Towards Silicon Photonics 4.0

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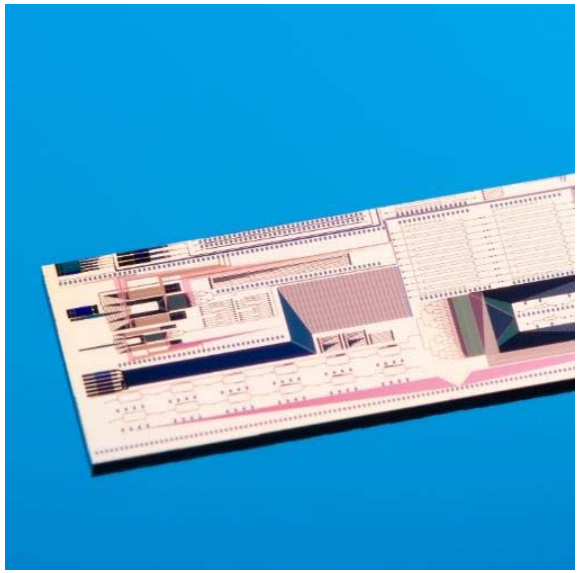
Ghent University (UGent) – imec – ePIXfab

This presentation is based on a plenary presentation at the European Conference on Optical Communications (ECOC) in Frankfurt (22-26 Sept 2024)

SILICON PHOTONICS

The implementation of high density photonic integrated circuits by means of CMOS(-like) process technology on large silicon wafers



Pictures, courtesy of imec

Enabling complex optical functionality on a compact chip at low cost

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The Key Driver for Wafer Demand (So Far): Data Centers

For a typical data center:

- 100K to 1M servers
- multiple optical fiber connections per server
- 100's MWatt energy consumption

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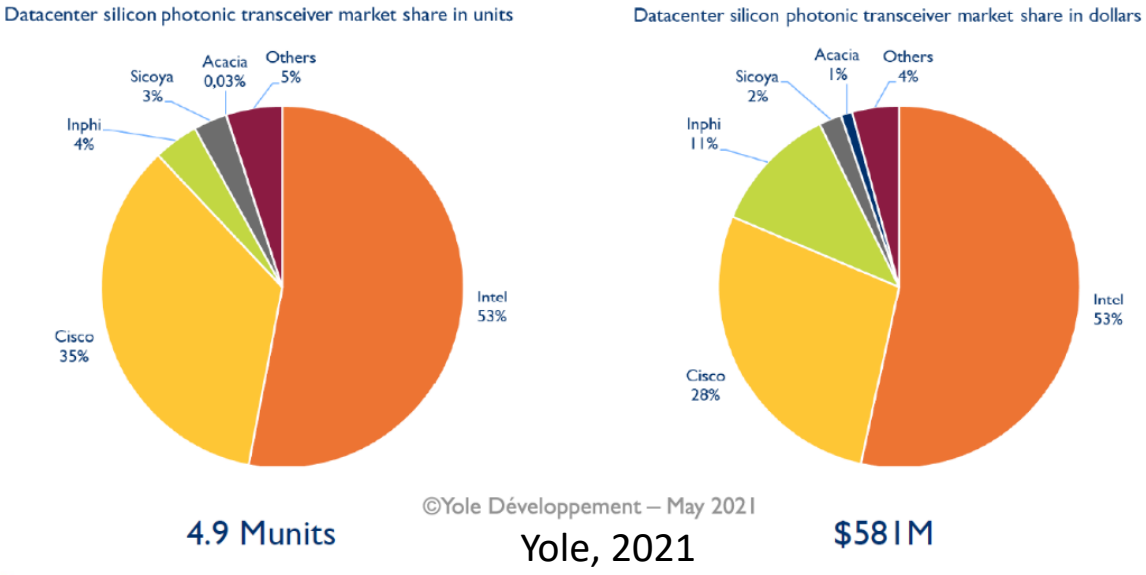
Silicon Photonics Transceivers for Data Centers and for Telecom



Typical data rate: 100-800 Gb/s

Typical symbol rate: 25-50 GBaud

- PSM4 (4 parallel fibers)
- WDM (4 wavelengths)
- Polarisation multiplexing
- PAM4
- Coherent (QPSK, 16-QAM)

Under development + early deployment:

Data rate: >800 Gb/s

Symbol rate: > 50 Gbaud

Evolution towards Co-Packaged Optics (CPO)

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Observations

- Most manufacturing and product companies in the field of silicon photonics are US based or SE/E-Asia based
- The EU has very strong R&D players in silicon photonics
- India is building up strong R&D capacity in silicon photonics
- The field is diversifying quickly (new materials, technologies, markets)
- The diversity will bring opportunities for both EU and India
- Cooperation may be key in this context

Outline

Trends in silicon photonics research

illustrated by imec's research portfolio

Transitioning from research to industrial supply chain

the challenges

Addressing the challenges

towards silicon photonics 4.0

The New Needs

Communication and Interconnect

Higher symbol rates, beyond 100 Gbaud, and lower latency

Higher interconnect bandwidth with higher spatial density

Higher energy efficiency

Seamless integration with light sources, with electronics, co-packaged optics

Other application areas

New wavelength ranges, from UV to mid-IR

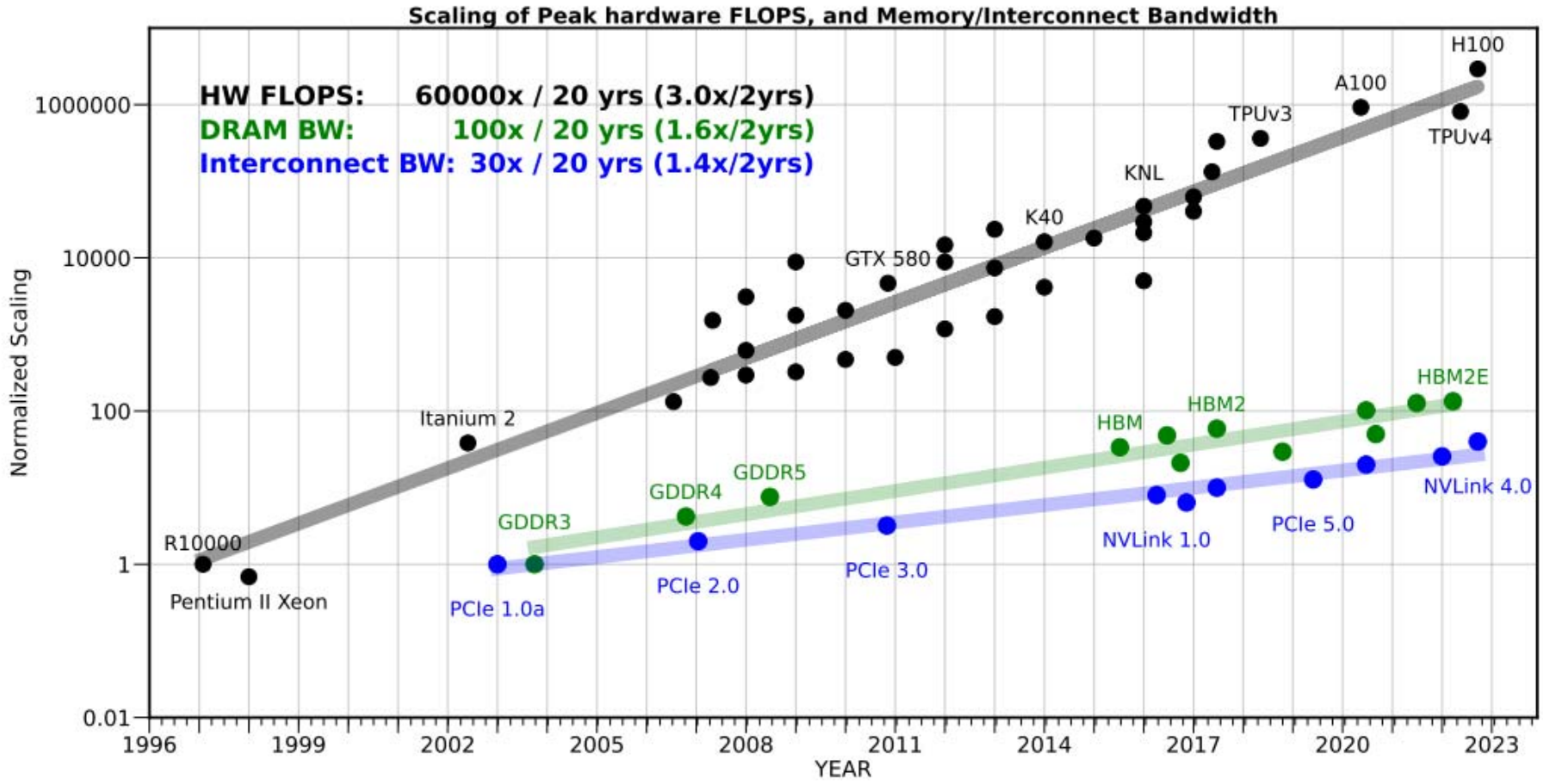
Higher optical powers

Lower optical losses

New on-chip photonic functions (advanced sources, isolators, non-volatile memory, …)

…

THE INTERCONNECT BOTTLENECK IN COMPUTE SYSTEMS



Amir Gholami et al, AI and Memory Wall, IEEE Micro 2024, https://arxiv.org/pdf/2403.14123

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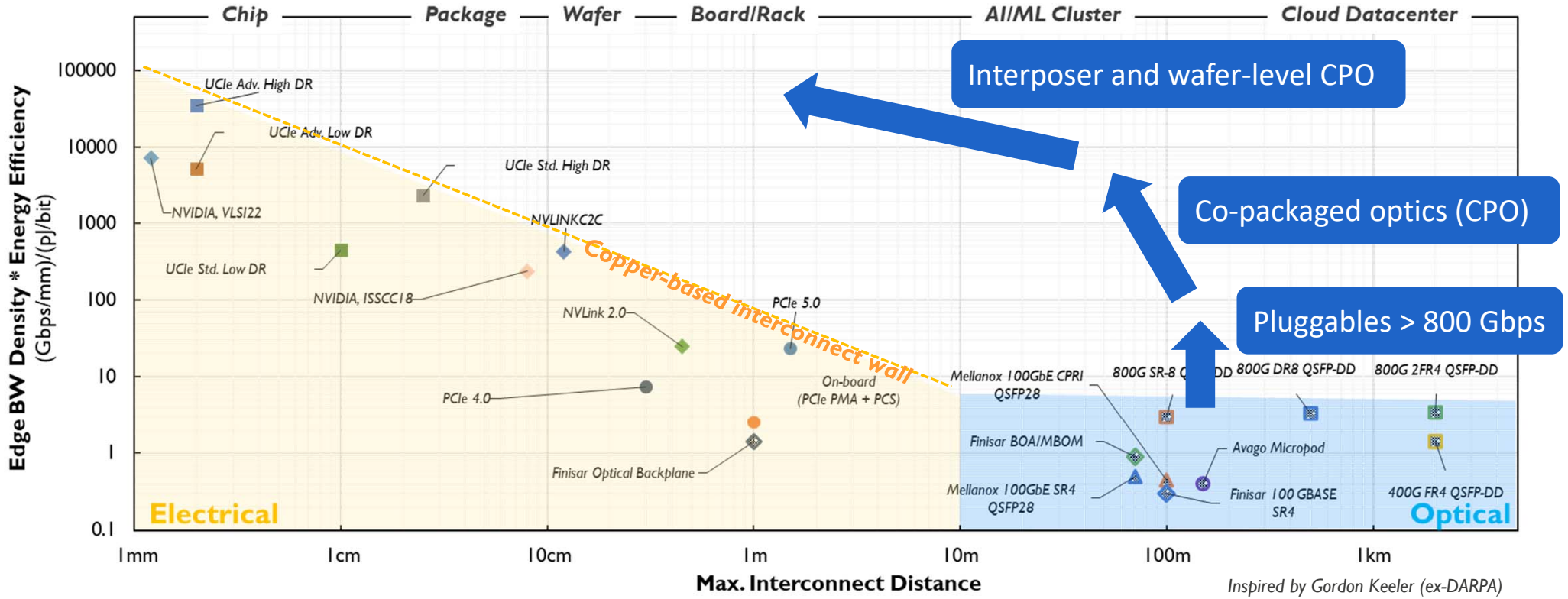
THE INTERCONNECT ROADMAP



Inspired by Gordon Keeler (ex-DARPA)

- bandwidth density
- power efficiency
- latency
- error free w/o FEC

- bandwidth per fiber/lane
- distance
- cost

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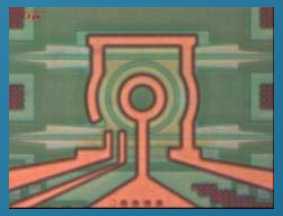
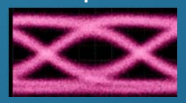
R&D Technology Developments – Some Examples

- integrated laser sources
- modulators with higher bandwidth / lower power
- optically interconnected system-on-wafer

iSiPP: IMEC'S SILICON PHOTONICS TECHNOLOGY

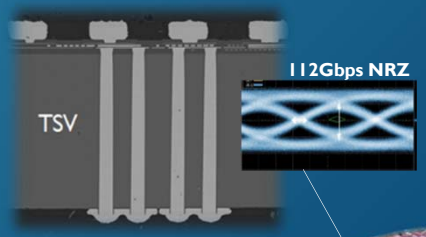
Silicon Ring Modulator



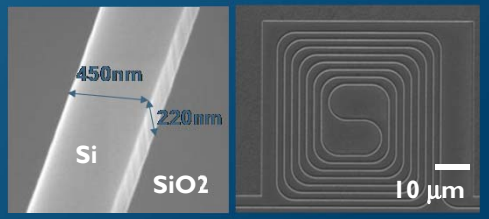


Y. Tong et al., PTL 2020

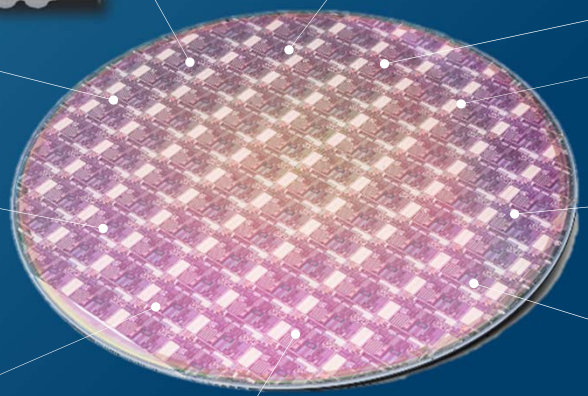
High-Speed TSV *(300mm only)*



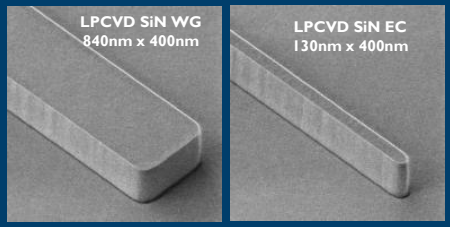
High-density Si Waveguides *(0.5-2dB/cm)*



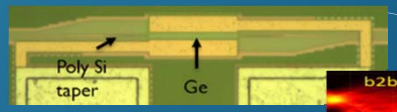
Ultra-Compact Si WDM filters *(193nm immersion)*
with high thermal tuning efficiency (→1mW / P_{π})

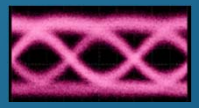


Integrated LPCVD SiN Waveguides

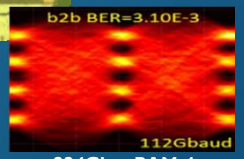


GeSi Electro-Absorption Modulator





56Gbps NRZ



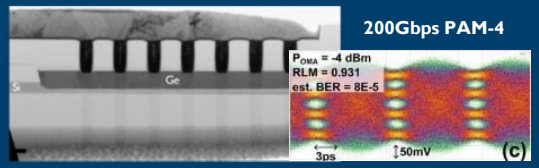
224Gbps PAM-4
D. Chan et al., JLT 2022

Silicon Mach-Zehnder Modulator

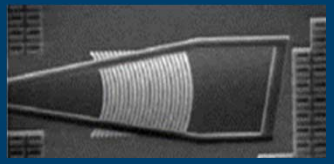
106Gbps PAM-4

56Gbps NRZ

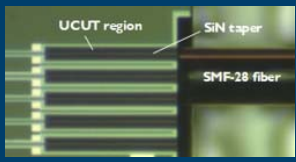
Ge Photodetector



SMF Grating Coupler *(<2dB)*

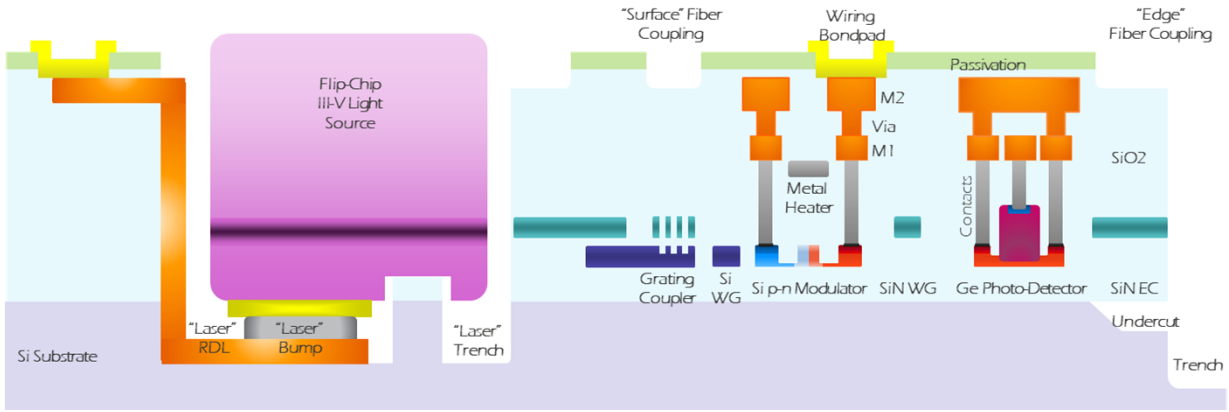


High-NA *(<2dB)* &
SMF Edge Couplers *(~2dB)*



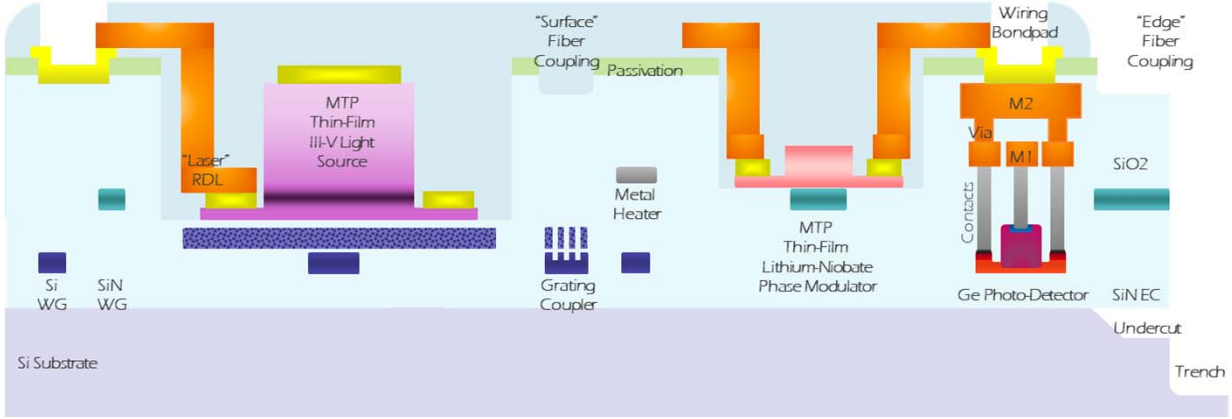
imec

LASER/SOA INTEGRATION



Flip-chipped III-V light source

Butt coupling to SiPh waveguide



Micro-transfer printed thin-film III-V light source

Evanescent coupling to SiPh waveguide

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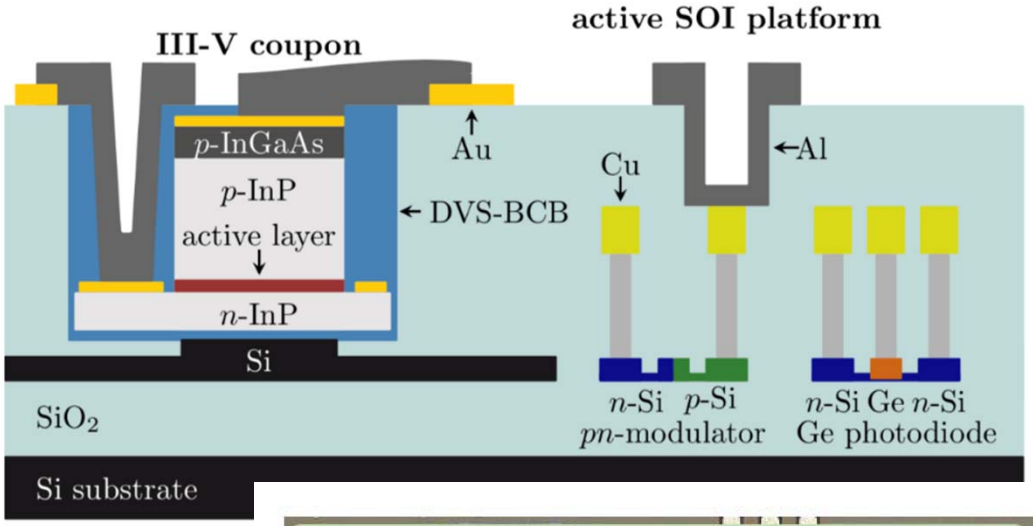
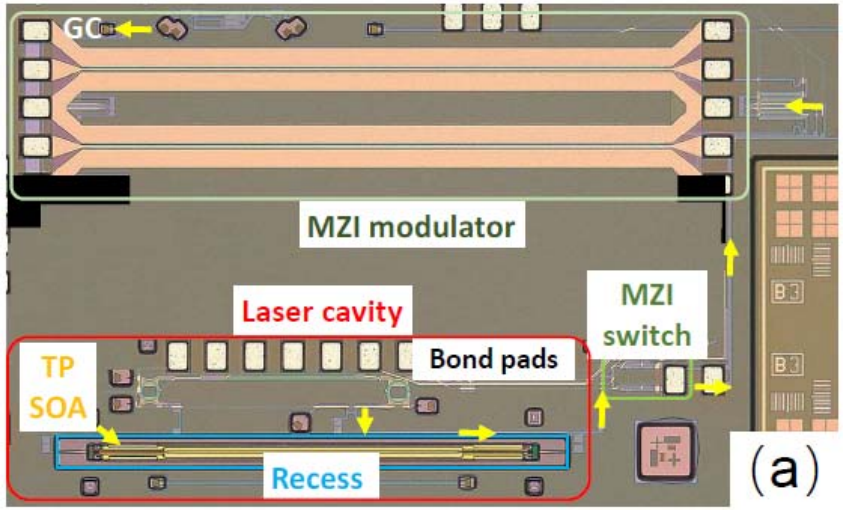
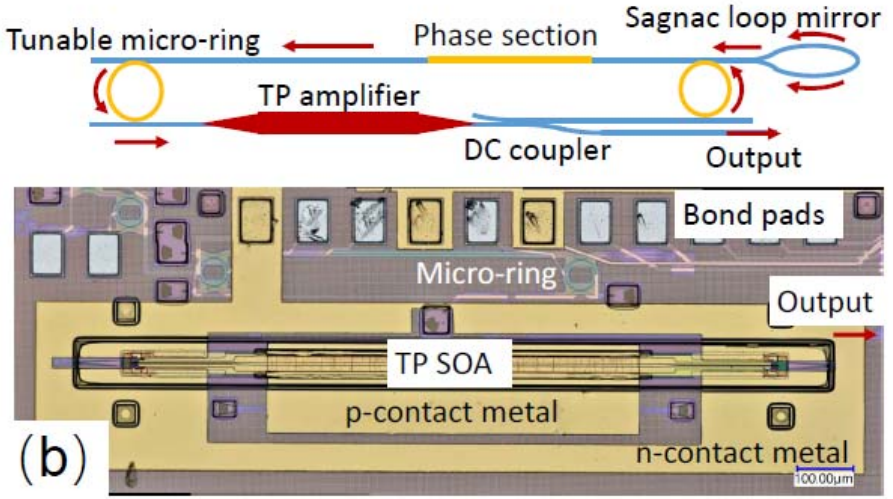
MICRO-TRANSFER-PRINTING (MTP) OF AN INP C-BAND SOA ON ISIPP



J. Zhang et al, OFC 2022,
doi:10.1364/OFC.2022.Tu2D.2





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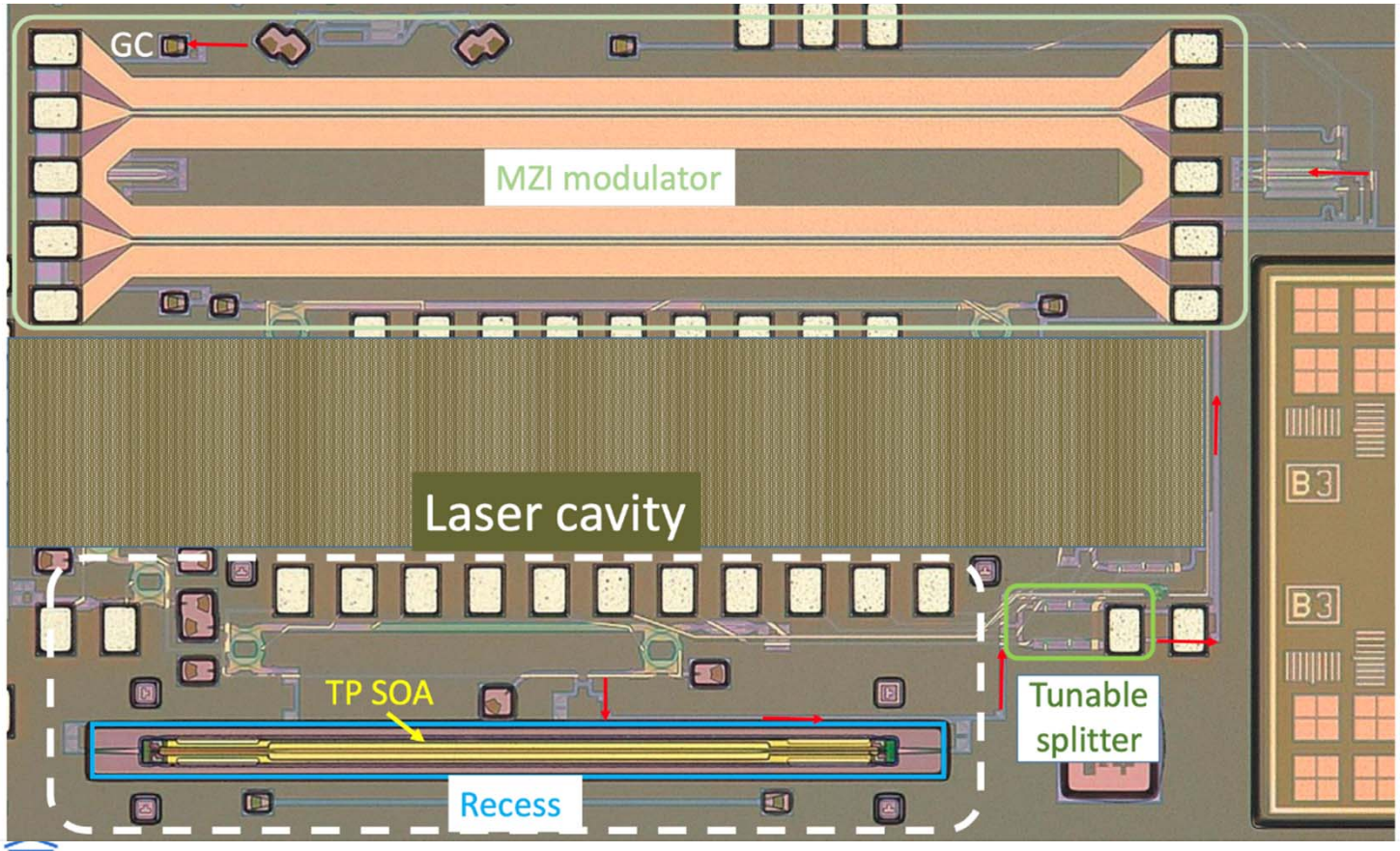
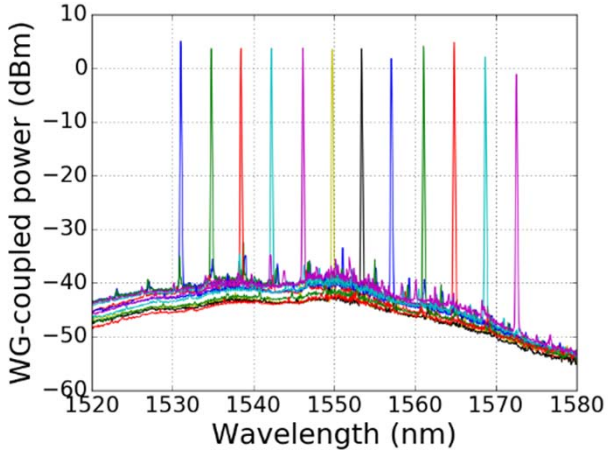
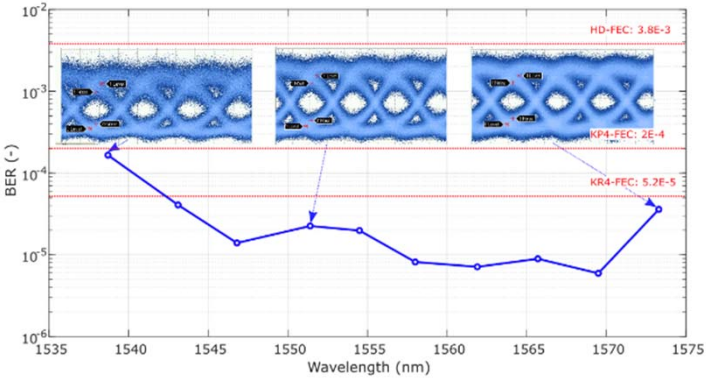
MICRO-TRANSFER-PRINTING (MTP) OF AN INP C-BAND SOA ON ISIPP

InP/Si hybrid laser cavity with Vernier wide tuning







J. Zhang et al, OFC 2022, doi:10.1364/OFC.2022.Tu2D.2

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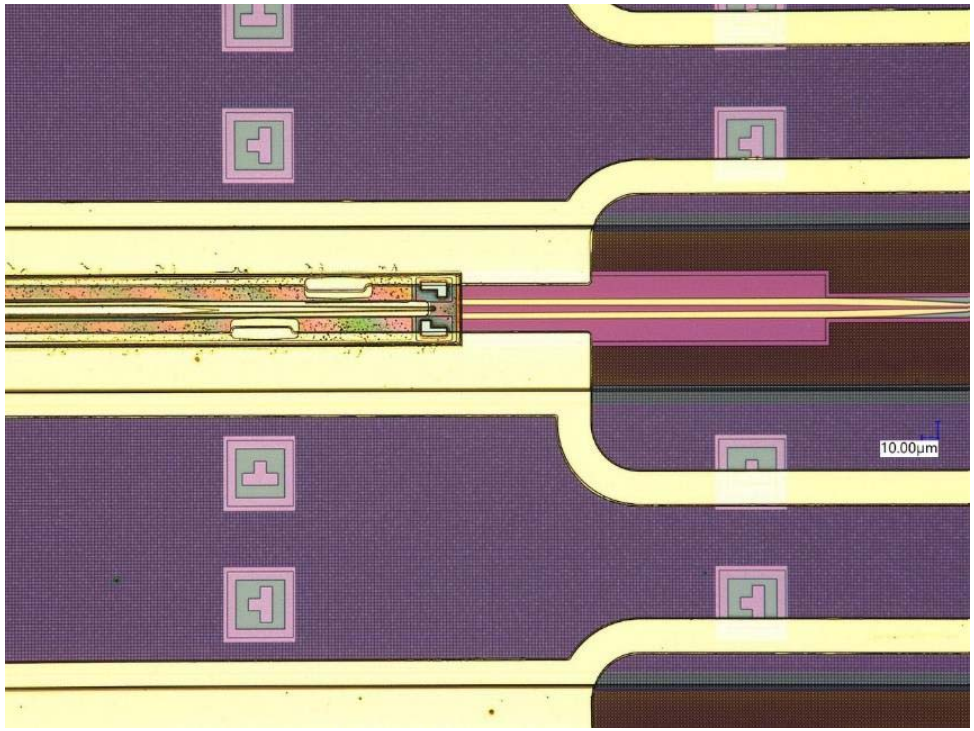
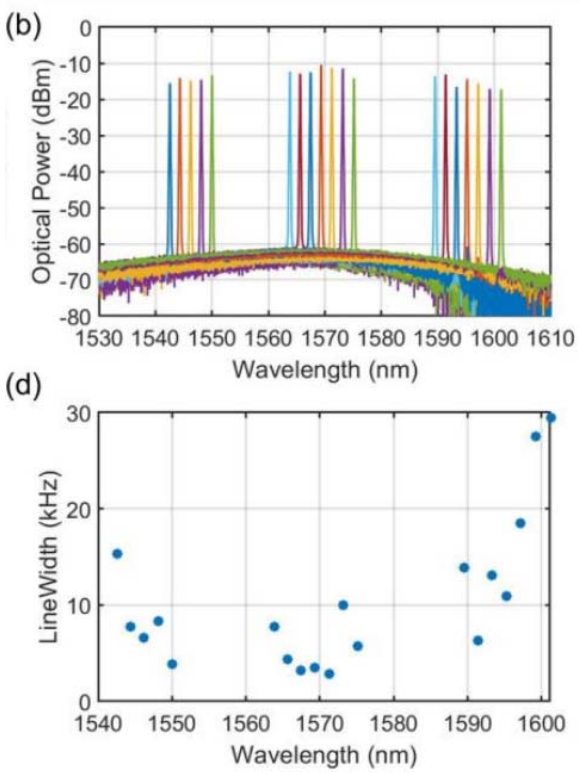
MTP-ED NARROW LINEWIDTH TUNABLE LASERS (INP ON SIN PIC)



- Si-on-SiN chip: imec
- InP SOA coupon: III-V Lab
- Micro-transfer printing: imec-UGent



B. Pan et al. OFC 2023, [doi:10.1364/OFC.2023.Th3B.5](doi:10.1364/OFC.2023.Th3B.5)

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MTP-ED O-BAND INAS/GAAS QDOT DFB LASERS

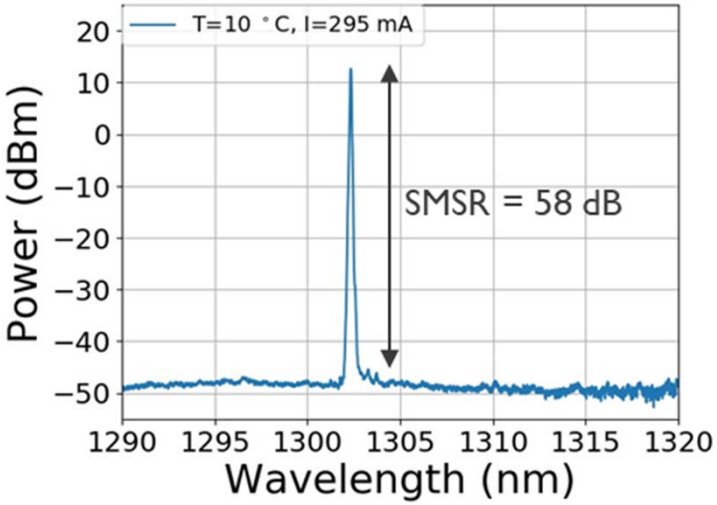
GaAs QD SOA coupon length: 2.16 mm

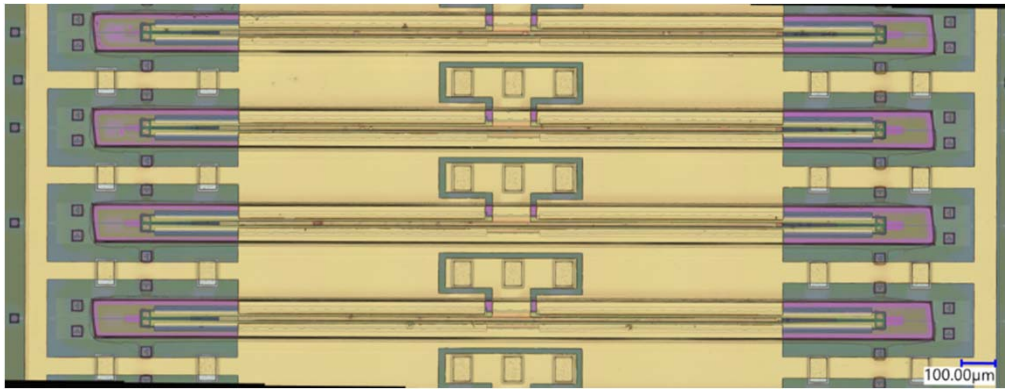
2nd order Bragg grating

DFB grating length: 1.4 mm

Maximum waveguide-coupled power: 20 mW@10℃

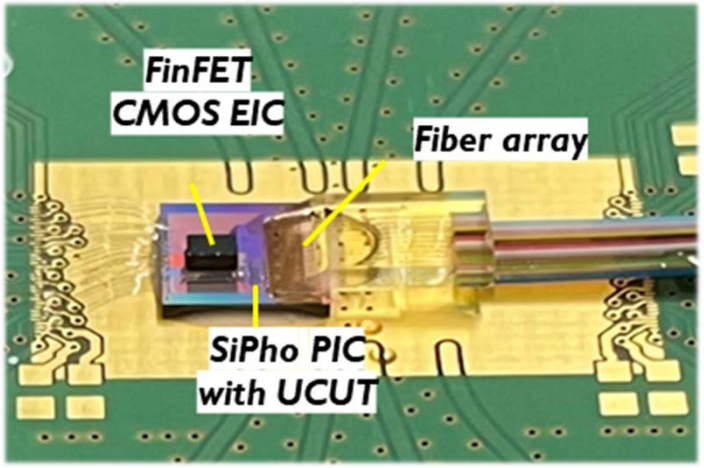
Side-mode-suppression-ratio: 60 dB

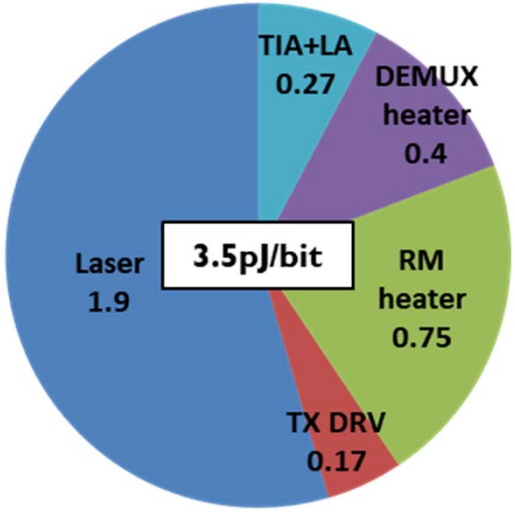


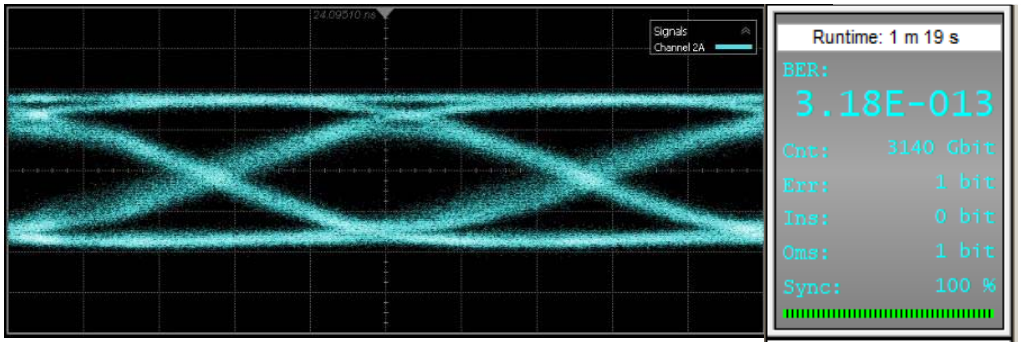


J. Zhang et al, ECIO 2023

SOI Ring Resonator Modulator for O-Band WDM Transceiver







Y. Ban et al., OFC 2023
https://opg.optica.org/viewmedia.cfm?r=1&uri=OFC-2023-W3D.5&seq=0

Error-Free with ~ 3.5pJ/bit Optical Energy

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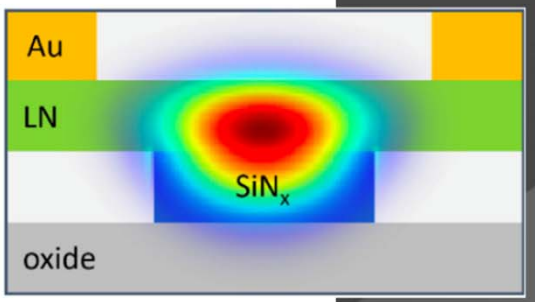
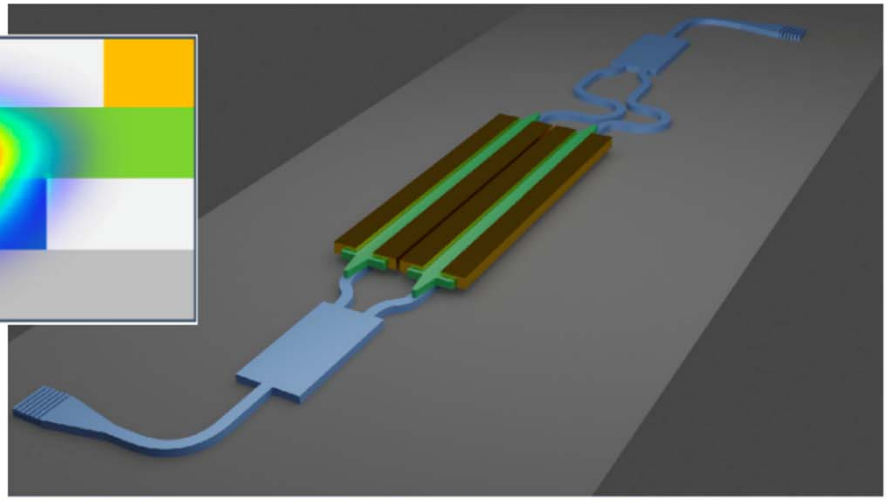
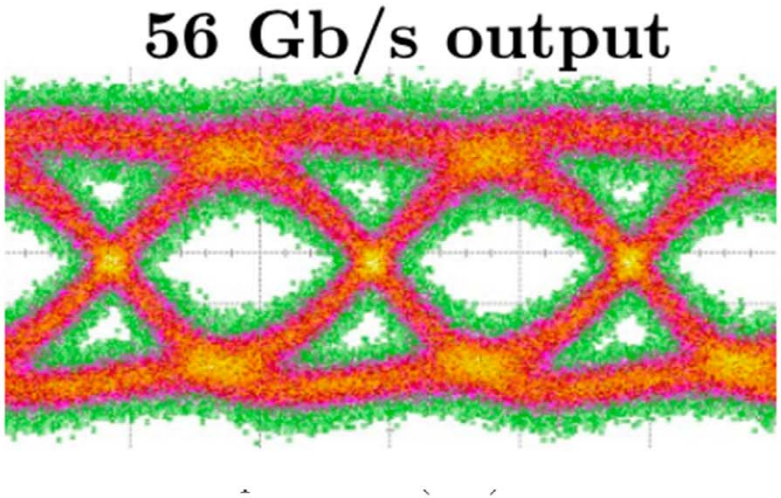
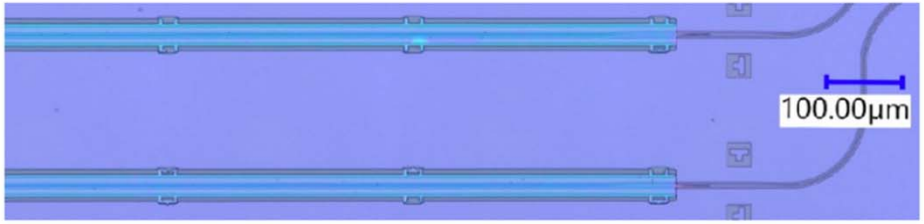
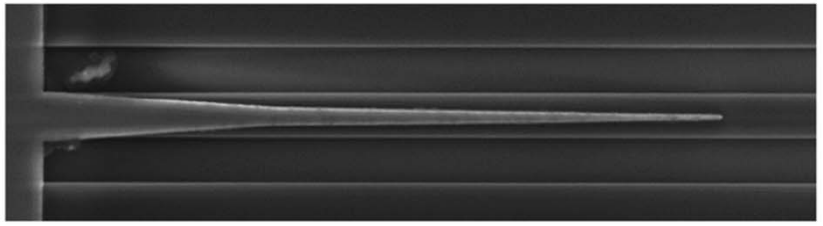
$LiNbO_3$ on SiN Modulator by Micro-transfer Printing











T. Van Ackere et al., CLEO 2023

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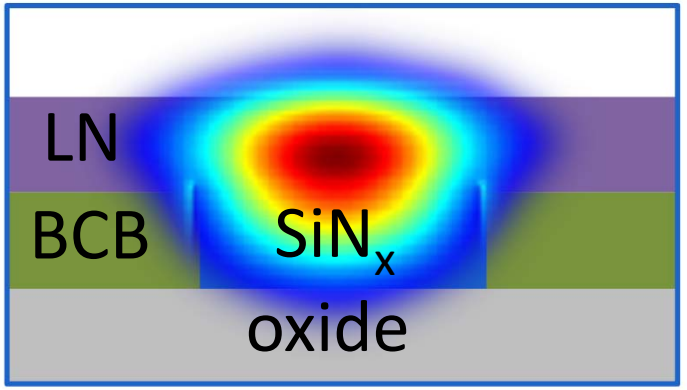
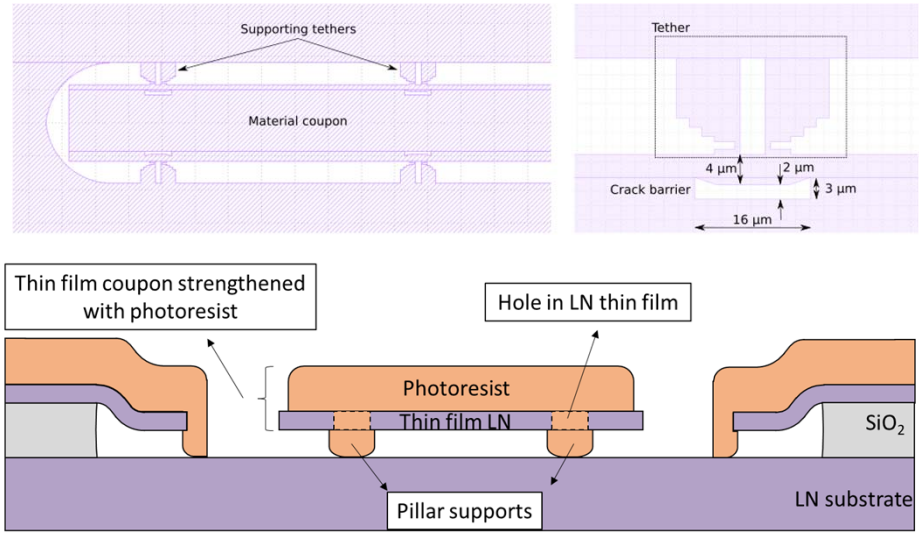
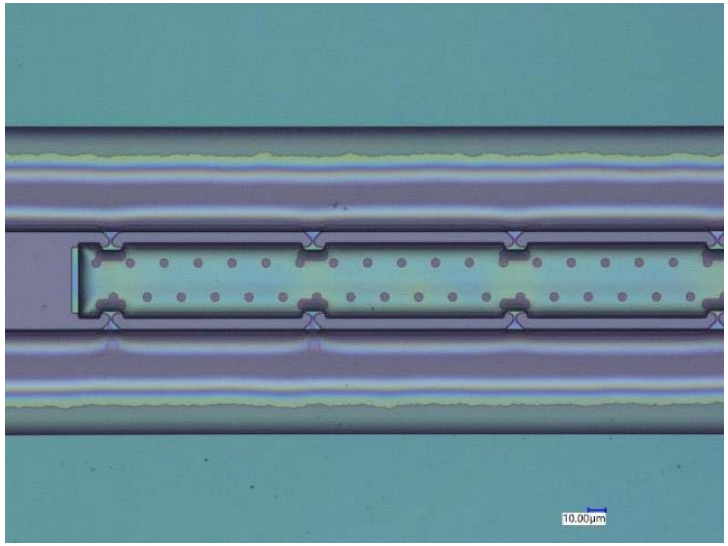
$LiNbO_3$ ON SiN MODULATOR BY MICRO-TRANSFER PRINTING (MTP)

- Transfer printing of $LiNbO_3$ thin films on Si/SiN
- Transfer from LNOI wafers
  - Introduction of crack barriers
  - Introduction of pillars avoiding collapse (because of liquid HF)





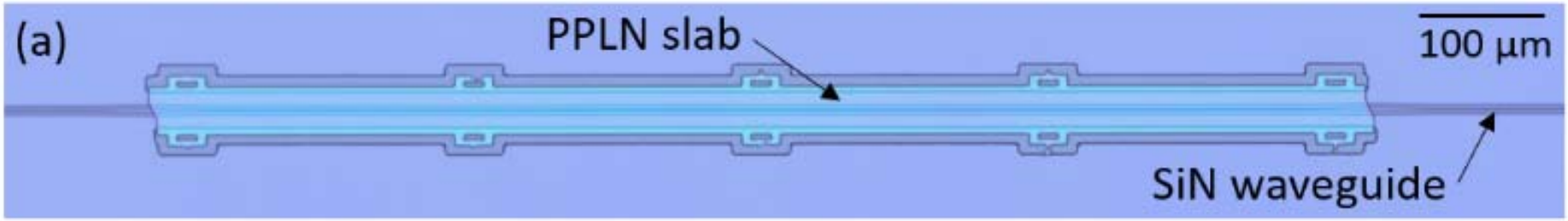


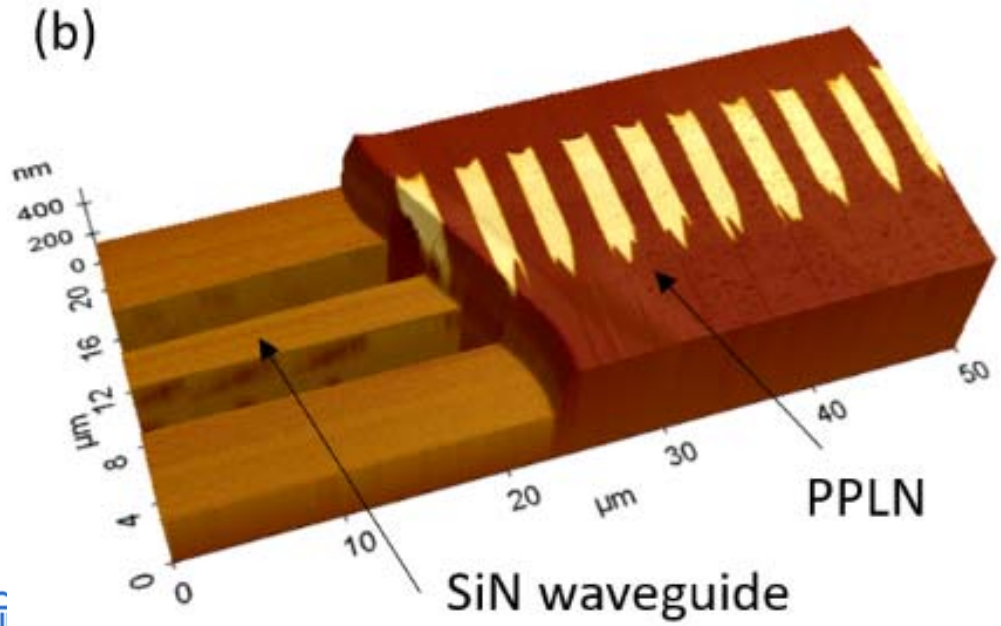
High-yield and reliable transfer printing of LN

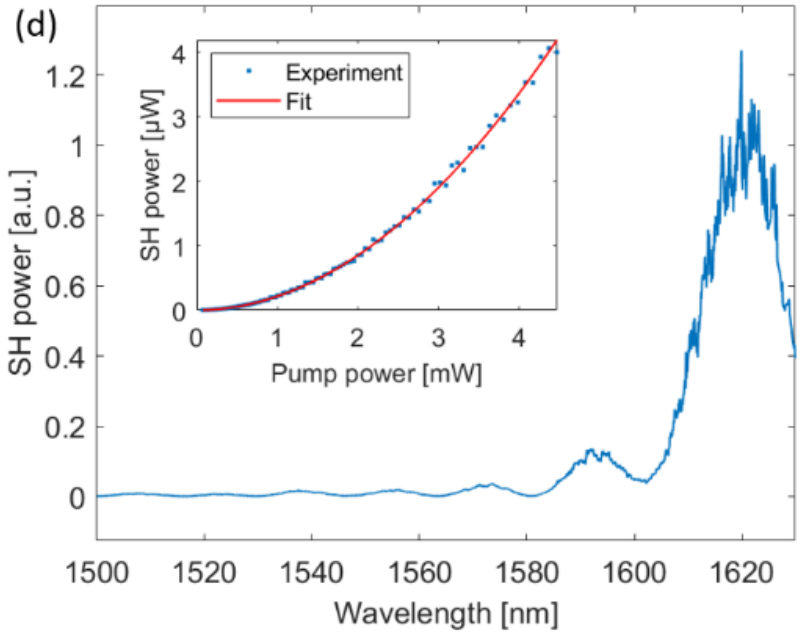
GHENT UNIVERSITY imec

T. Vandekerckhove, Opt. Mat. Expr. 2023 https://doi.org/10.1364/OME.494038

SECOND HARMONIC GENERATION IN PERIODICALLY POLED $LiNbO_3$ ON SiN







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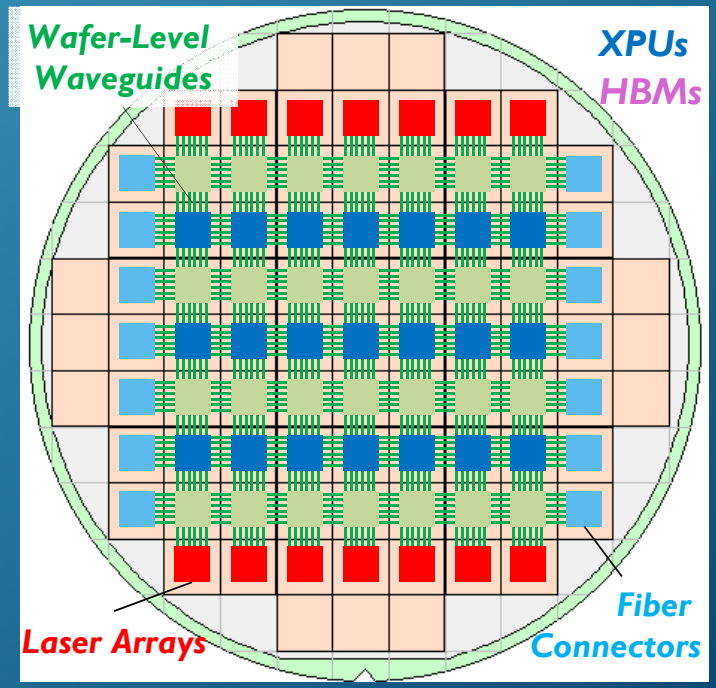
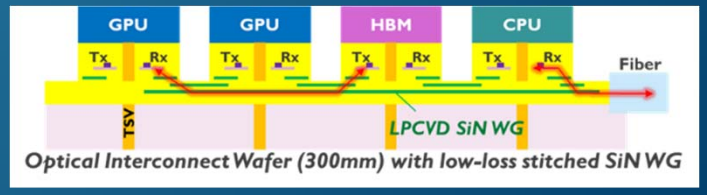
T. Vandekerckhove, CLEO 2024

VISION: TOWARDS OPTICALLY INTERCONNECTED SYSTEMS-ON-WAFER

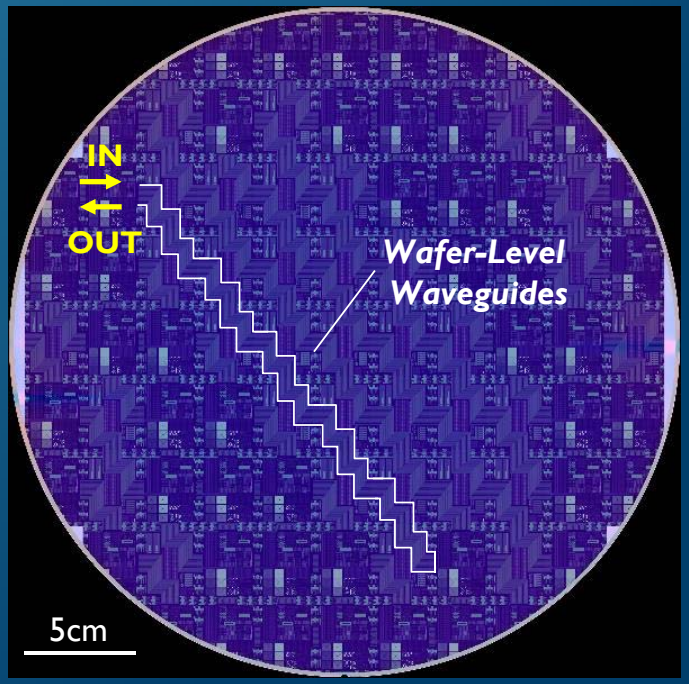
Optically Interconnected System-on-Wafer



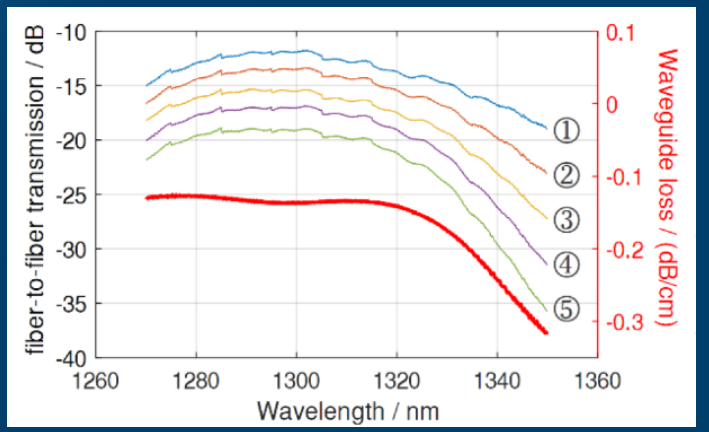


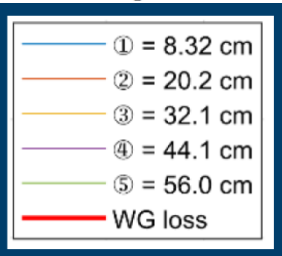
Optical Interconnect Wafer (300mm) with low-loss stitched SiN WG

First 300mm wafer-level reticle-stitched interconnect waveguides (imec)



Measured Wafer-level Loop-back SiN Waveguides





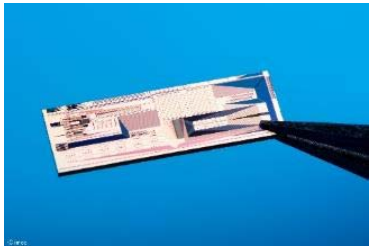
300-mm wafer-level waveguides up to **56cm long,** with **low all-in propagation loss (0.15dB/cm)**

Xu et al., OFC 2024, M4A.3

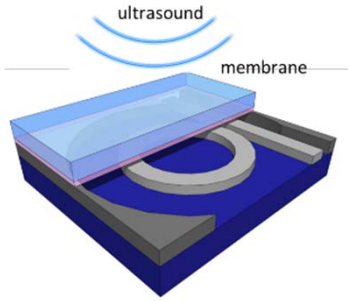
imec

Many More Research Cases in Sensing and Life Science @ IMEC

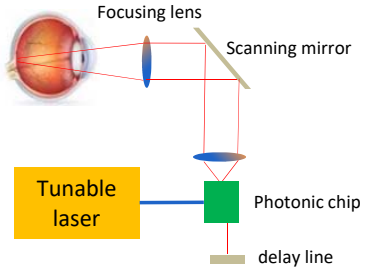
PICs for LIDAR



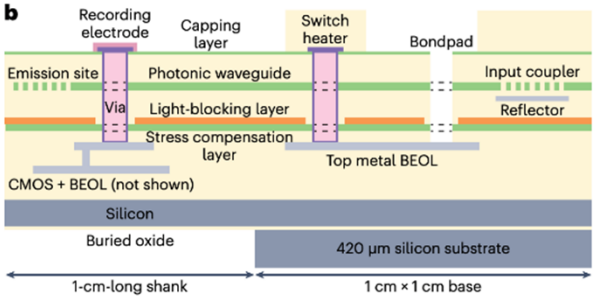
PICs for Ultrasound Transducers

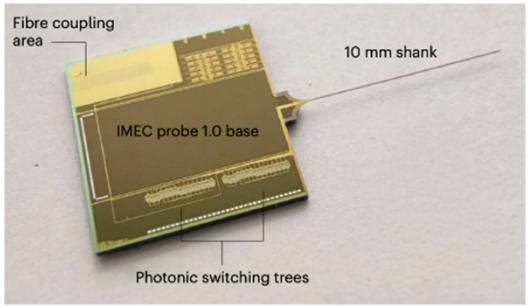


PICs for OCT

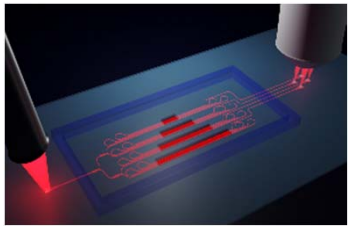


PICs for Optogenetics

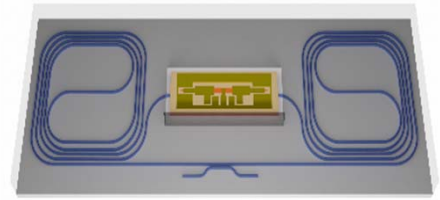




PICs for Biosensing



PICs for Comb Sources



PICs for Cardiovascular Monitoring

… and many more

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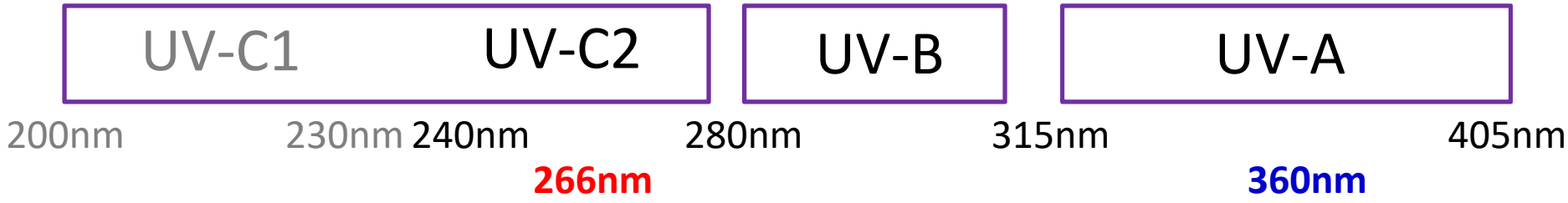
THE NEED FOR UV-PICS

All bio-molecules/bio-organisms provide fluorescence under UV illumination



Viral inactivation
Bacterial disinfection
Water disinfection
Free space communications
Material processing

Resonant Raman sensing
Fluorescence sensing

Label free imaging
SIM-PIC
QPI-PIC
Quantum Computing
Optical clocks

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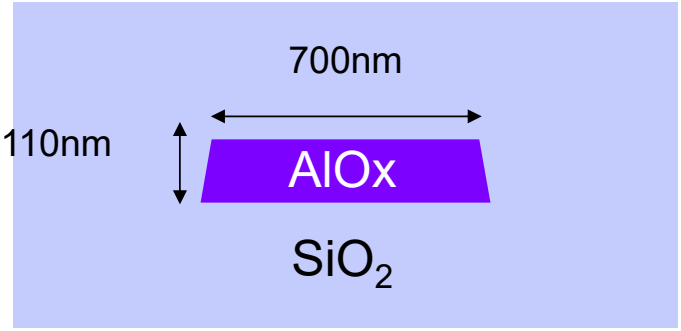
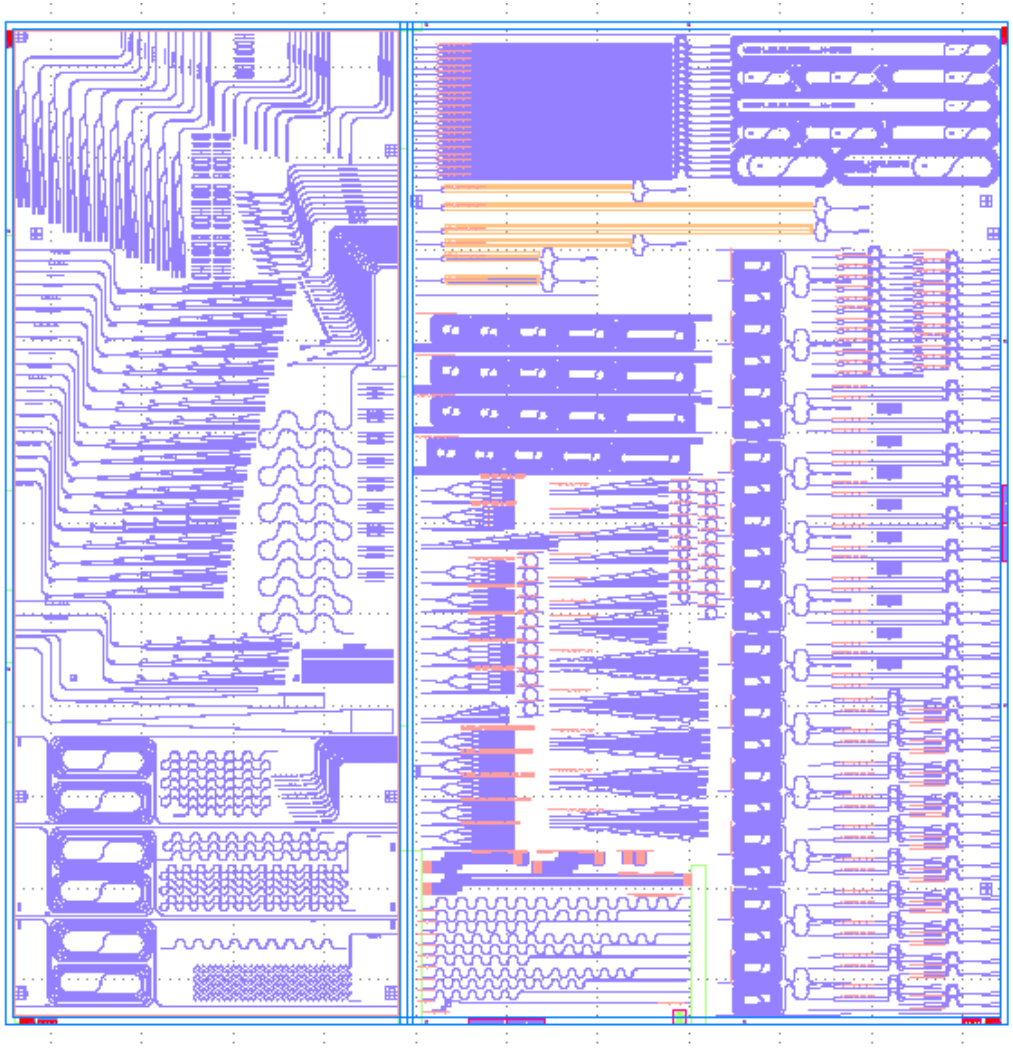
TOWARDS A UV-A PLATFORM AT IMEC

AlOx by ALD in a CMOS fab



<1dB/cm at λ_P=360nm



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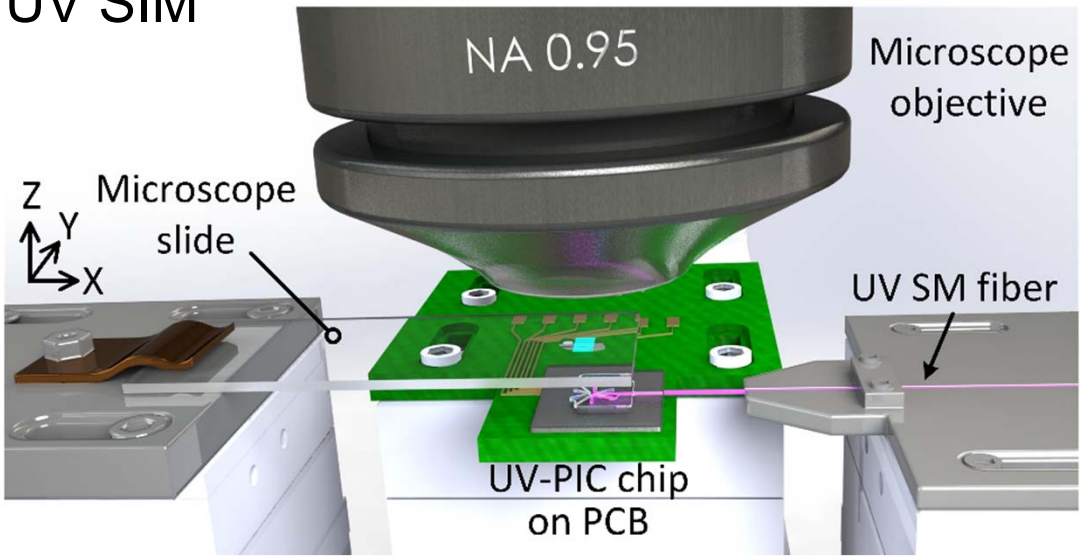
UV-A PICs (360nm) for Structured Illumination Microscopy (SIM)

UV SIM



nature communications

Article

https://doi.org/10.1038/s41467-022-31989-8

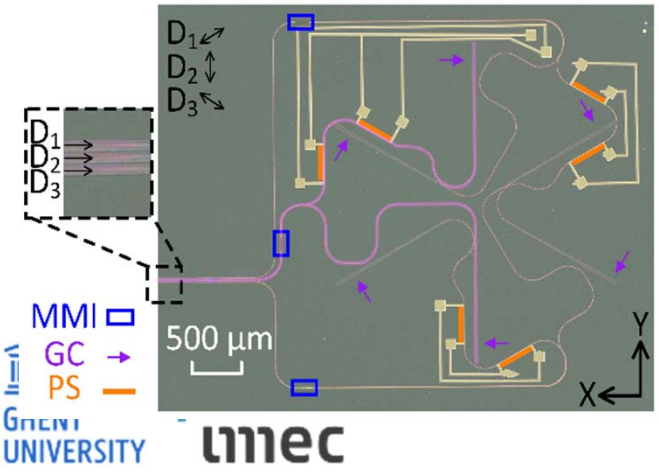
UV photonic integrated circuits for far-field structured illumination autofluorescence microscopy

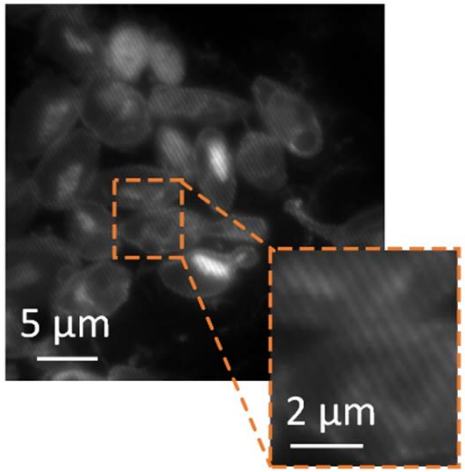
Received: 7 February 2022

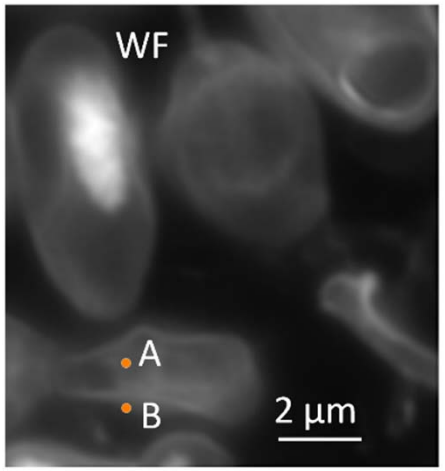
Accepted: 13 July 2022

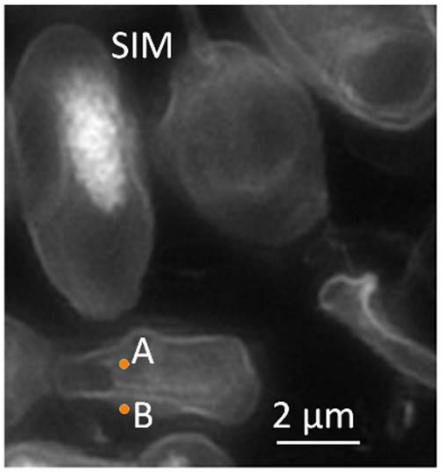
Published online: 27 July 2022

Chupao Lin[1,2], Juan Santo Domingo Peñaranda[3], Jolien Dendooven[3], Christophe Detavernier[3], David Schaubroeck[4], Nico Boon[5], Roel Baets[1,2] & Nicolas Le Thomas[1,2]









UVC LOW LOSS IN SiO_2 SPIRAL WGS

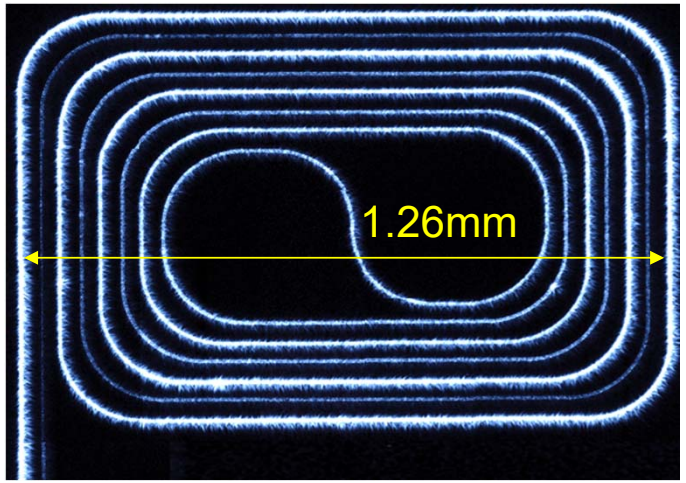
E_g=8.9eV ➔ λ_{abs}~140nm

Loss at λ_P=266nm with air cladding:

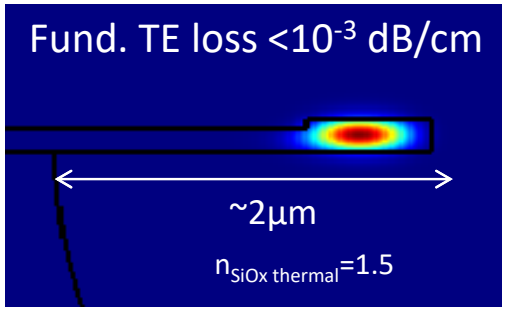
- 2 dB/cm for MM WG
- 5 dB/cm for SM WG

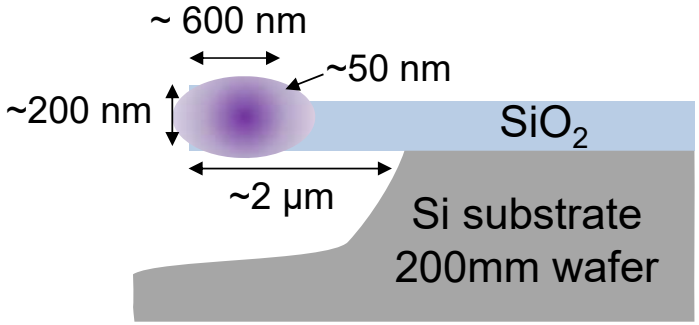
Water cladding: 4 dB/cm at λ_P=266nm

λ_P=266nm



In ⇅ Out





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C. Su *et al.* Optics Letters 2024

IMEC @ ECOC2024

W1F.1 - Joint **Optical Wireless** Communication and **LiDAR** Sensing using A Highly Integrated Optical Phased Array - **Xuebing Zhang**

W1F.3 - Experimental Evaluation of Passive 2D Optical Beam Scanners for FMCW LiDAR Applications - **Mennatallah Kandil**

W1G.5 - High-performance Silicon Optical Phase Shifter Targeting Large-scale **Programmable Photonic Circuits** - **Huaqing Qiu**

W4G.4 - All-Silicon Hybrid-integrated **128-GBd** Analog Demultiplexing **Optical Receiver** - **Jakob Declercq**

Th2G.3 - A 40 Gb/s NRZ **O-band Silicon Disk Modulator** with **5.4 THz FSR** and 60 GHz/mW Heater Efficiency - **Minkyu Kim**

+ imec-co-authored papers

Be welcome at booth A101

40 YEARS imec

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Outline

Trends in silicon photonics research

illustrated by imec's research portfolio

Transitioning from research to industrial supply chain

the challenges

Addressing the challenges

towards silicon photonics 4.0

The Diversity of New Solutions (beyond SOI and SiN PICs)

New platforms on silicon wafers

- Thin Film Lithium Niobate (TFLN) PICs
- Al_2O_3 PICs
- AlN PICs
- Diamond PICs
- Germanium-on-Silicon PICs

Adding new materials to existing platforms (SOI, SiN)

- SiN on SOI
- III-V on SOI/SiN (InP, GaAs,…)
- Electro-optic or piezo-electric materials on SOI/SiN ($LiNbO_3$, BTO, PZT, polymers, AlN…)
- 2D-materials (graphene, WSe_2, WS_2, MoS_2…) on SOI/SiN
- Diamond on SOI/SiN
- Colloidal quantum dots on SOI/SiN
- Liquid crystals on SOI/SiN
- Magneto-optic materials on SOI/SiN

Diversity in Integration Technology for New Materials

Processes for monolithic integration

- epitaxy and hetero-epitaxy
- chemical vapour deposition
- atomic layer deposition
- physical vapour deposition
- spin coating (polymers)
- sol-gel process
- …

Processes for hybrid integration

- flip-chip solder bump processes
- chip-to-chip butt-coupling attach
- photonic wire bond
- fiber (array) attach
- co-packaged optics (assembly substrates, motherboards)
- photonic wire bond
- …

Processes for heterogeneous integration

- wafer-to-wafer and die-to-wafer bonding
- micro-transfer printing
- flip chip solder bump (wafer level)
- wafer reconstitution, fanout wafer-level packaging, etc.
- micro-optic bench attach
- …

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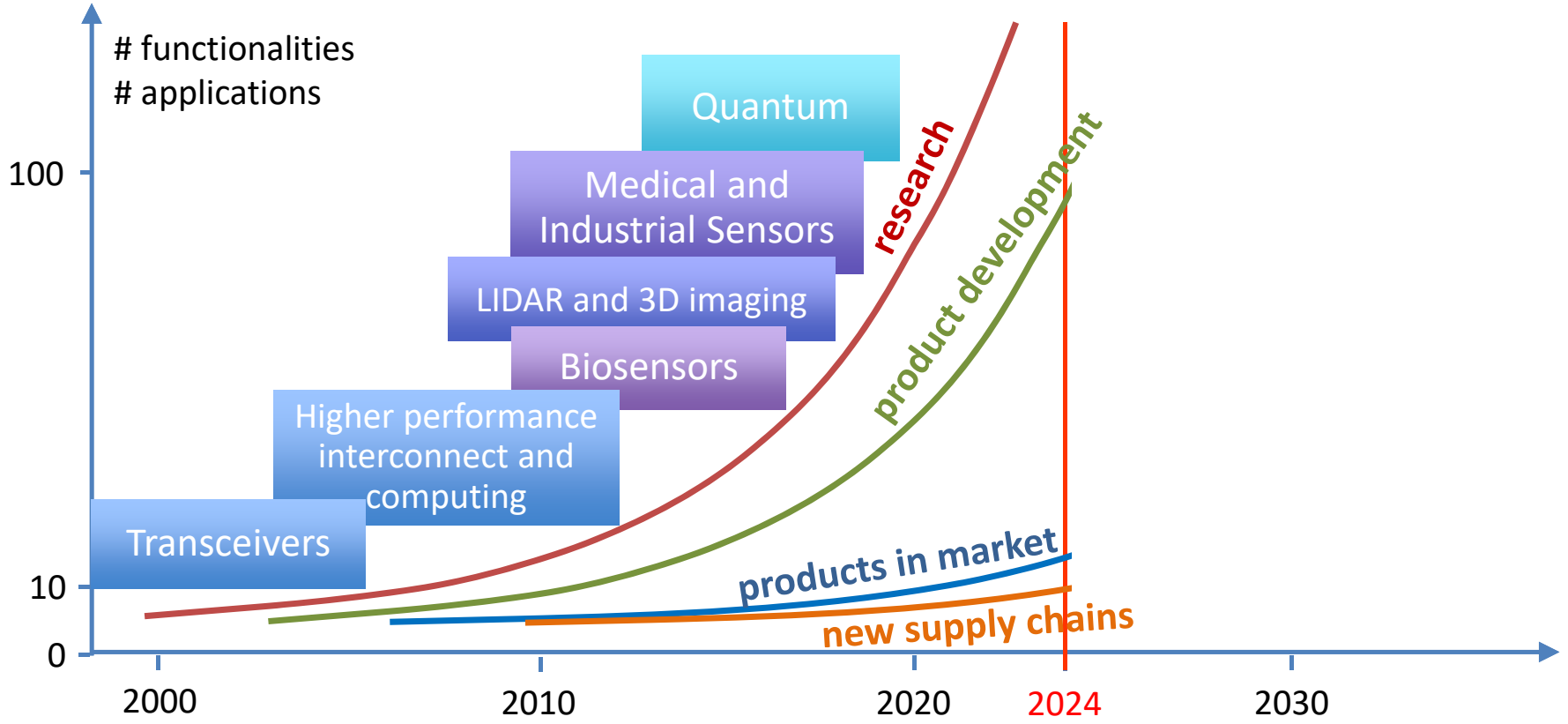
DIVERSITY OF FUNCTIONALITIES/APPLICATIONS ENABLED BY SIPH



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NON-TRANSCEIVER PIC-BASED **PRODUCTS** IN THE MARKET

Genalyte: biosensors for diagnostics

Quix quantum processor: research tool

Sentea, PhotonFirst: Fiber Bragg Grating Interrogators

Anello: gyroscope evaluation kit

iPronics: programmable photonic processor

ThorLabs: E-O converter

SENTEA'S PIC-BASED FIBER BRAGG GRATING INTERROGATOR

Multi-parameter & multi-point for more data

Strain Temperature Vibration

MULTIPOINT FBG SENSING FIBER

Dashboard

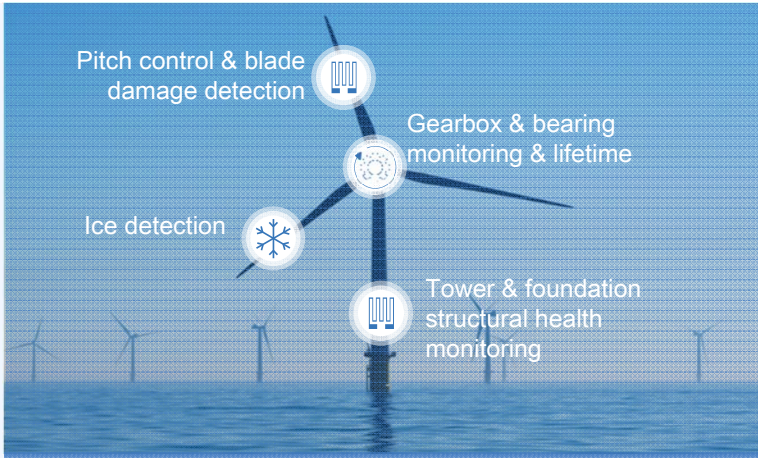
Control system

SENTEA INTERROGATOR

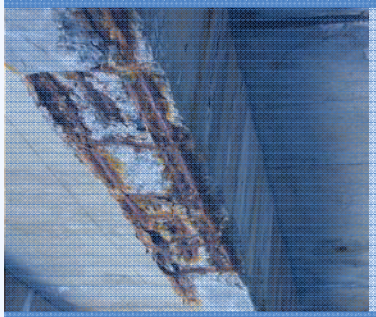
Extreme temperatures | Electromagnetic interference | Lighting strikes | Corrosive environment | Safe in explosive environments

Outperforming other sensors in harsh environments

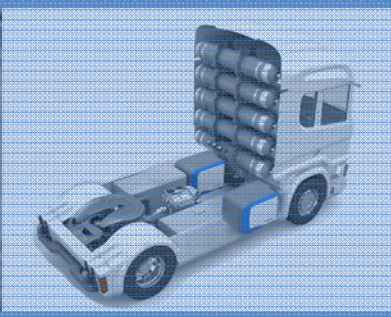
Cost-effective through **Silicon Photonics**



Wind turbine monitoring



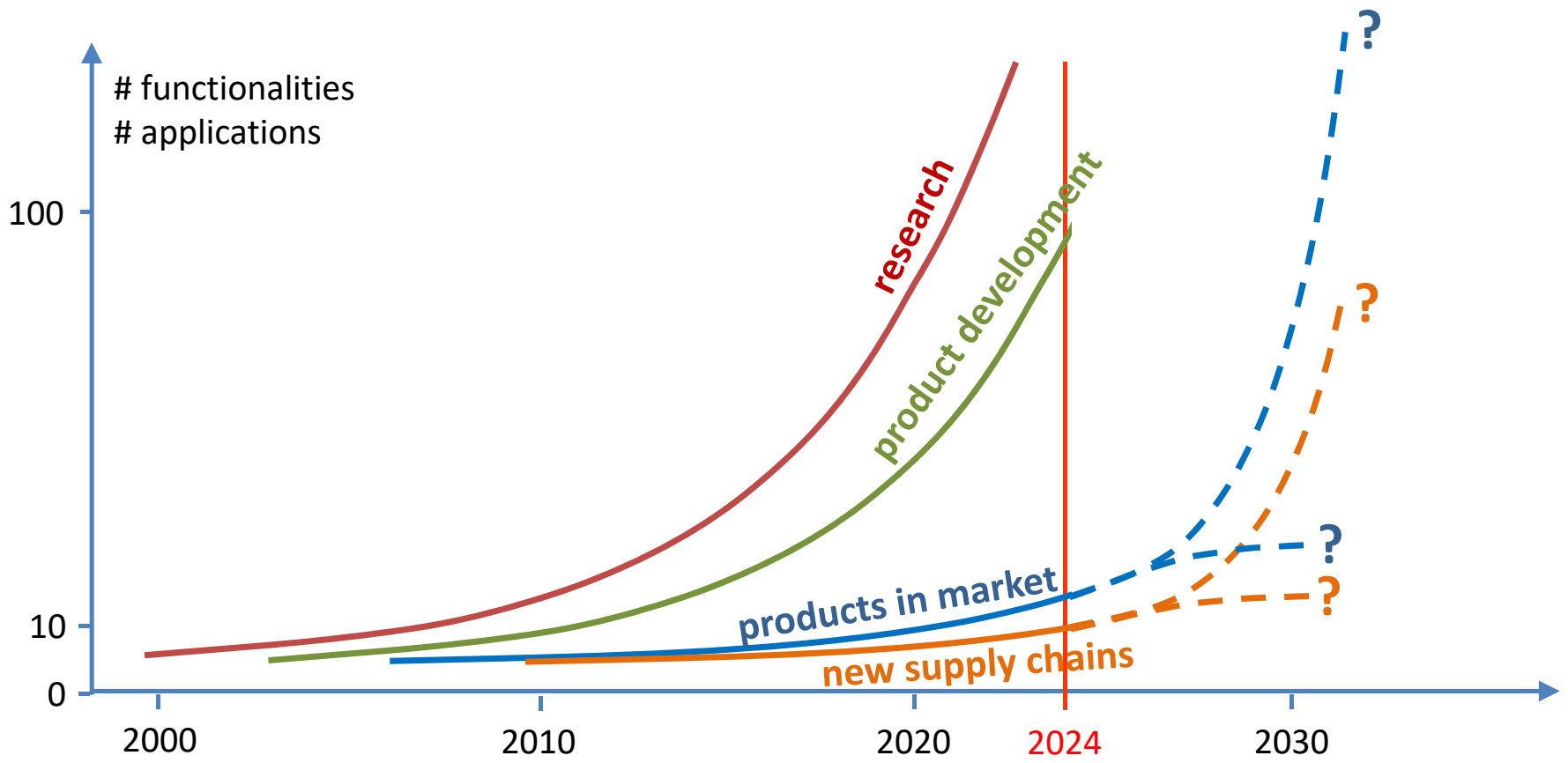
Structural integrity Monitoring



EV battery, hydrogen vessels and drivetrain

SENTEA

DIVERSITY OF FUNCTIONALITIES/APPLICATIONS ENABLED BY SIPH



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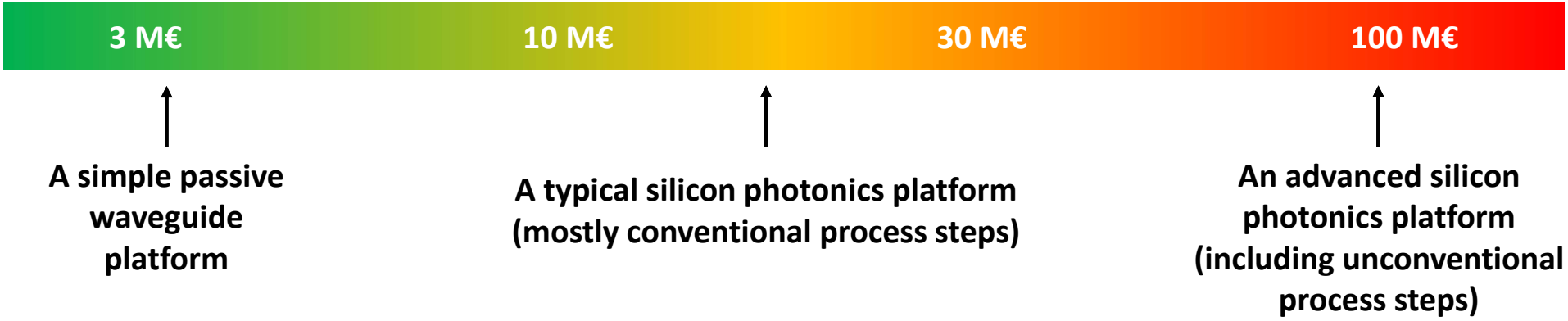
KEY BARRIER FOR AN SME DEVELOPING A SIPH-BASED PRODUCT

High NRE-cost + slow prototyping

- expensive prototyping of wafers made on an existing process flow
- first-time-right is still hard ⇒ multiple prototyping cycles
- long time-to-market ⇒ high personnel cost
- costly development of new process flow (if needed)



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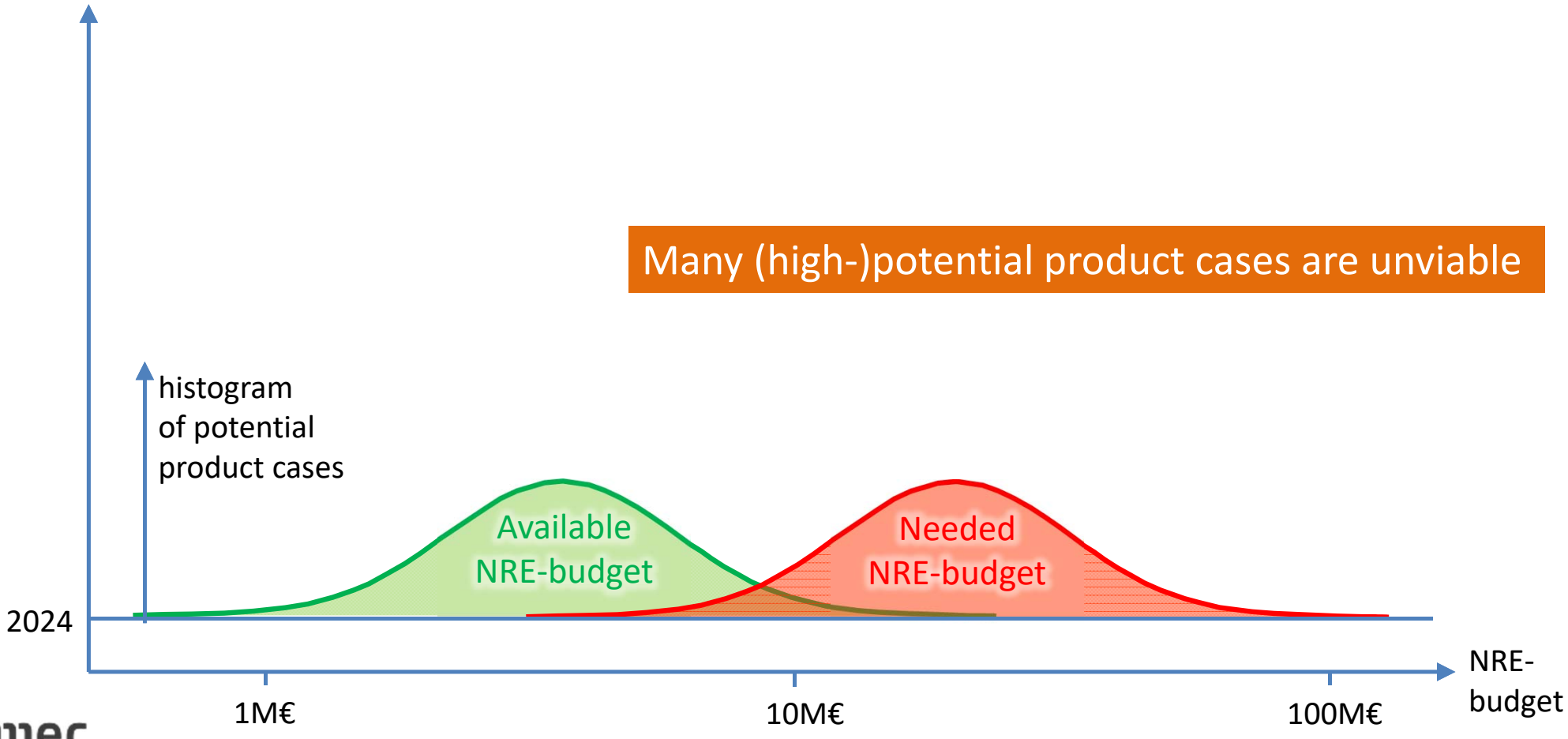
THE NRE-GAP



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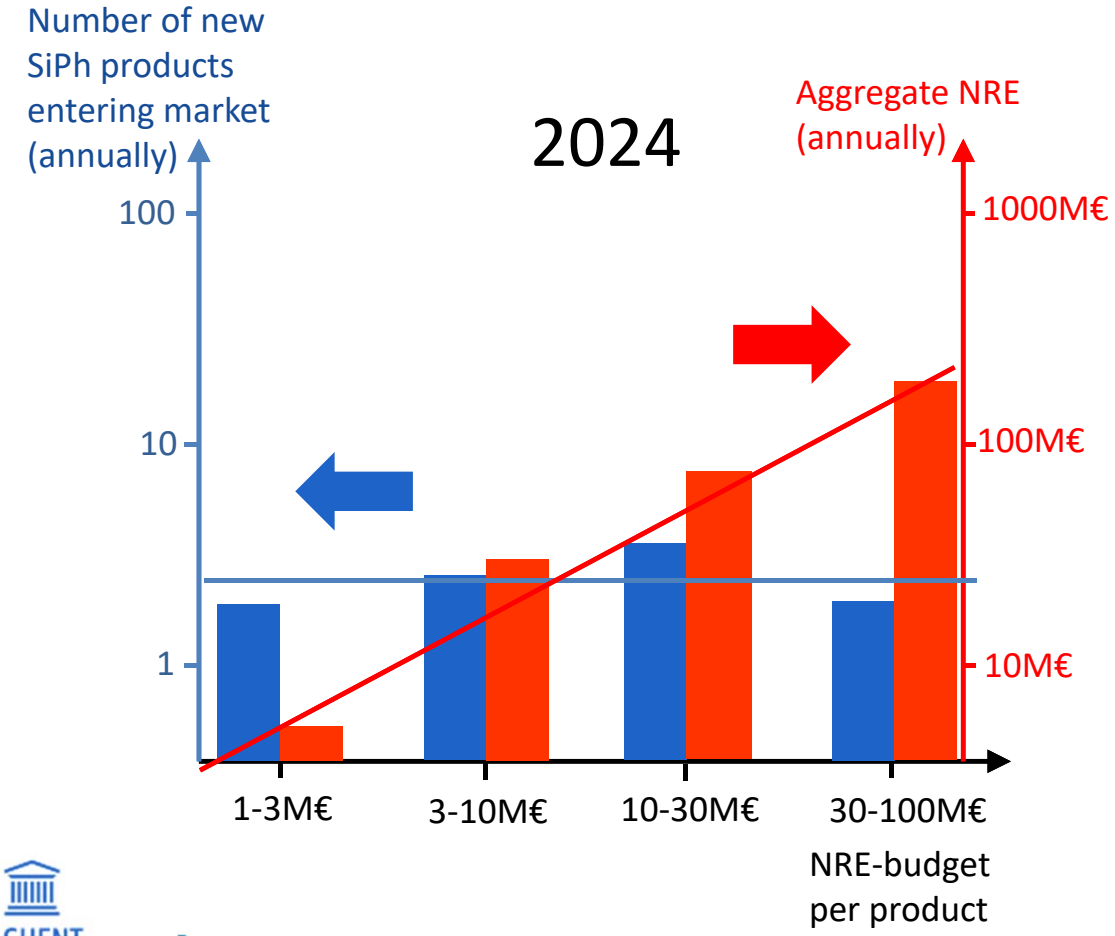
THE NRE-BIAS



Most process flow development focuses on high NRE-cases

Low NRE-cases are ‘left in the cold’

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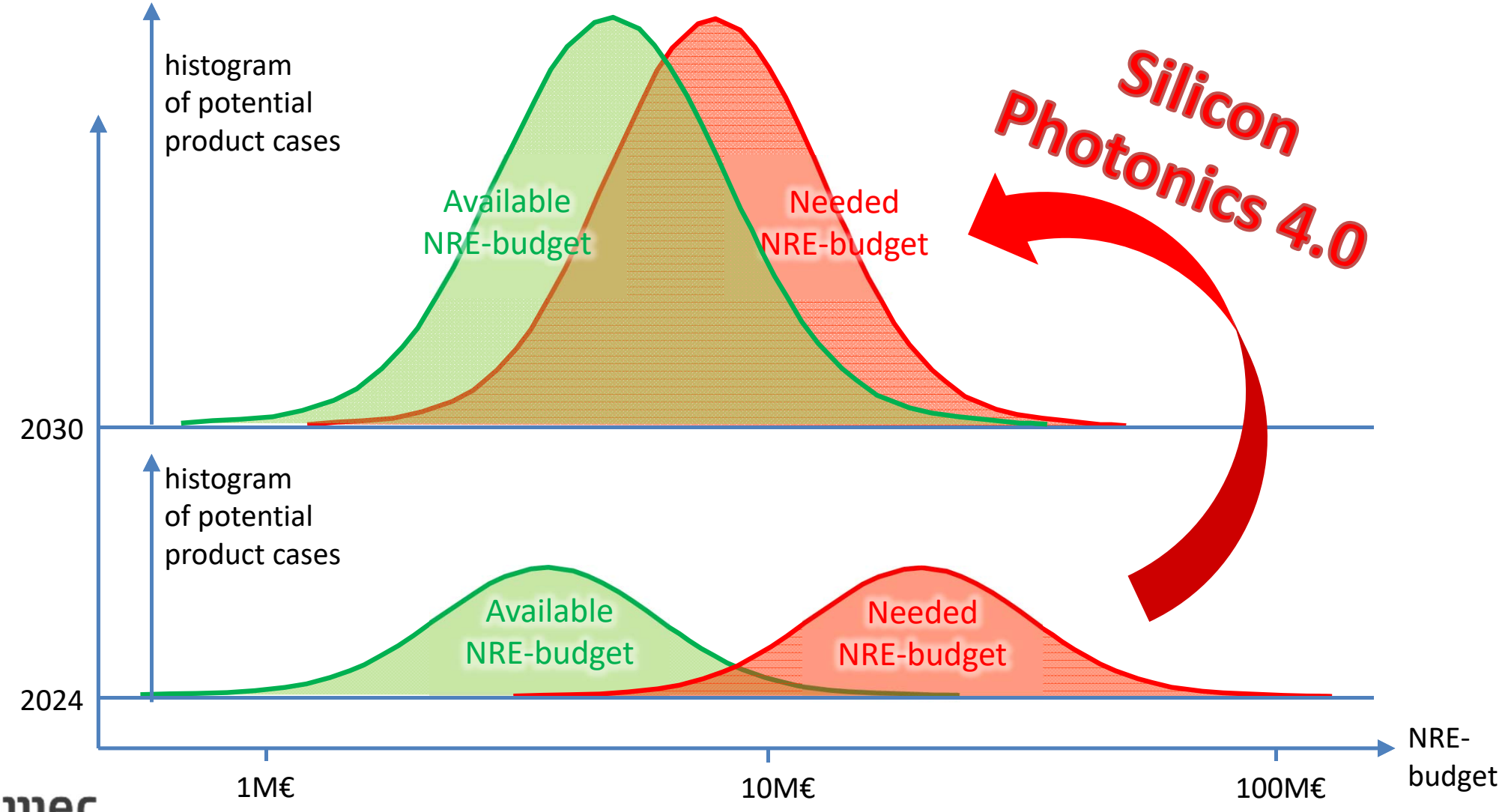
towards silicon photonics 4.0

(my personal vision)

THE NRE-GAP



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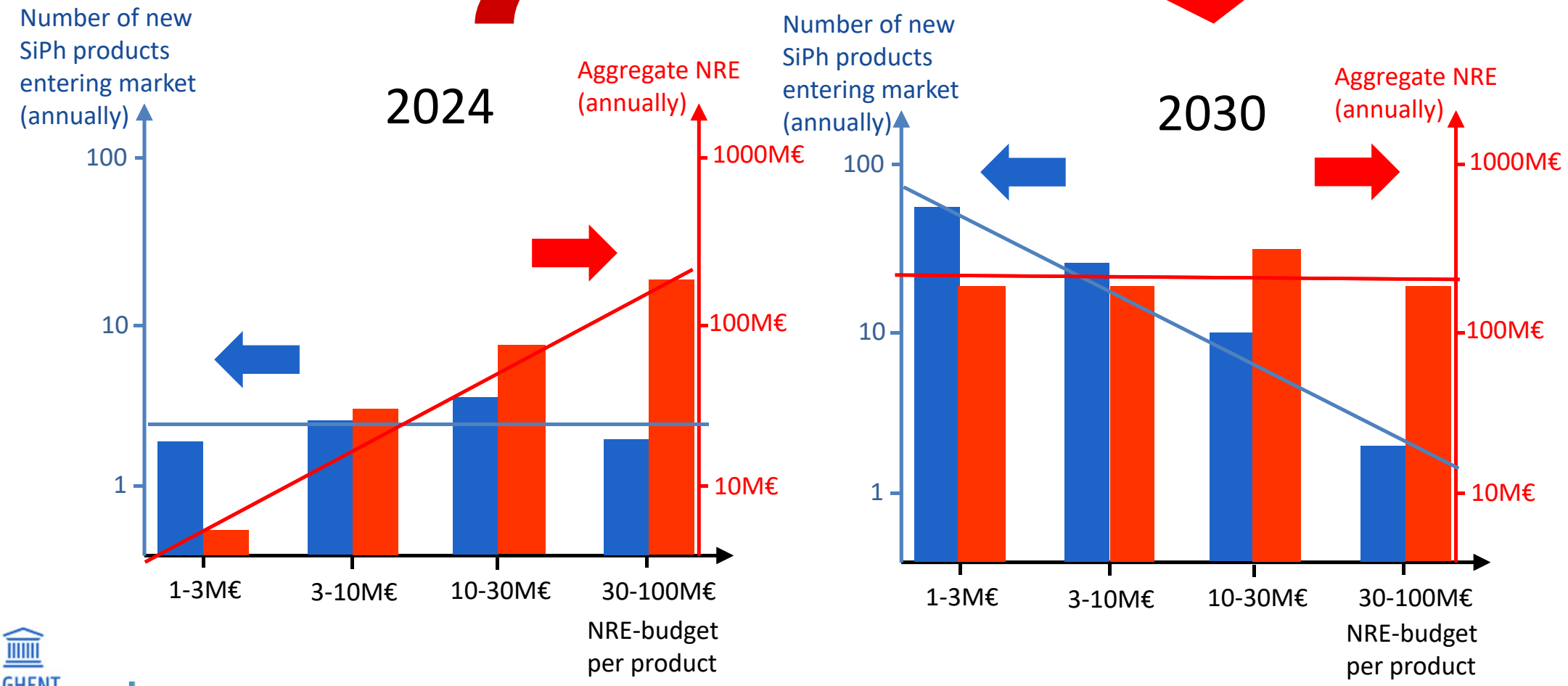
THE NRE-BIAS

Silicon Photonics 4.0



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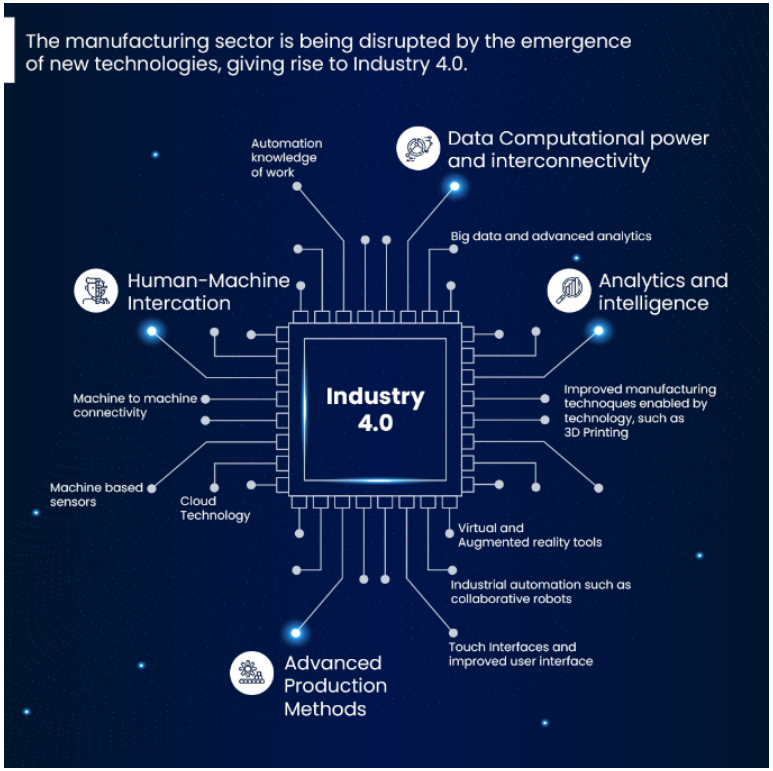
INDUSTRY 4.0

Smart manufacturing

- Innovation-based and science-based
- Flexibility and agility
- Decentralized model of operations
- Manufacturing as a Service
- Data-driven automation, sensing and IoT, machine learning and AI
- Additive manufacturing
- Optimisation for sustainability
- Upskilling and reskilling of personnel



Understanding Semiconductor Industry 4.0
https://www.acldigital.com/blogs/industry-40-future-advanced-semiconductor-manufacturing

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TOWARDS SILICON PHOTONICS 4.0

Break down supply chain barriers, especially for innovative start-ups and scale-ups, in spite of diversifying technologies, applications and markets

A mix-and-match smart manufacturing approach to design and build innovative PIC-products, with:

- a decentralized open access foundry and supply chain model
- additive chiplet-based backend manufacturing approaches
- technology service providers that offer robust technology modules
  - standardized modules that can be reused for multiple applications
  - data driven, thorough, open-access module-PDKs
  - elaborate specification of “interfaces” between modules
  - parametrized models, for designers to use
  - seamless interfacing to non-photonic modules (electronic, mechanical, chemical, fluidic…)
  - process control monitor circuits (PCMs) to assess compliance of individual modules with specs
- development of multi-stakeholder PDKs for complete process flows
- programmable PICs for rapid prototyping

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TOWARDS SILICON PHOTONICS 4.0

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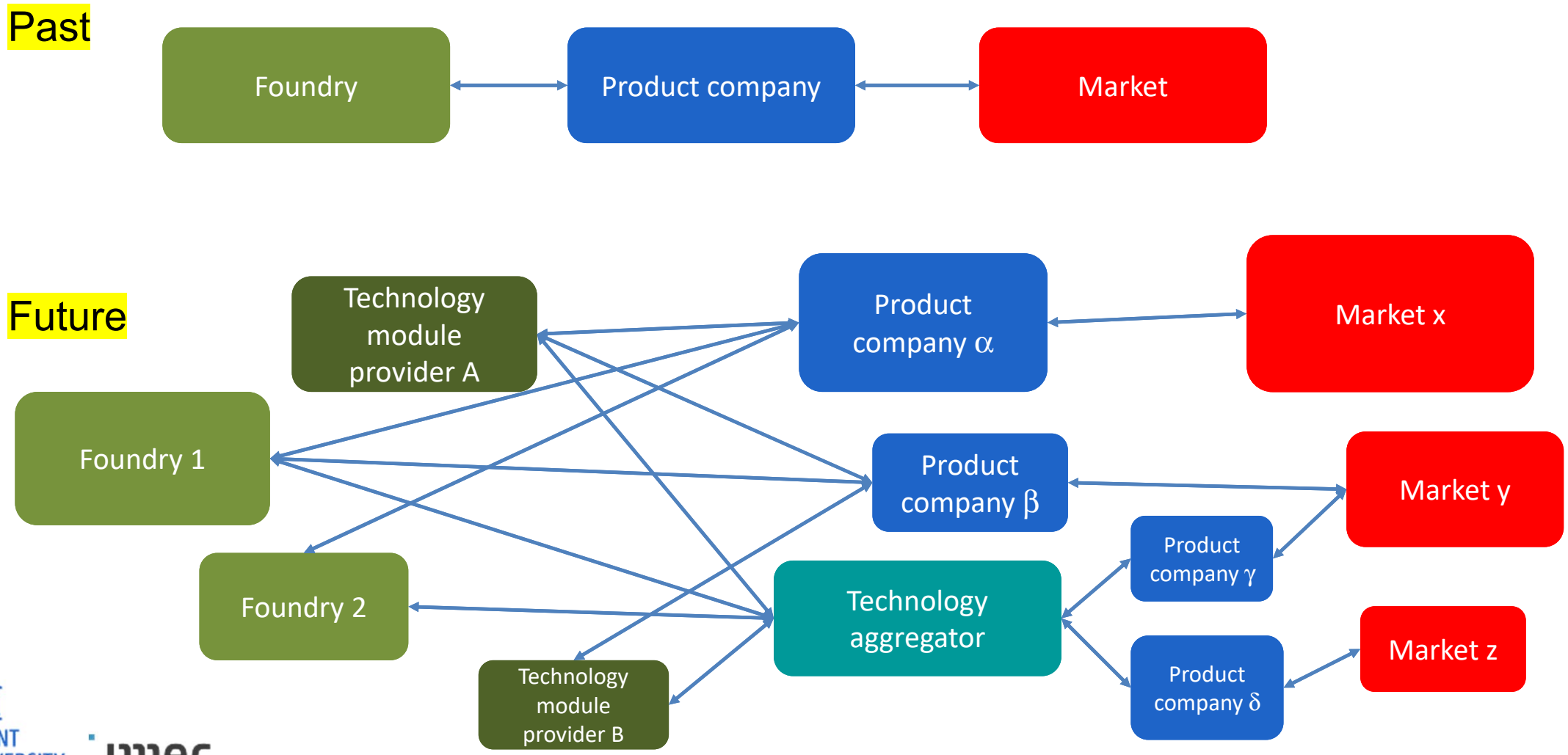
TOWARDS SILICON PHOTONICS 4.0



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BUILDING A EUROPEAN SILICON PHOTONICS VALUE CHAIN

photonixFAB

X-FAB Silicon Foundries SE | Press Release March 27, 2024

xfab

Press Release

photonixFAB Consortium now open for first prototyping

New customer engagement portal enables early technology access

Tessenderlo, Belgium – March 27, 2024

Pushing ahead with the European Union (EU) funded photon
consortium partners have taken the first step on the path to i
silicon photonics value chain by providing early access to R&
manufacturing through technology partners.

Press release

Imec demonstrates the
quality SiN waveguide te
silicon photonics platfor

LEUVEN (Belgium), January 31, 2023 — *Today, at an invited talk at SPIE Photonics West (San Francisco), imec, a world-leading research and innovation hub in nanoelectronics and digital technologies, announced that it demonstrated co-integration of its high-quality silicon nitride waveguide technology with its silicon photonics platform—without performance degradation of the high-bandwidth active devices. An important*

LIGENTEC

Press Information

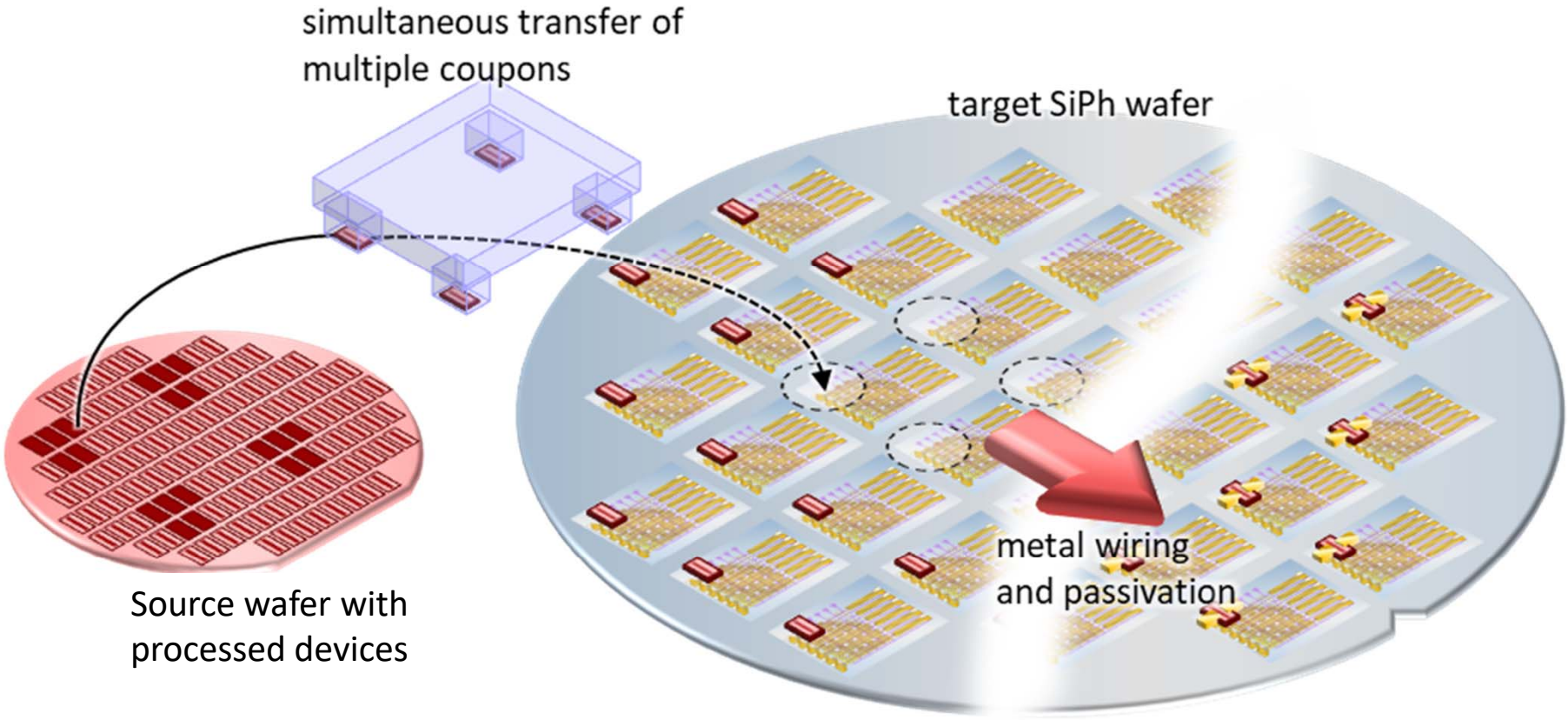
Lausanne, Switzerland – 20th September, 2024

World's first integrated value chain platform initiative for heterogeneous integration in photonics

Three leaders in photonic integrated circuits announce collaboration to offer a seamless path for heterogeneous integration with micro-Transfer Printing (MTP).

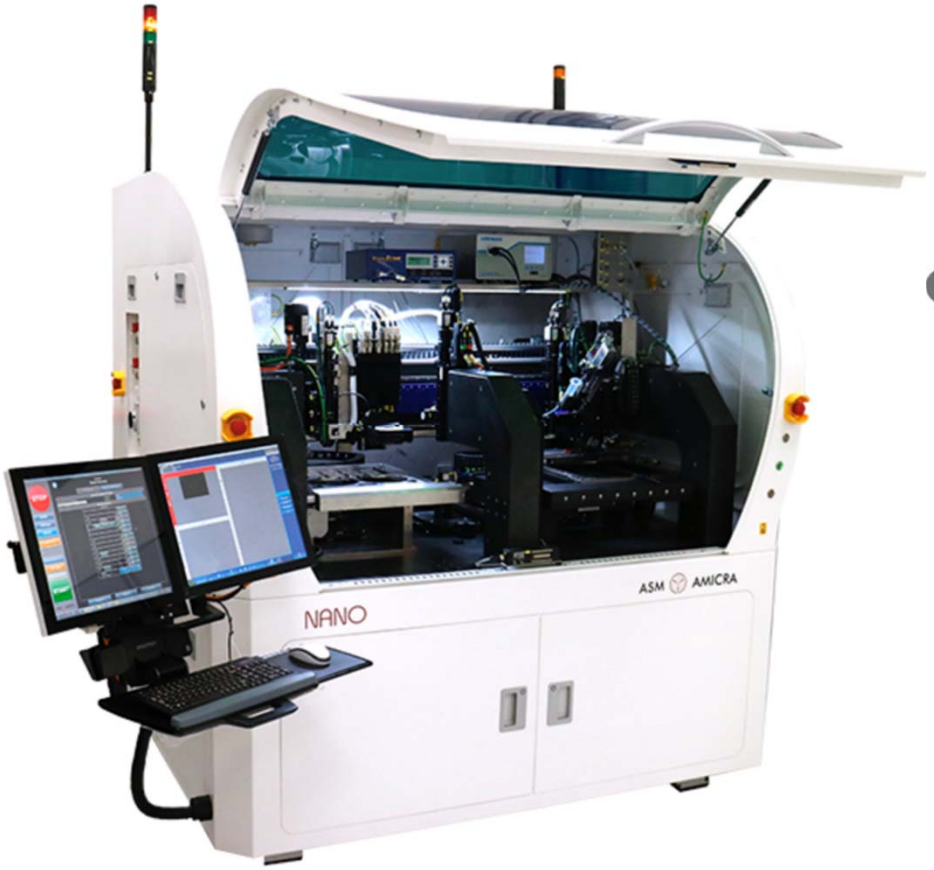
Lausanne, Cork, Erfurt, September 20th, 2024 – In a bold move to revolutionise photonic integrated circuits (PICs), three of the industry's foremost leaders, X-Celeprint, Ligentec, and X-FAB, are aligning their efforts to simplify and enhance heterogeneous integration through Micro Transfer Printing (MTP). This collaboration is set to close existing gaps in the value chain and offer a seamless journey from R&D to mass production.

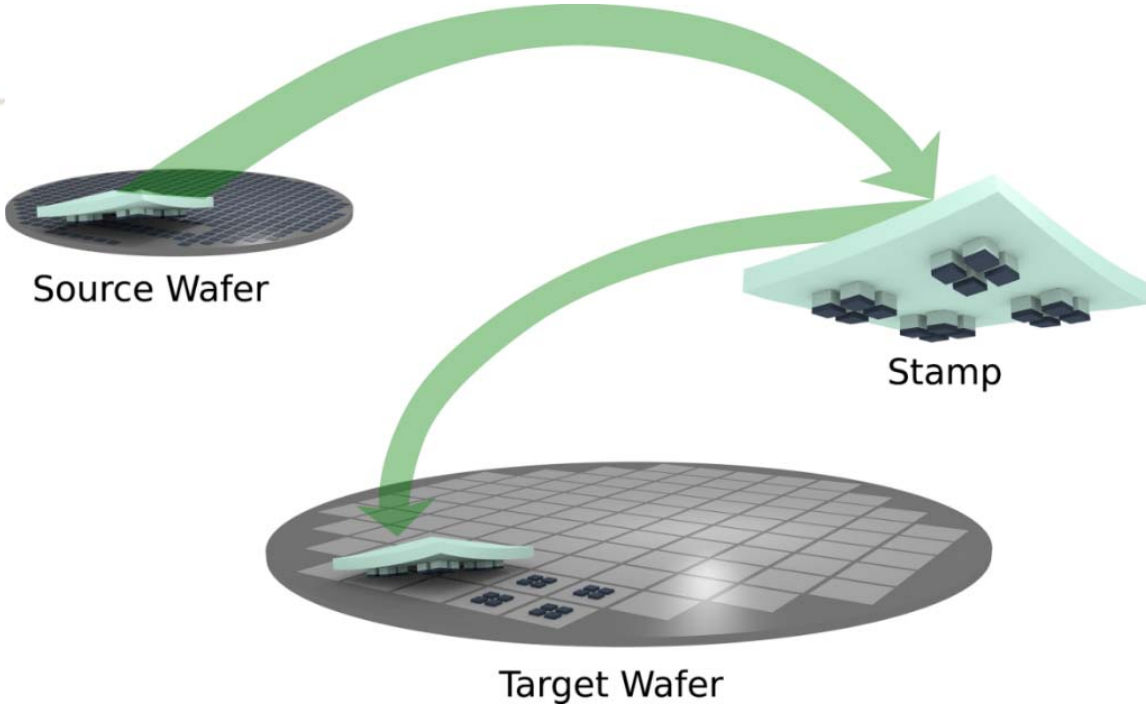
Additive Manufacturing through Micro-transfer Printing



Inherits advantages of FC (known-good die, back-end) & D2W (high throughput, efficient coupling)

Additive Manufacturing through Micro-transfer Printing

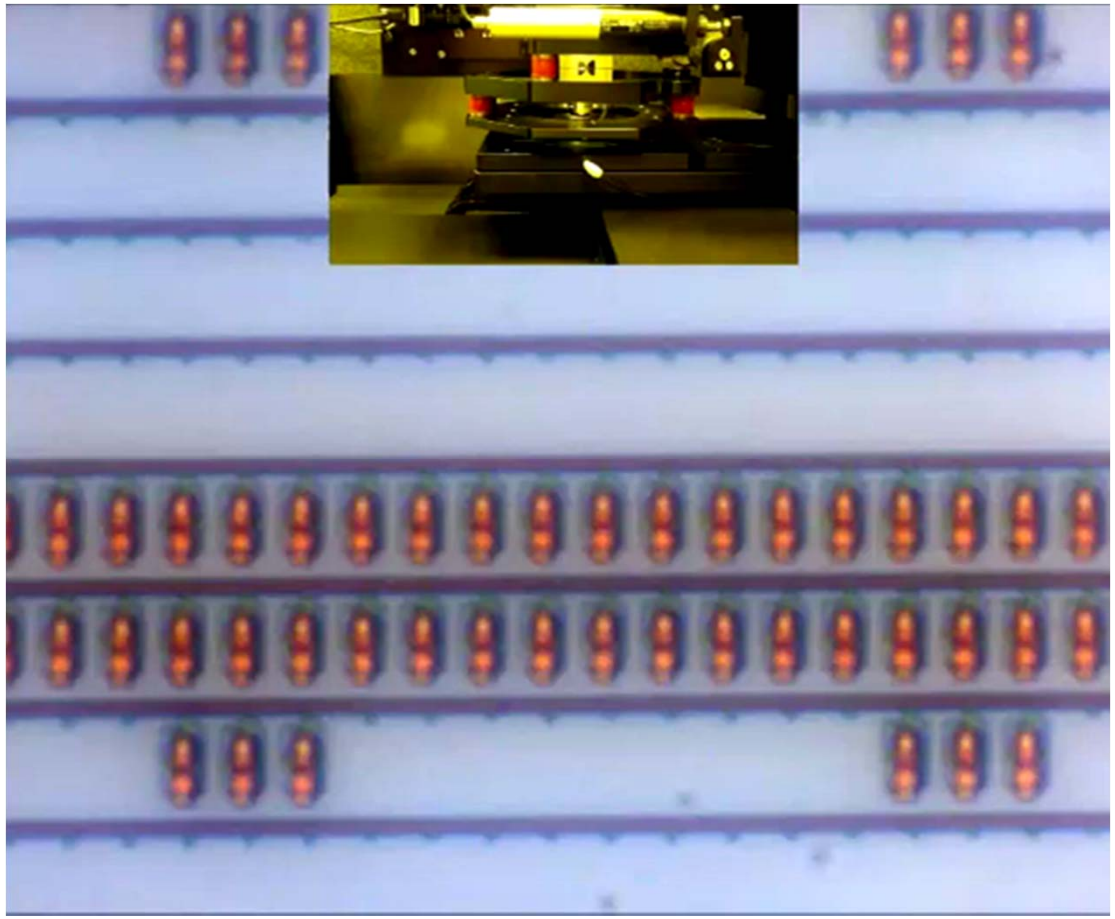




Position tolerance of +/- 0.5 µm at 3σ in 2cmx2cm arrays
1 print cycle: 45 sec

MICRO-TRANSFER PRINTING BASICS

Micro-transfer printing in action



- 1 cm^2 stamp,
- 10,000 posts,
- > 1M LEDs/hr

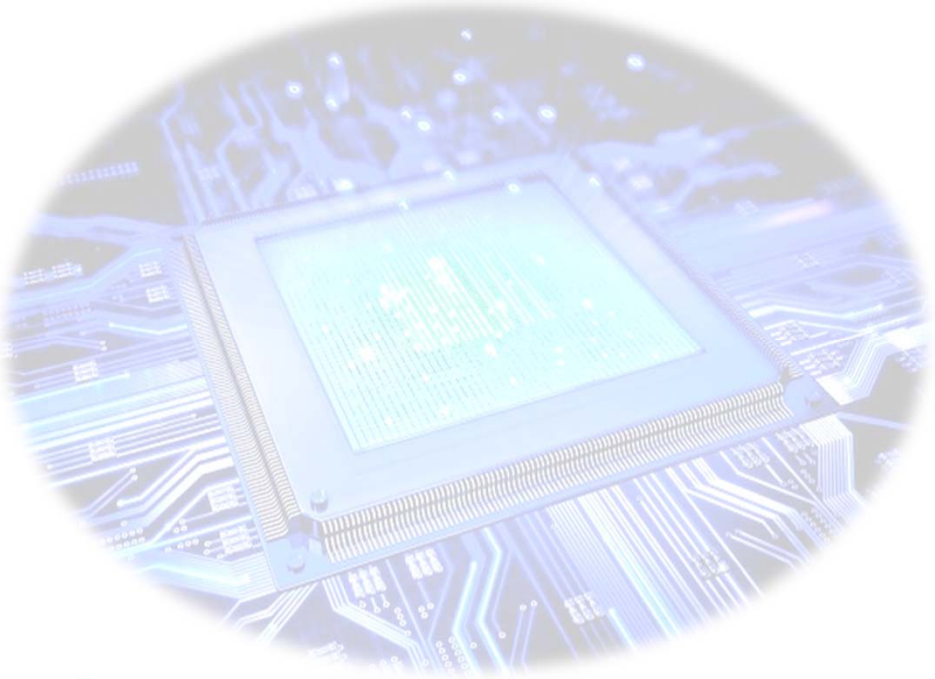
PROGRAMMABLE PHOTONICS

or photonic FPGAs

reconfigurable photonics

photonic processors

universal photonic circuits …



Photonic Integrated Circuits

that **can be reconfigured**

using **software**

to perform **different functions**.

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PROGRAMMABLE PHOTONICS

Lower development cost

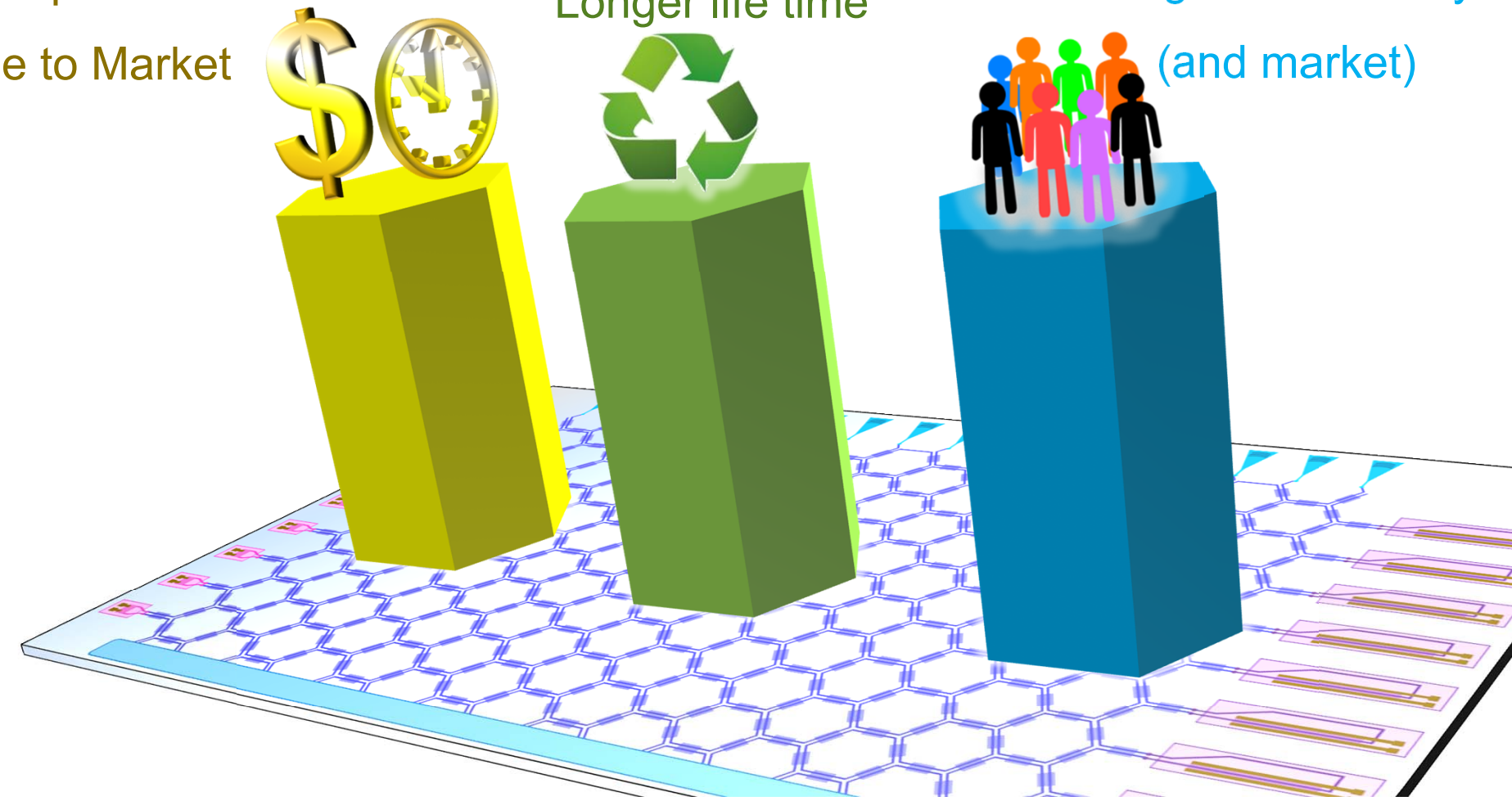
Shorter time to Market

Upgradability - Reuse

Longer life time

Larger Community

(and market)



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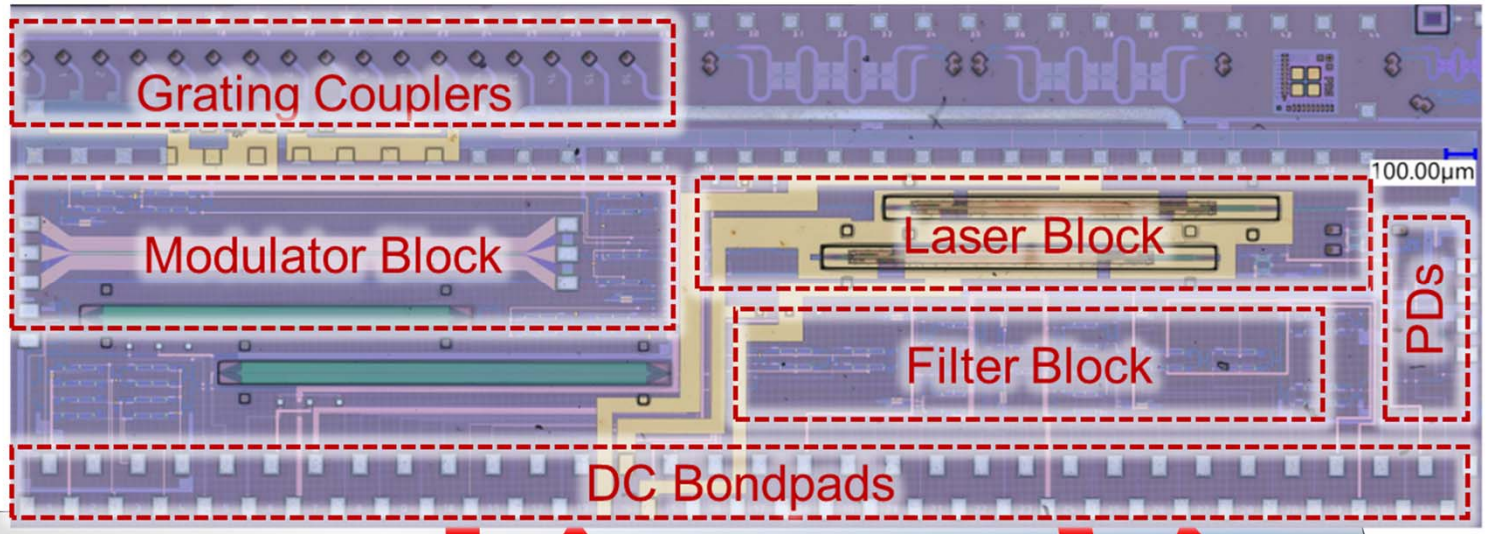
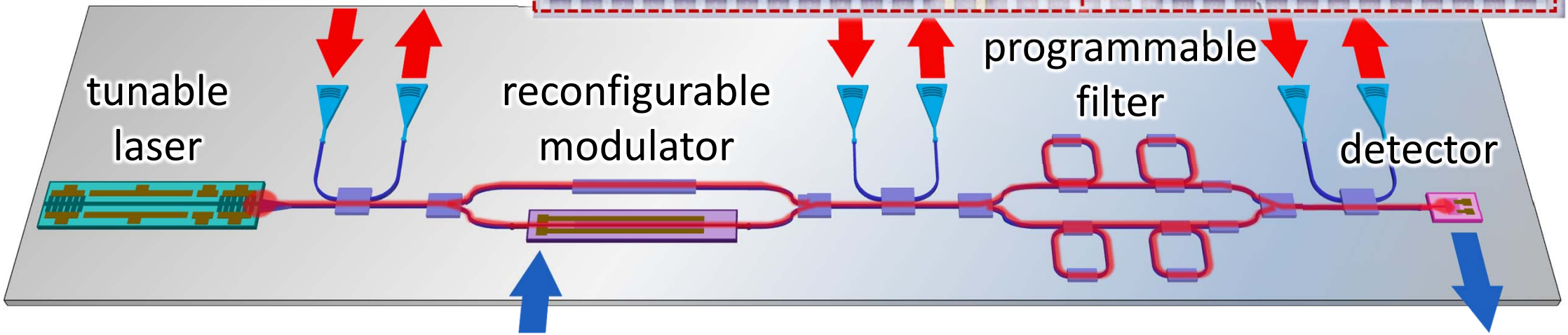
PROGRAMMABLE MICROWAVE PHOTONIC PROCESSOR

Implemented in IMEC's iSiPP50G platform





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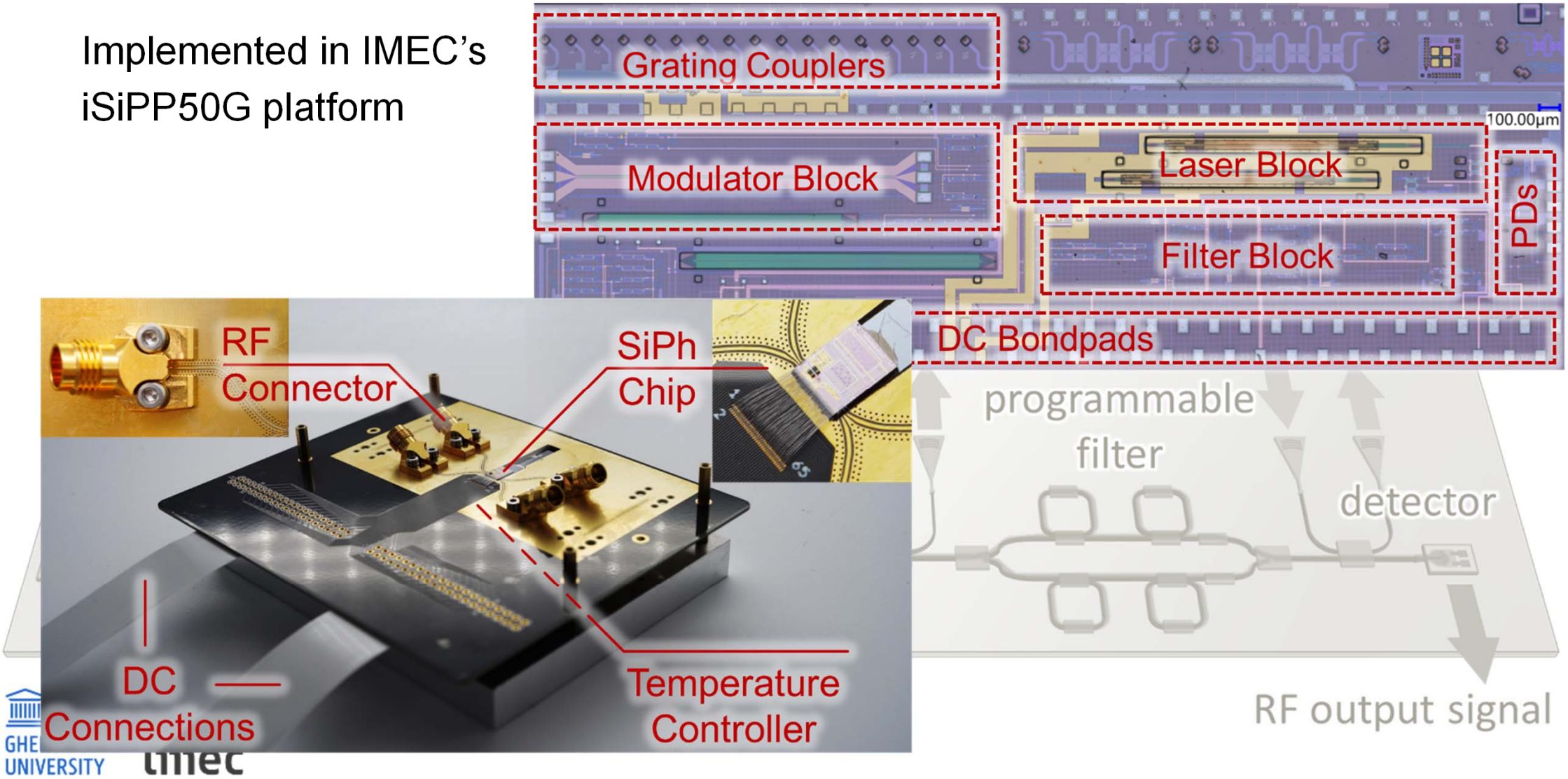
PROGRAMMABLE MICROWAVE PHOTONIC PROCESSOR

Implemented in IMEC's iSiPP50G platform



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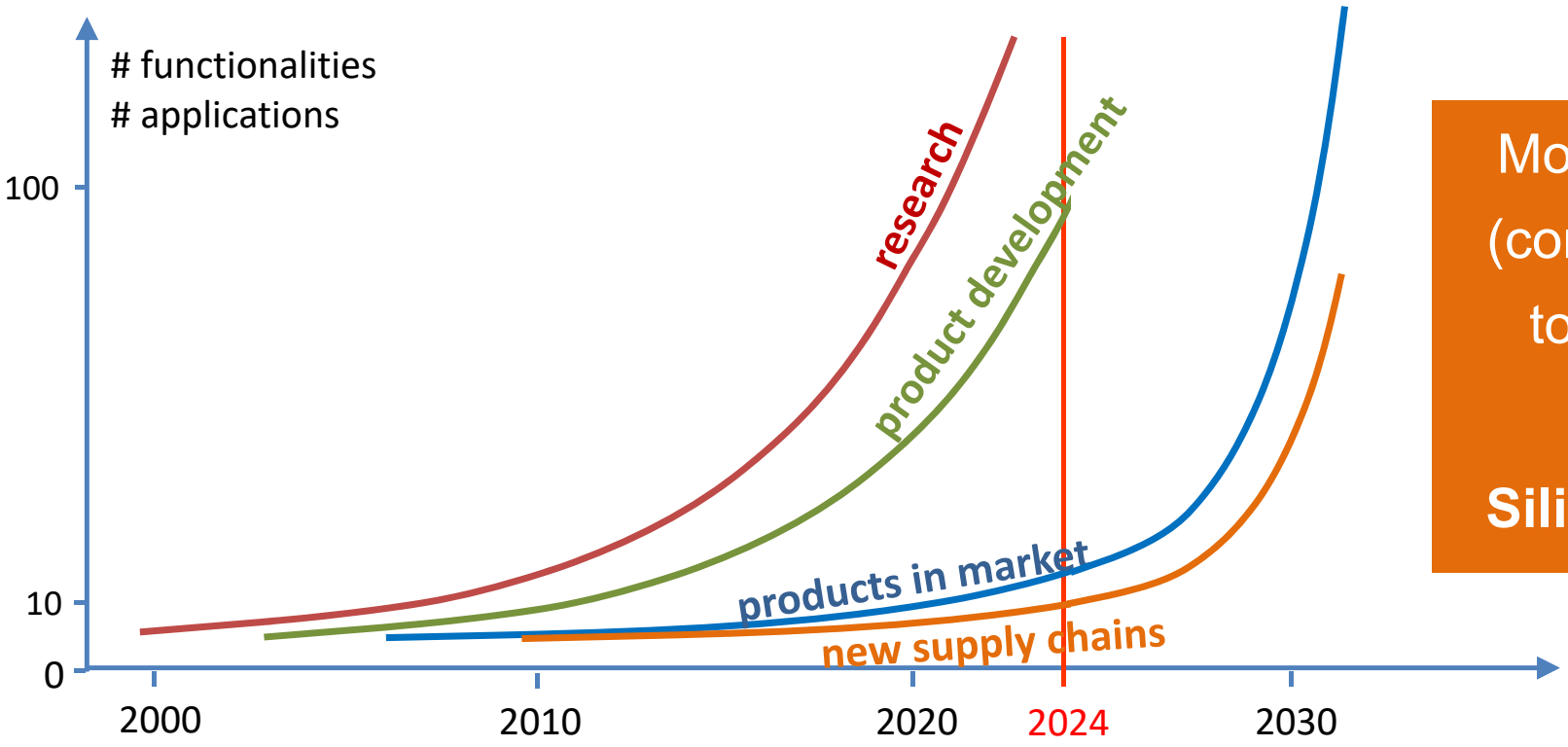
In Conclusion



Mobilize all resources (corporate, VC, public) towards a common vision, towards **Silicon Photonics 4.0**

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Observations

- Most manufacturing and product companies in the field of silicon photonics are US-based or SE-Asia-based
- The EU has very strong R&D players in silicon photonics
- India is building up strong R&D capacity in silicon photonics
- The field is diversifying quickly
- The diversity will bring opportunities for both EU and India
- Collaboration may be key in this context

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