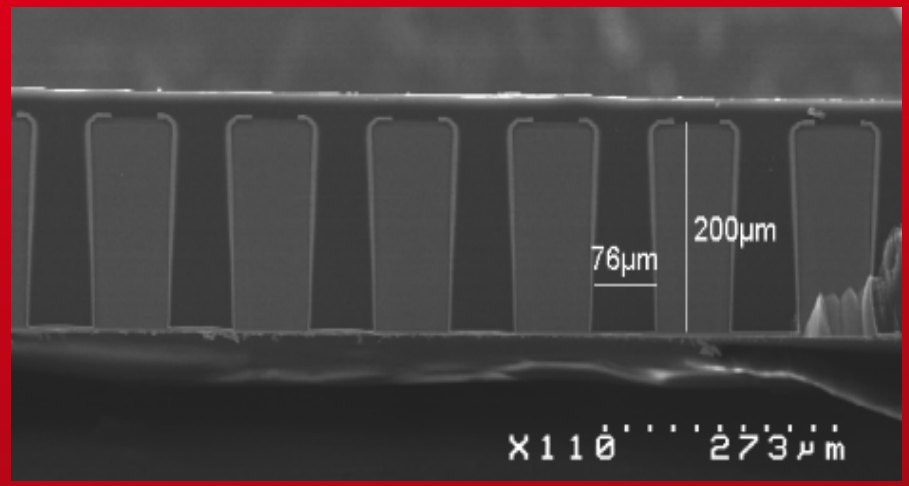




- ✓ 2-λ DFB: 1295nm & 1312nm
- ✓ Single mode émission
- ✓ SMSR = 44dB
- ✓ Power up to 0.8mW in waveguides

Q. Wilmart, SSDM (2020)

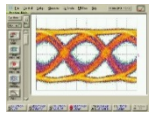
ADVANCED PACKAGING



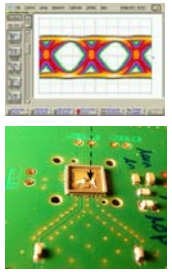
HIGH SPEED MODULES USING LETI PLATFORM

Wire bonding ***Flip Chip*** ***TSVs***

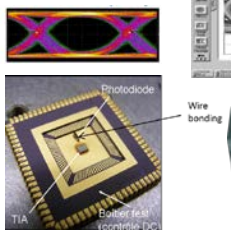
Integration/Co-integration level



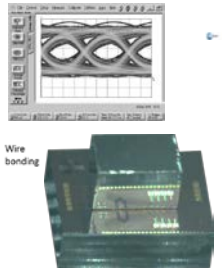
Module Rx 8Gbps
Wire bonding



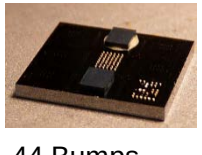
Module Rx 12,5Gbps
Wire bonding



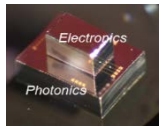
Module Rx 25Gbps
Wire bonding



Module Rx 25Gbps
Flip Chip



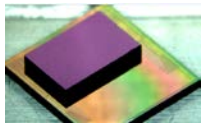
44 Bumps
(SBB)



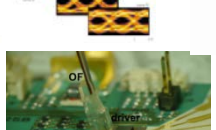
100 Bumps

144 bumps

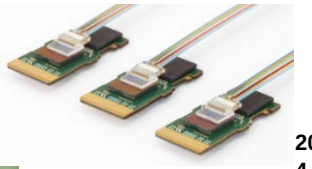
484 bumps



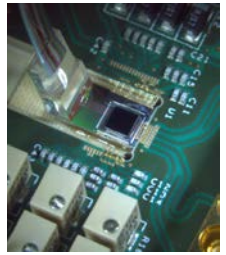
2091 bumps



Module Rx 100 Gbps
Chip On Board

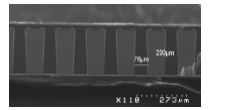


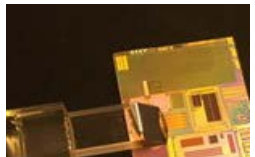
200 Gbps Tx/Rx
MBOM



200 Gbps/ (50G NRZ, WDM-2)
4 fibers (2 Rx/2Tx)

Enabler for 400Gbps++



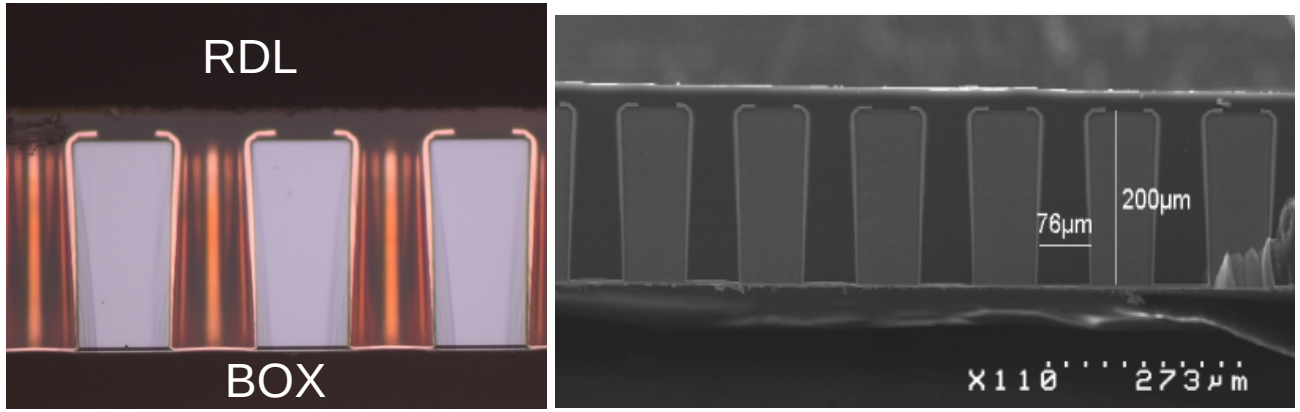


800 Gbps intra DC

2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021

3D INTEGRATION @ LETI

- **3D Integration**



- **TSV last**
  - Backside Etching
  - 2µm Cu liner

- **TSV mid**
  - Frontside Etching
  - Grinding to 100µm thickness
  - Study of stress/strain on photonics layers

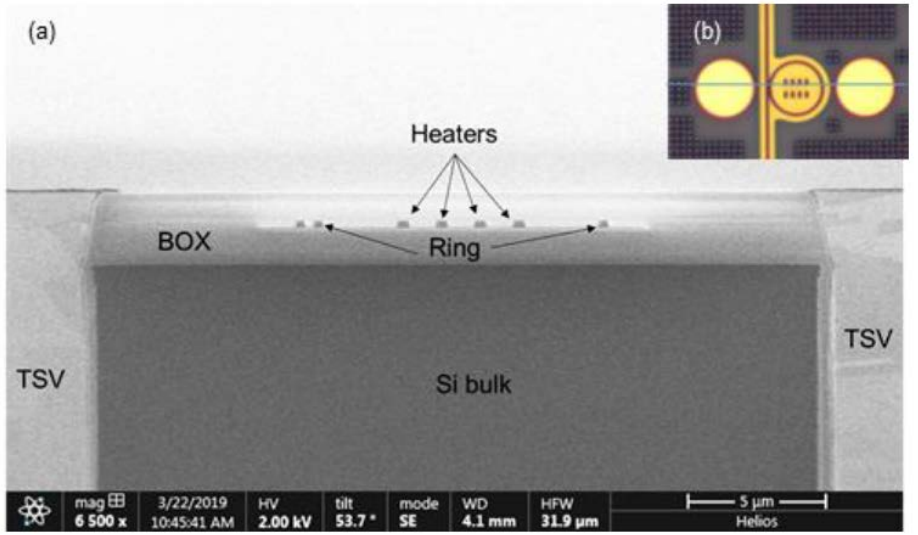


Fig. 4. a) SEM cross section of the TSV-surrounded ring before BEOL, b) optical top view of the ring and its TSVs and corresponding cross section plane

G. *Parès, Leti Internal report*
P.Tissier , ESTC , 2020

CONCLUSION

Silicon Photonics is now part of commercial modules for 100G / 400G inter/intra DC links

800G + applications are setting new challenges

Increased data rate :

- Requiring PAM-4 and WDM
- ***SiN add-on*** enhances existing libraries with broadband and Mux athermal devices

Increased density:

- Following the co-packaging roadmap
- ***3D packaging*** is a must

Increased complexity:

- Increased size of circuits
- Require ***low loss waveguides*** and photonics EDA tools

All these challenges (+ laser integration) are addressed by CEA-LETI through add-on plugged on an existing standard Silicon Photonics Platform (200mm ready, 300mm available in 2021)

Acknowledgements :

Leti Photonics team

Thanks

Leti, technology research institute
Commissariat à l'énergie atomique et aux énergies alternatives
Minatec Campus | 17 avenue des Martyrs | 38054 Grenoble Cedex | France
www.leti-cea.com

Acknowledgement

Co-funded by the Horizon 2020
Framework Programme of the European Union

MASSTART project is co-funded by the Horizon 2020 Framework Programme of the European Union with Grant Agreement Nr. 825109. https://cordis.europa.eu/project/rcn/219912/factsheet/en

MASSTART project is an initiative of the **Photonics Public Private Partnership** www.photonics21.org

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