ESSCIRC/ESSDERC 2023

SiNANO-ICOS Workshop

"European Strengths and Gaps in Emerging Semiconductor Technologies"

Silicon Photonics: A review of main EU and international activities and technologies

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Lisbon, September 11, 2023

The European Silicon Photonics Alliance

ePIXfab - The European Silicon Photonics Alliance

ePIXfab's mission is to act as a catalyst for European academia and industry to strengthen the worldwide silicon photonics ecosystem.

Advocate
Innovation opportunities enabled by SiPh

Represent
European silicon photonics community

Train
Lift the workforce

Consult
About the ecosystem and supply chain

Roadmap
About the technological trends and evolution

ePIXfab
The European Silicon Photonics Alliance

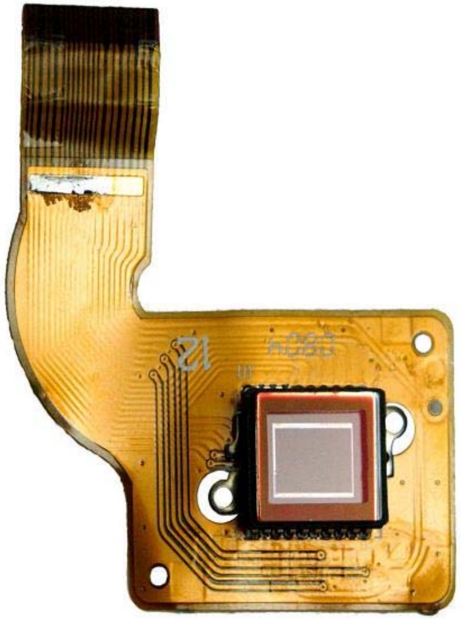
Outline

- Silicon Photonics: what?

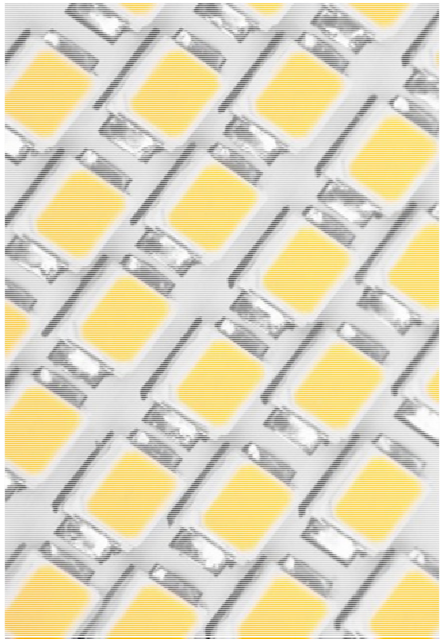
Silicon Photonics in the world

Key trends in silicon photonics

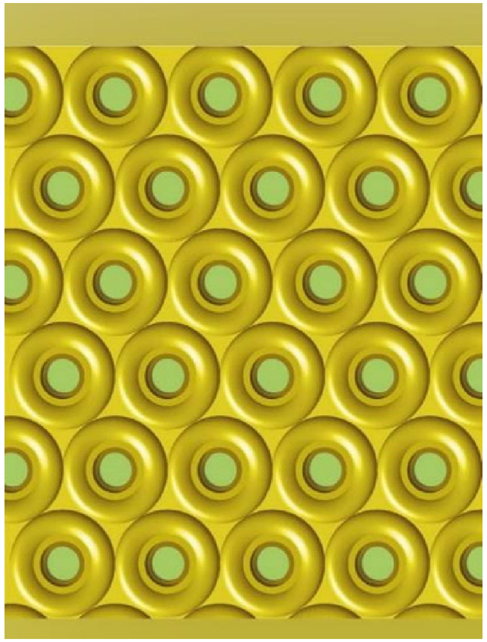
Classes of semiconductor-based photonics



CMOS Imagers



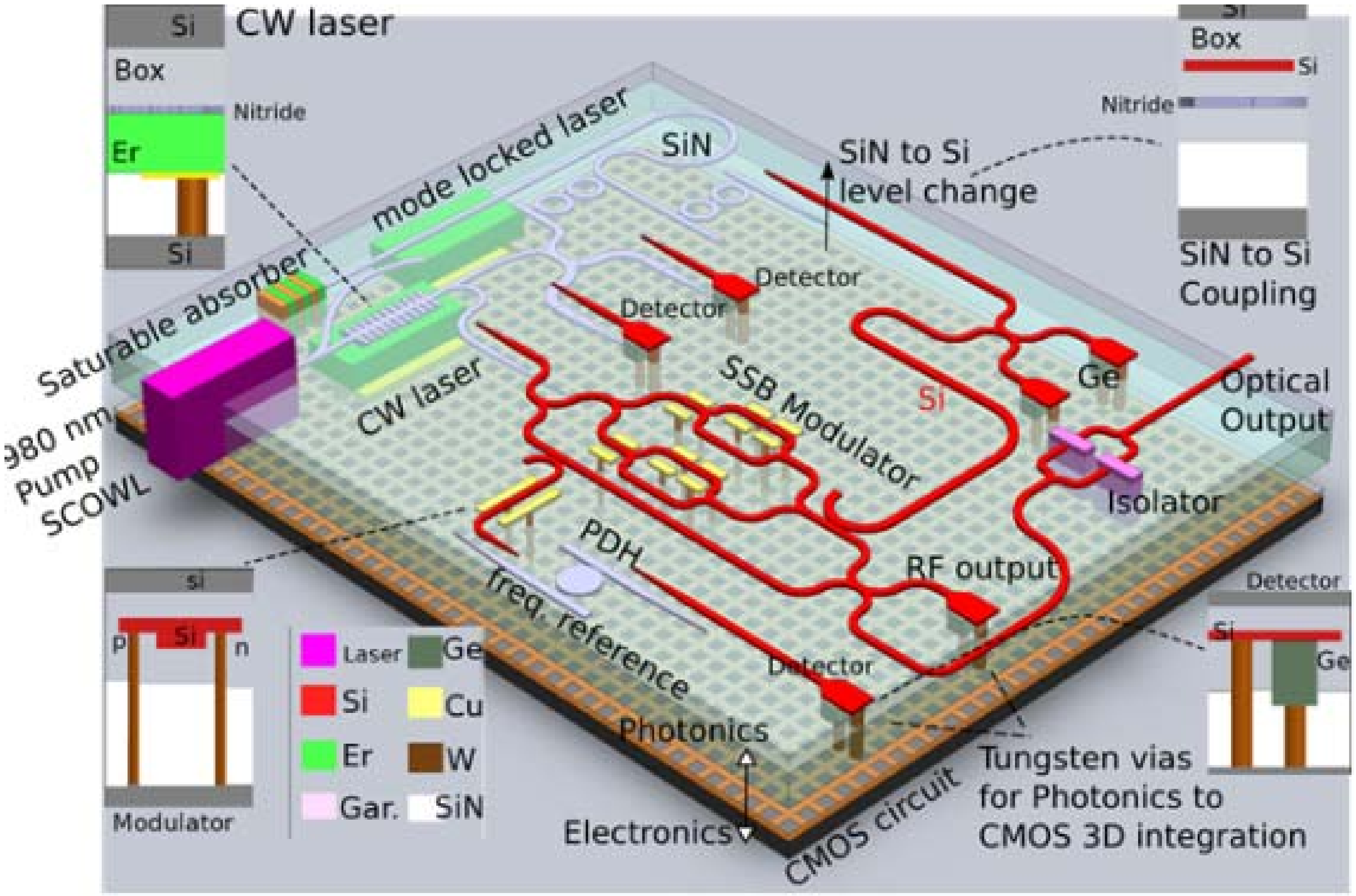
LEDs



VCSELs

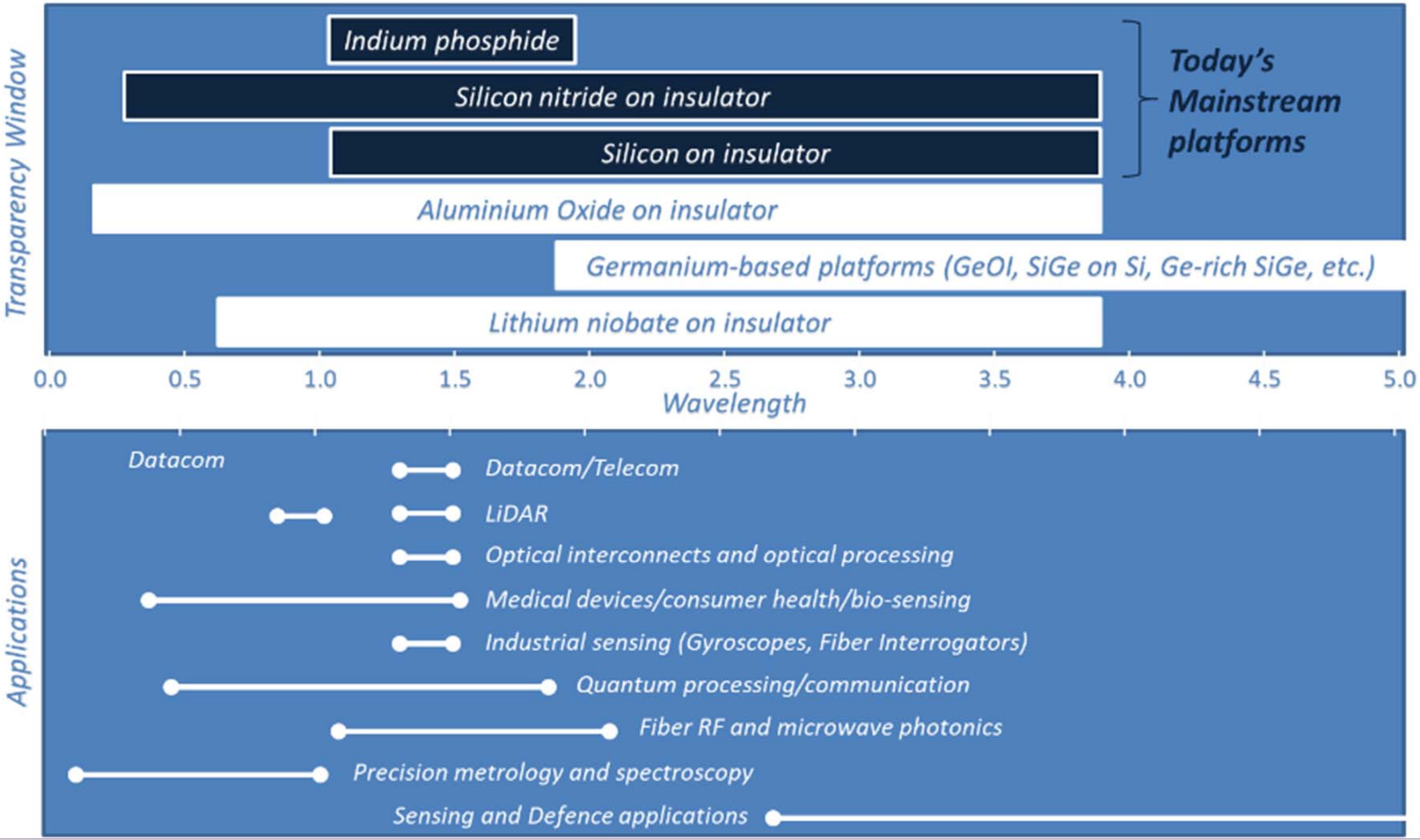
Photonic ICs

Photonic Integrated Circuits (PICs)

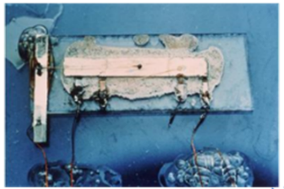


A tale of different materials

Not exhaustive

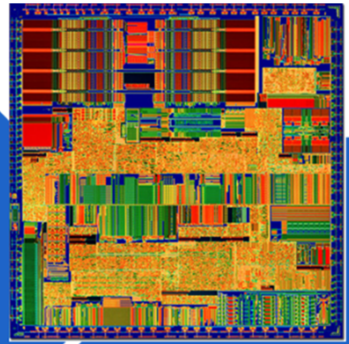


From discrete functions to circuits



Jack Kilby

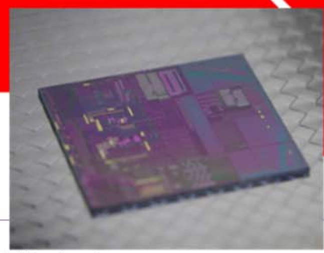
1958



Electronic IC (EIC)

Silicon technology

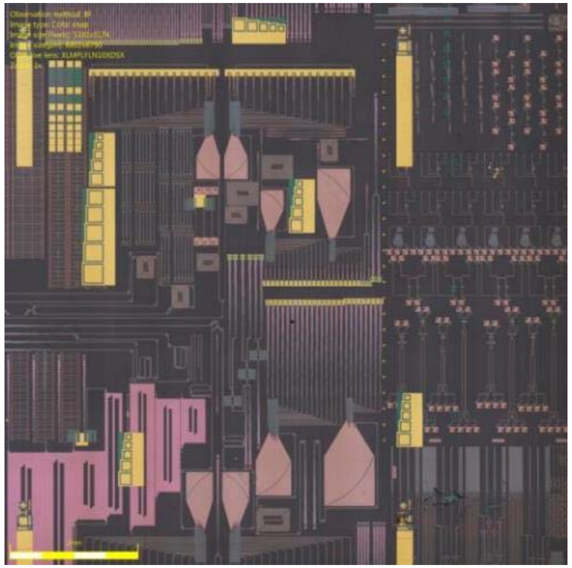
~2000



Photonic IC (PIC)

Silicon Photonics

The implementation of high density photonic integrated circuits by means of CMOS process technology in a CMOS fab

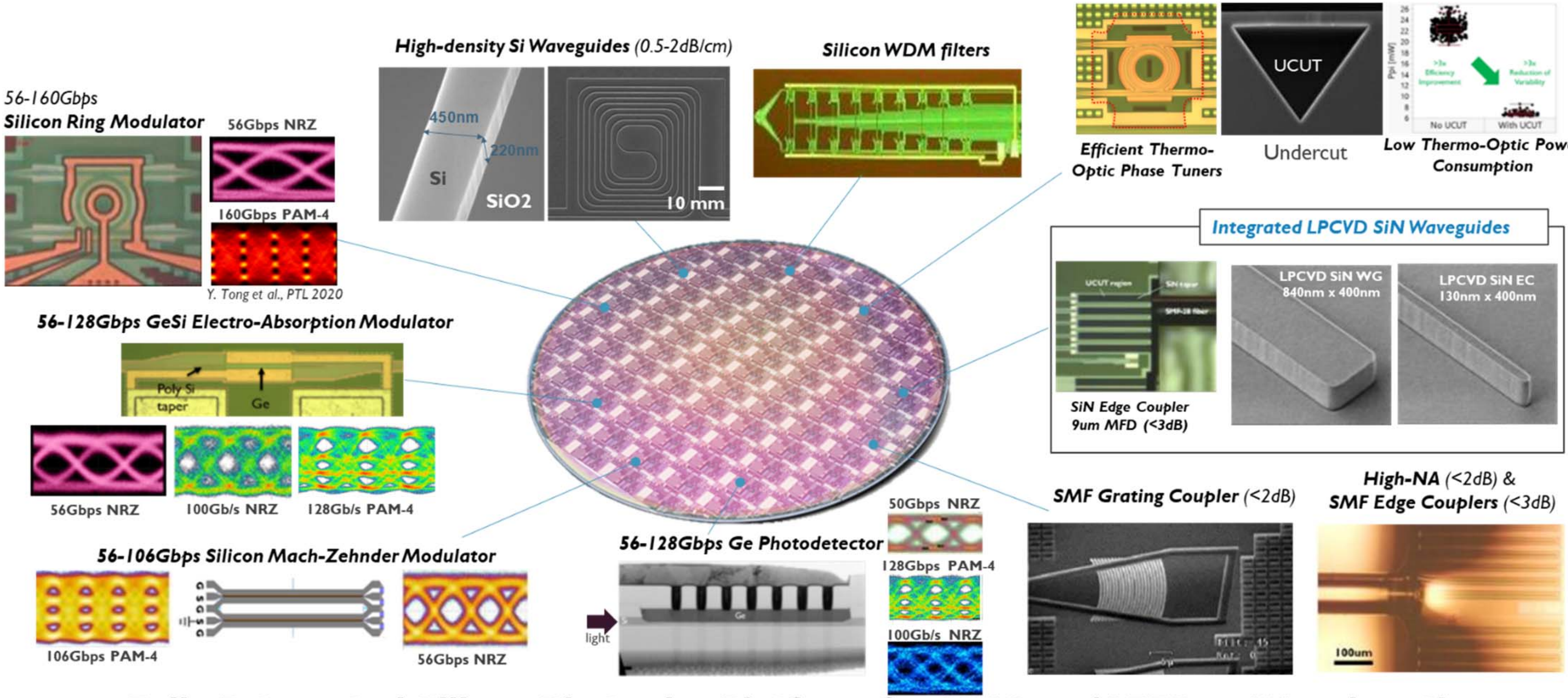


Enabling complex optical functionality on a compact chip at low cost

A typical silicon photonics platform:

Imec's *iSiPP200N technology*

RB1



Fully Integrated Silicon Photonics Platform for 1310nm/1550nm Wavelengths

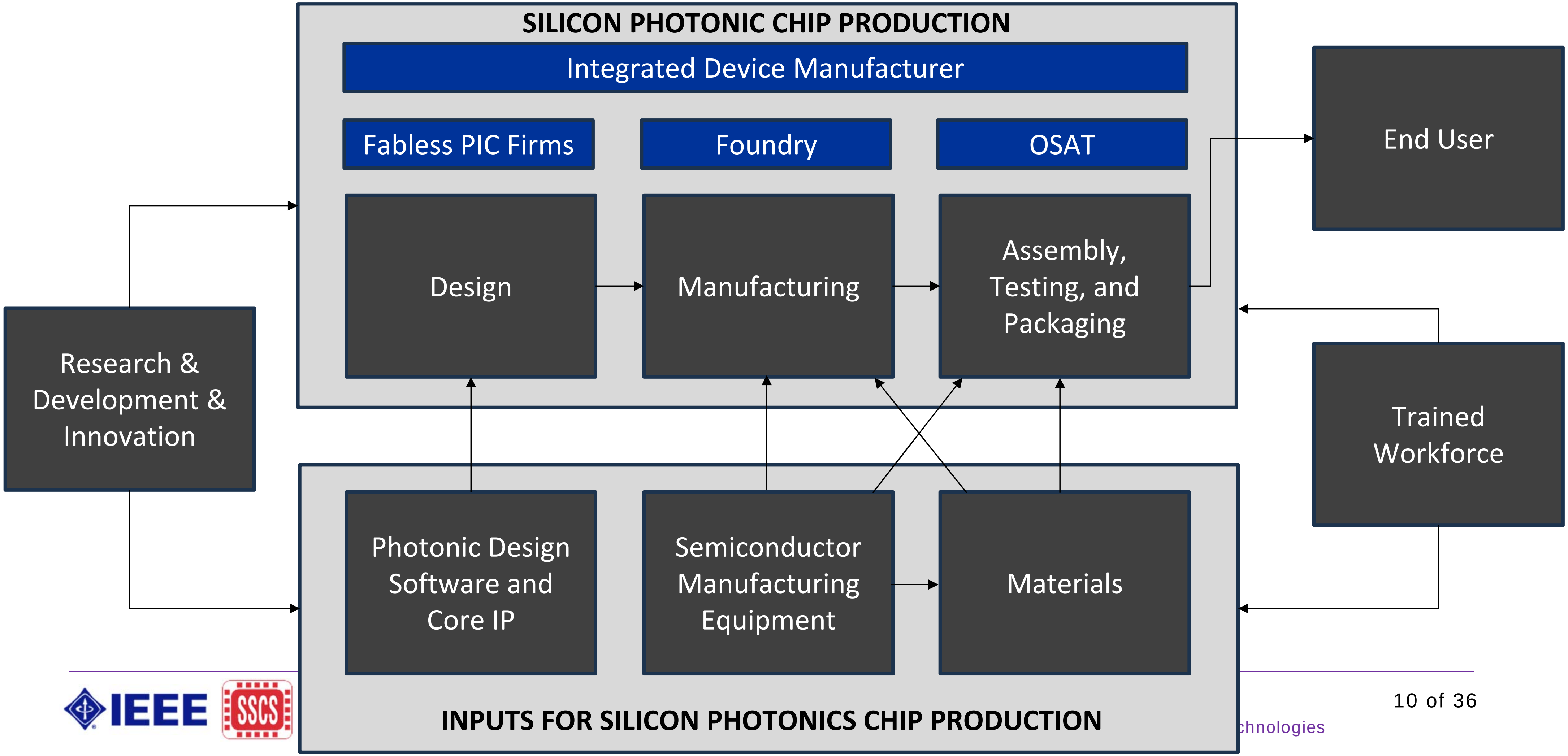
- Low-loss Passive Silicon Waveguide Devices and Fiber Coupling Structures
- 56Gb/s+ (Ge)Si Modulators and Ge(Si) Photodetectors

Diapositive 9

RB1 Roel Baets; 10/09/2023

Silicon photonics supply chain:

Not very different from CMOS supply chain



Today’s dominant application:
Transceivers for data centers and for telecom

- ☐ **Typical data rate: 100-400 Gb/s**
- ☐ **Typical symbol rate: 25-50 GBaud**
- PSM4 (4 parallel fibers)
- WDM (4 wavelengths)
- PAM4
- Polarisation multiplexing
- Coherent (QPSK, 16-QAM)

Under development + early deployment:

Data rate: >800 Gb/s

Symbol rate: 100 Gbaud

Evolution towards Co-packaged Optics

Beyond today's mainstream applications

Biosensors

Medical and Industrial Sensors

LIDAR

Computing (AI, quantum, programmable)

Higher speed interconnect & communication

Beyond today's mainstream applications

Genalyte
DELTA DIAGNOSTICS
SiPhox
SURFIX
meep
bialoom

Rockley Photonics
indigo
SENTEA
aryballe
BROLIS SENSOR TECHNOLOGY
ANELLO

ANALOG PHOTONICS
SCANTINEL PHOTONICS Scan | Detect | Navigate
AEVA
SiLC
pointcloud
mobileye An Intel Company
Aurora
VOYANT PHOTONICS

XANADU
LIGHTELLIGENCE
LIGHTMATTER
Lighton APPLIANCE
LUMINOUS
Optalysys
OPTELLIGENCE
iPRONICS Programmable Photonics
SPARROW QUANTUM

POLARITON TECHNOLOGIES
LIGHTWAVELOGIC
Lumiphase

Not exhaustive

Outline

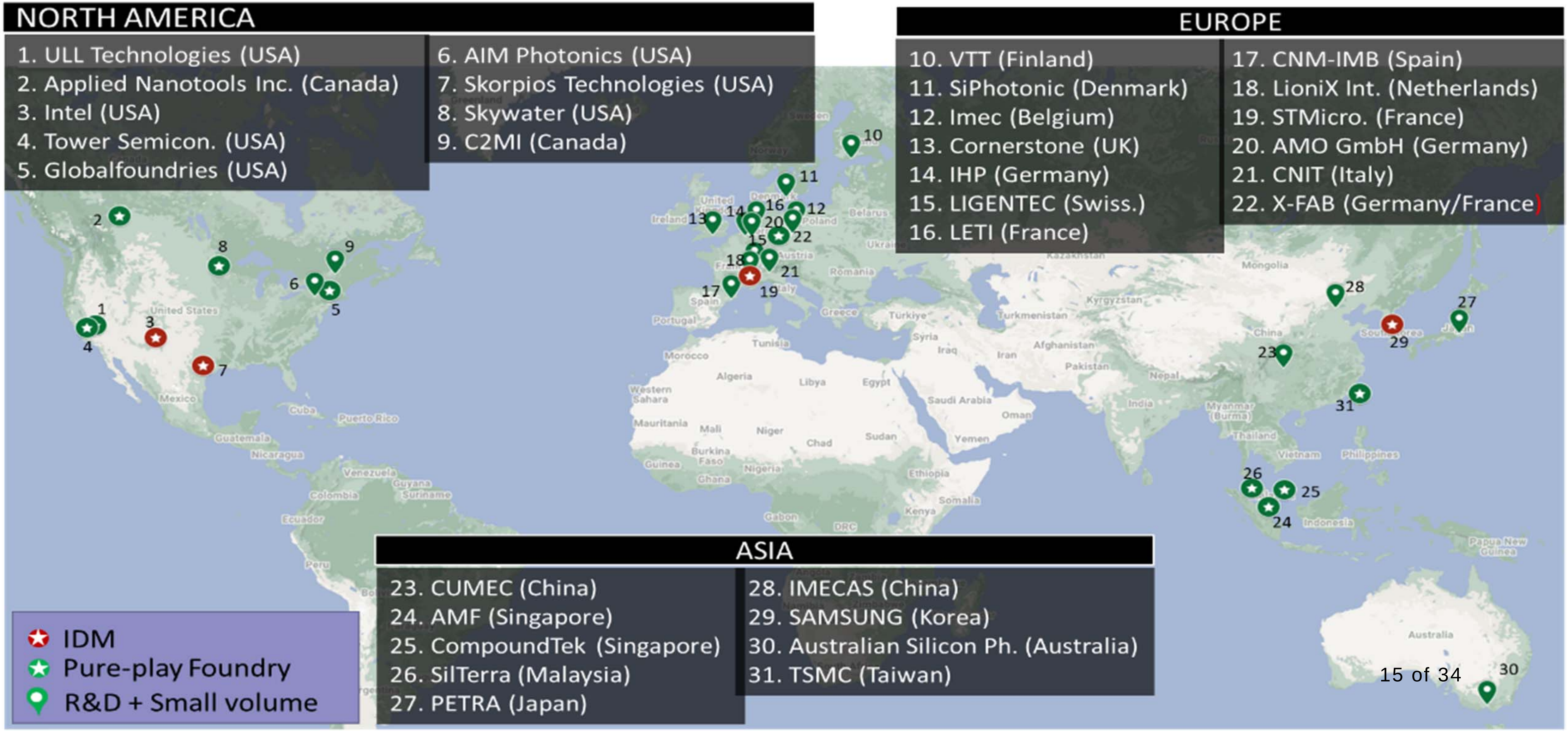
Silicon Photonics: what?

➡ Silicon Photonics in the world

Key trends in silicon photonics

Silicon Photonics manufacturing

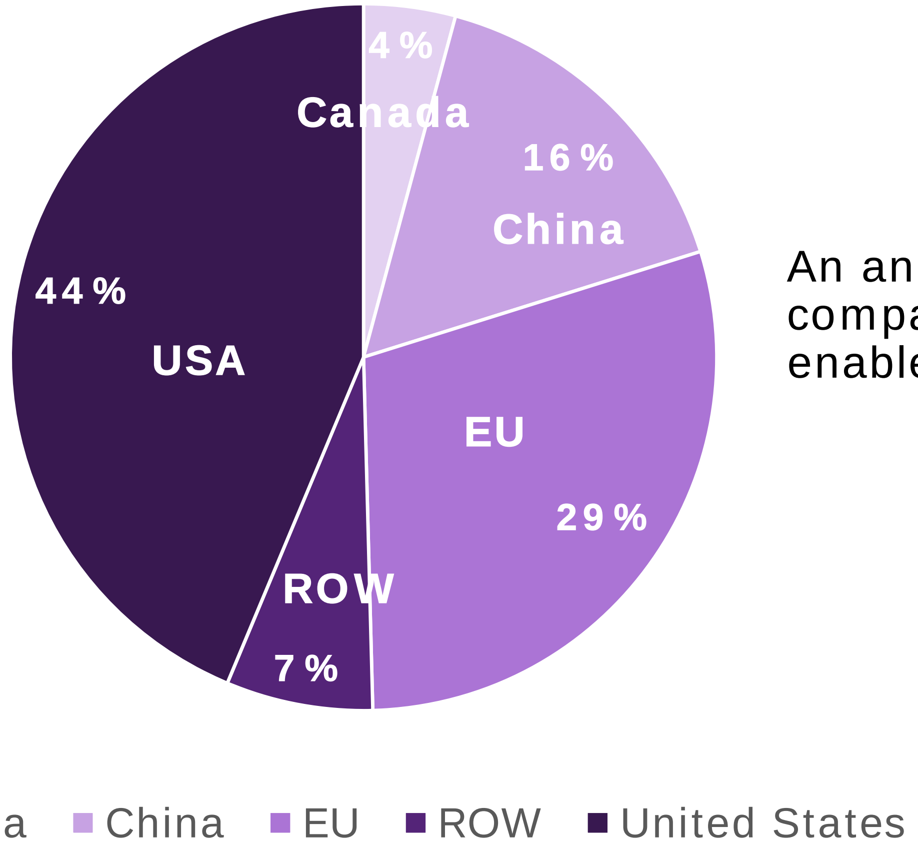
Enabled by IDMs, pureplay foundries and R&D Institutes



Silicon photonics firms:
based on the location of their HQs

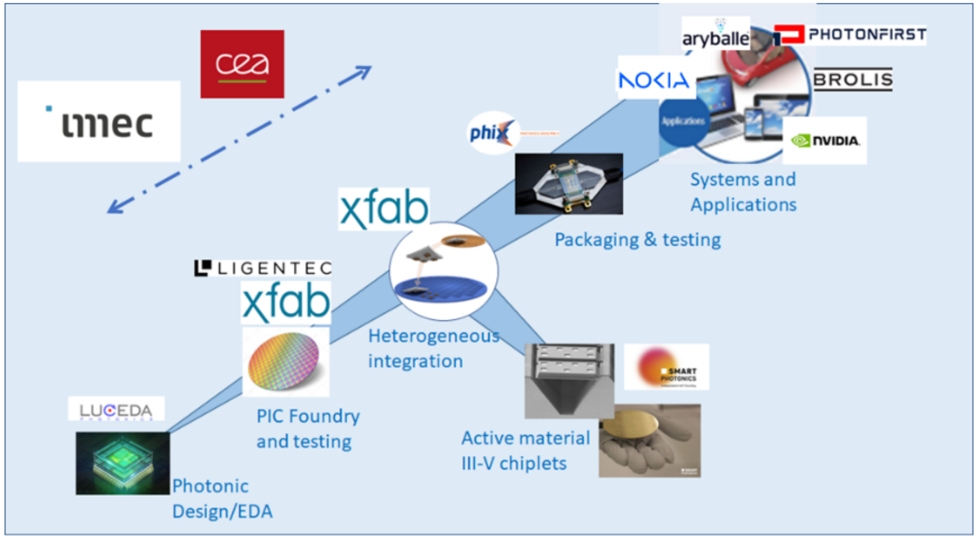
Industries served:

- ☐ Agrifood
- ☐ Automotive
- ☐ HPC
- ☐ Industrial sensing
- ☐ Medical Diagnostics
- ☐ Optical IO
- ☐ Photonics AI
- ☐ Quantum Computing
- ☐ Telecom/datacom



An analysis based on 125 companies developing SiPh-enabled products

KDT-JU PROJECT PHOTONIXFAB
ENABLING A EUROPEAN **INDUSTRIAL** SILICON PHOTONICS VALUE CHAIN



Key numbers & facts

- Industry driven initiative (XFAB led)
- Kick-off in May 2023 - 3.5 years
- 47.6M€ public + private funding
- 13 partners, 9 countries
- 2 photonic (Si and SiN) platforms
- InP heterogenous integration
- 6 application-oriented demonstrators

European industry driven consortium supported by two major RTO's

Enabling *initial* PIC manufacturing capability in XFAB high volume fabs

Empower photonics innovation by start-ups, SMEs and large entities with Multi-project wafer access with path to EU high volume manufacturing

Enabling InP-chiplets and other materials for heterogenous integration

Enabling and strenghtening silicon photonic industrial value chains

220nm SOI (imec) platform – ideal for datacom / telecom, sensing,…

Extending **Ligentec** world leading **ultra low loss SiN platform** – ideal for quantum computing, sensing and other applications

Heterogeneous integration of **InP (Smart Photonics)**, LNOI,.. on SiN and Si platforms

Photonics packaging & testing (**PHIX**)

Photonic design / EDA tool enablement and development (**Luceda**)

Value chain testing with 6 demonstrators from wide range of applications

Datacom and optical switch (**NVIDIA**), Coherent Telecom (**Nokia**),
IR spectrometer for sensing (**Brolis**)

Digital Olfaction sensor for Consumer Healthcare (**Aryballe**) and Health monitoring demonstrator (**PhotonFirst**)

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Co-funded by the European Union

photonixFAB is co-funded by the European Union under grant agreement no. 101111896.
The project is supported by the Key Digital Technologies Joint Undertaking and its members including top-up funding by Belgium, Germany, France, Israel, Italy and the Netherlands.

Outline

Silicon Photonics: what?

Silicon Photonics in the world

➡ Key trends in silicon photonics

Current technological trends

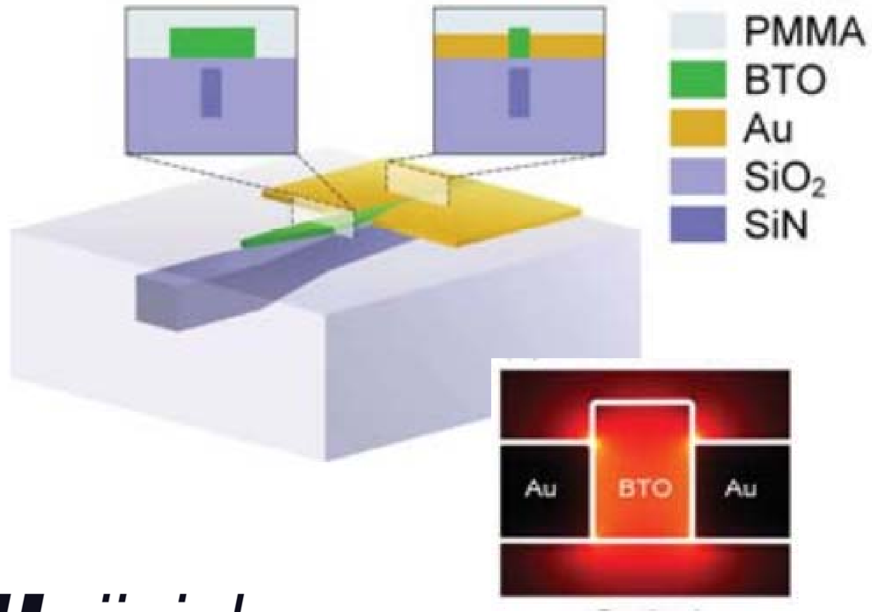
- Heterogenous silicon photonics
- Light source integration
- Large-scale photonic integration
- Higher intimacy between electronics and photonics

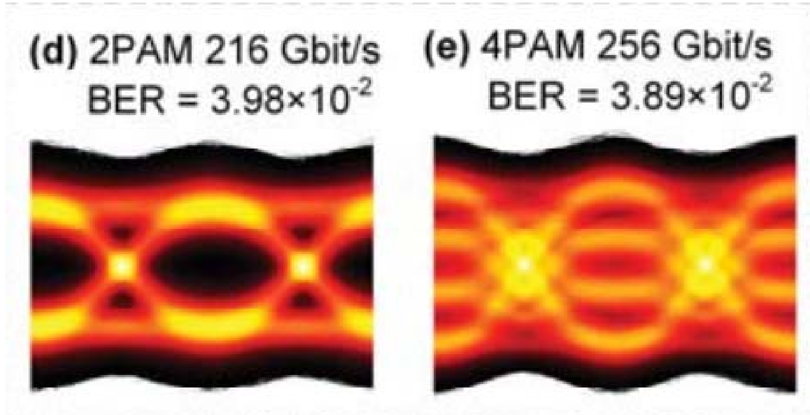
Trend 1: Heterogenous silicon photonics

- Wafer-scale integration of novel materials to boost the performance of silicon photonics building blocks
  - Example: high-speed phase modulator

Phase Modulators	**Amplitude Modulators**
■ $LiNbO_3$: thin films bonded on silicon (nitride) circuitry (Harvard, Stanford, Sun Yat-sen University, UCSD, Sandia, UCSB, EPFL, imec-UGent …) ■ BTO (Barium Titanate): epitaxially grown on silicon with STO buffer layer (IBM, Yale, imec, …) ■ PZT: sol-gel deposition on any substrate (Ghent University) ■ EO-polymers (SOH, plasmonic): (KIT, ETHZ…)	Graphene: layer transfer (Berkeley, CNIT, imec …) 2D TMDCs (Columbia University, George Washington University…)

Heterogenous silicon photonics:
Plasmonic BTO Modulator at >100 Gbaud

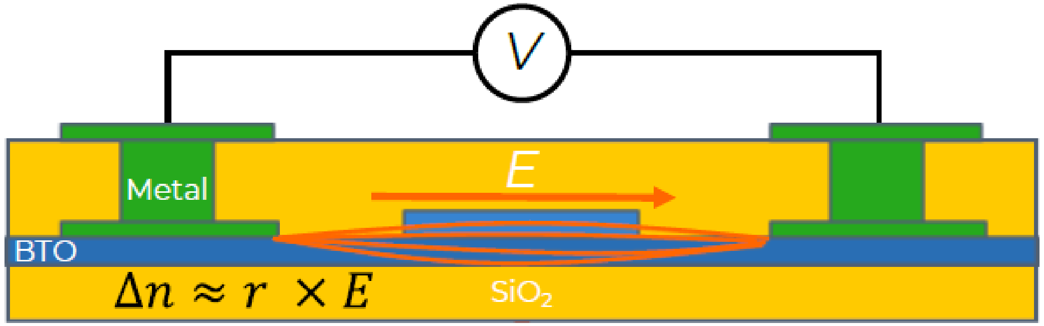




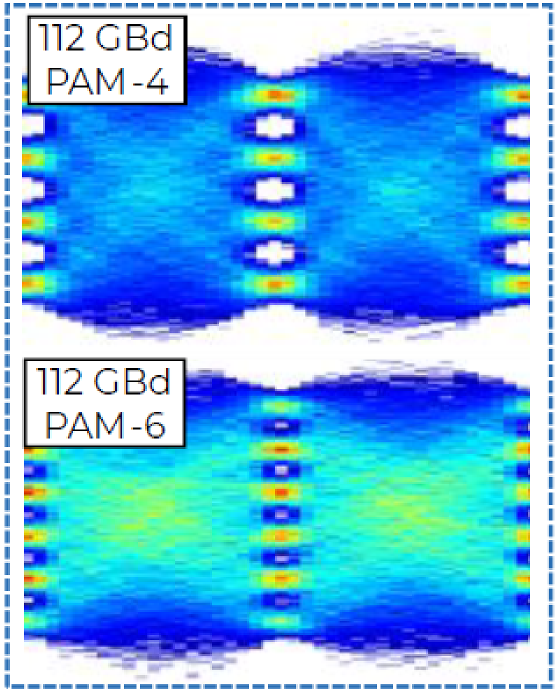
216 Gbaud OOK demonstrated

M. Kohli et al, J Leuthold, ECOC (2022)

Heterogenous silicon photonics:
Thin-film BTO-based MZM modulators at >100 Gbaud



112 Gbaud PAM4 and PAM6 demonstrated

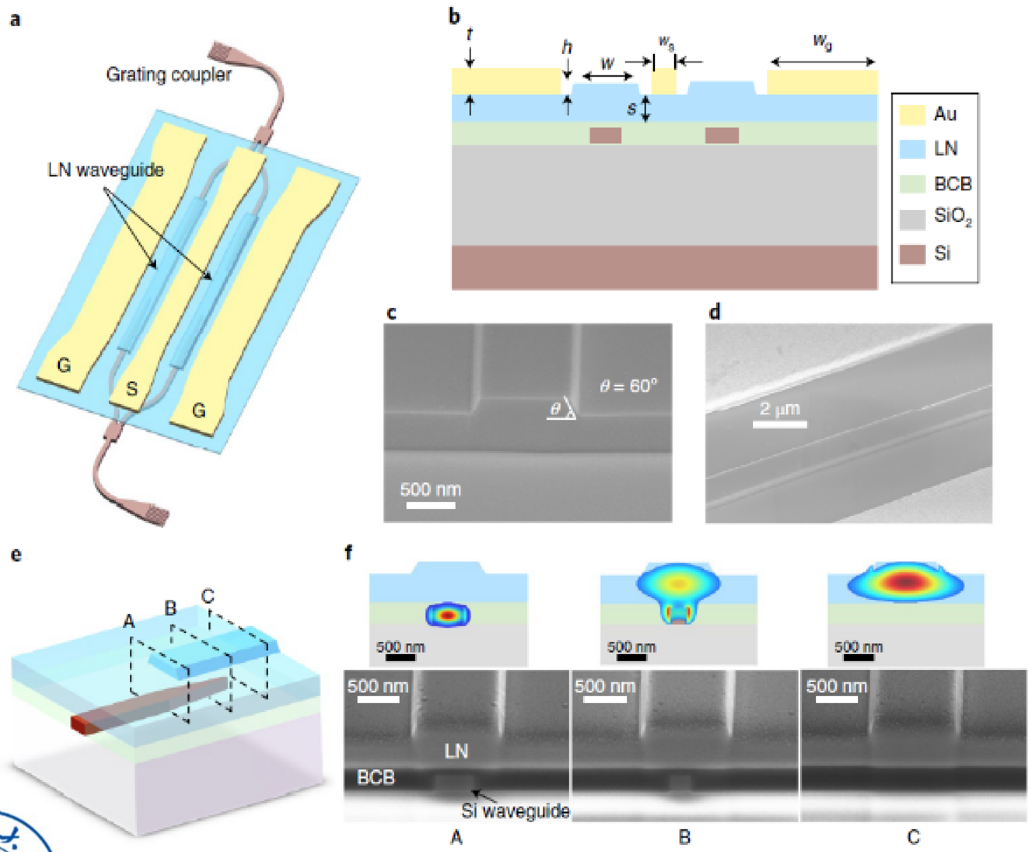


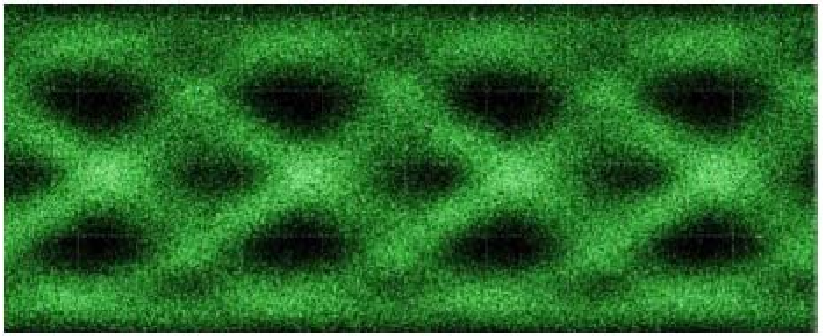
Lumiphase

F. Eltes et al, S. Abel, OFC2023 (post-deadline paper)

Heterogenous silicon photonics:

Bonding of thin-film LiNbO3 on SOI) at > 100 Gbud





100 Gb s^{-1} OOK

100 Gbaud OOK demonstrated

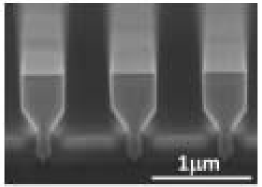
M. He, et al, Liu Liu, X. Cai, Nature Photonics (2019)

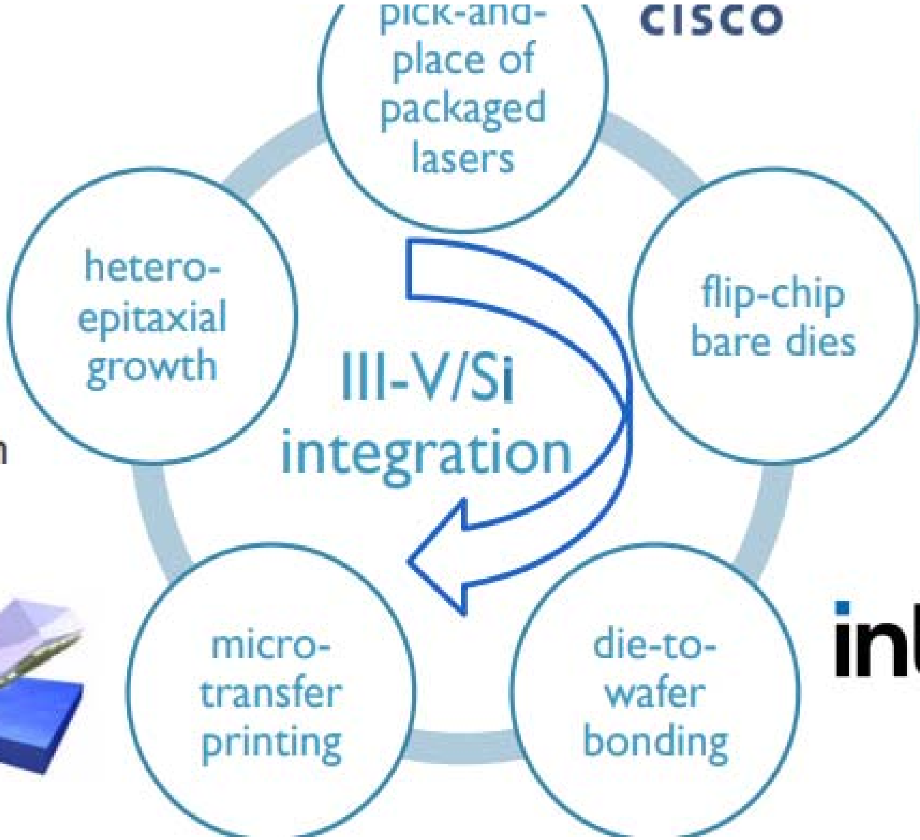
Trend 2: Light source integration with SiPh

Why integrated lasers on a Si PIC?

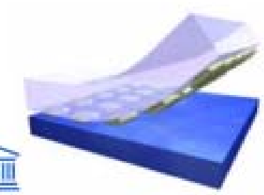
- More compact solution
- Lower cost in volume
- Many lasers on a PIC
- Higher performance!

Light source integration with SiPh:
Options

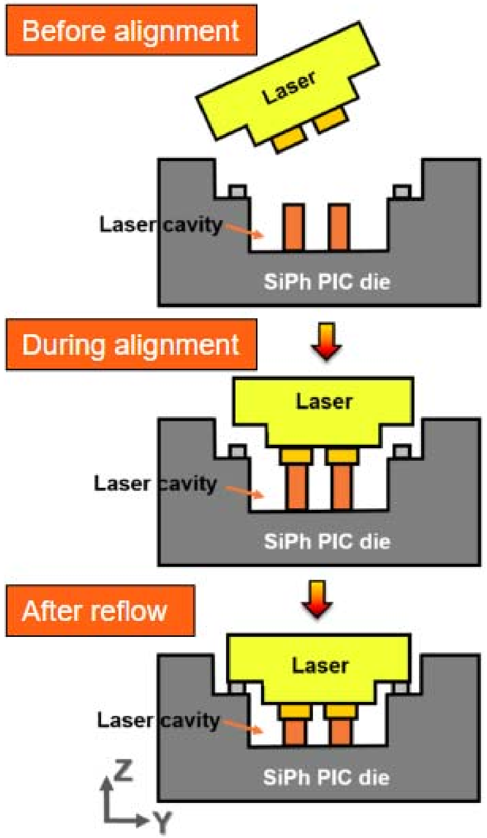


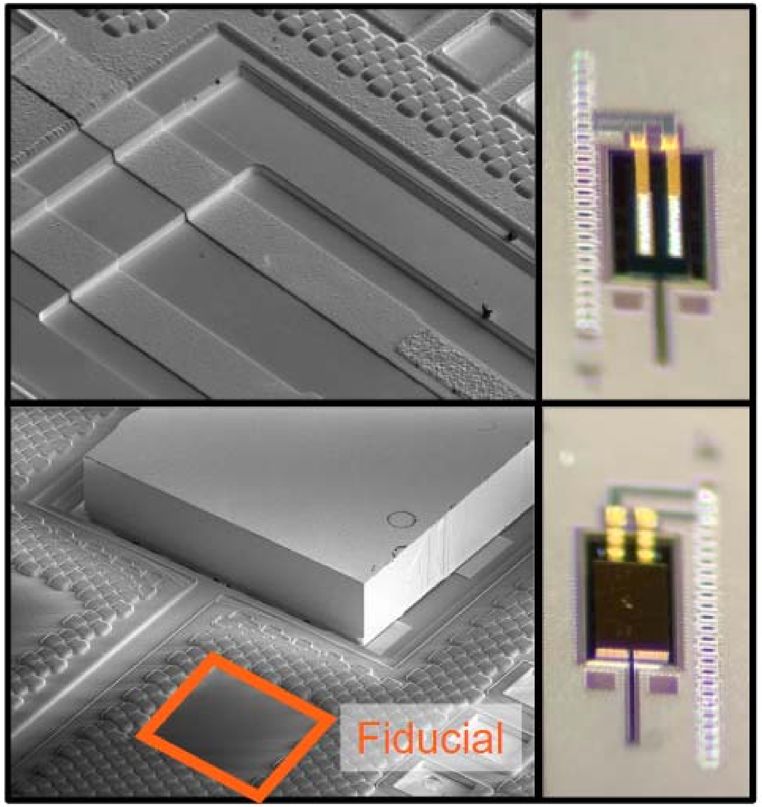


Current research
@UGent/imec



Light source integration with SiPh:
Flip-chip laser attach on a commercial SiPh platform

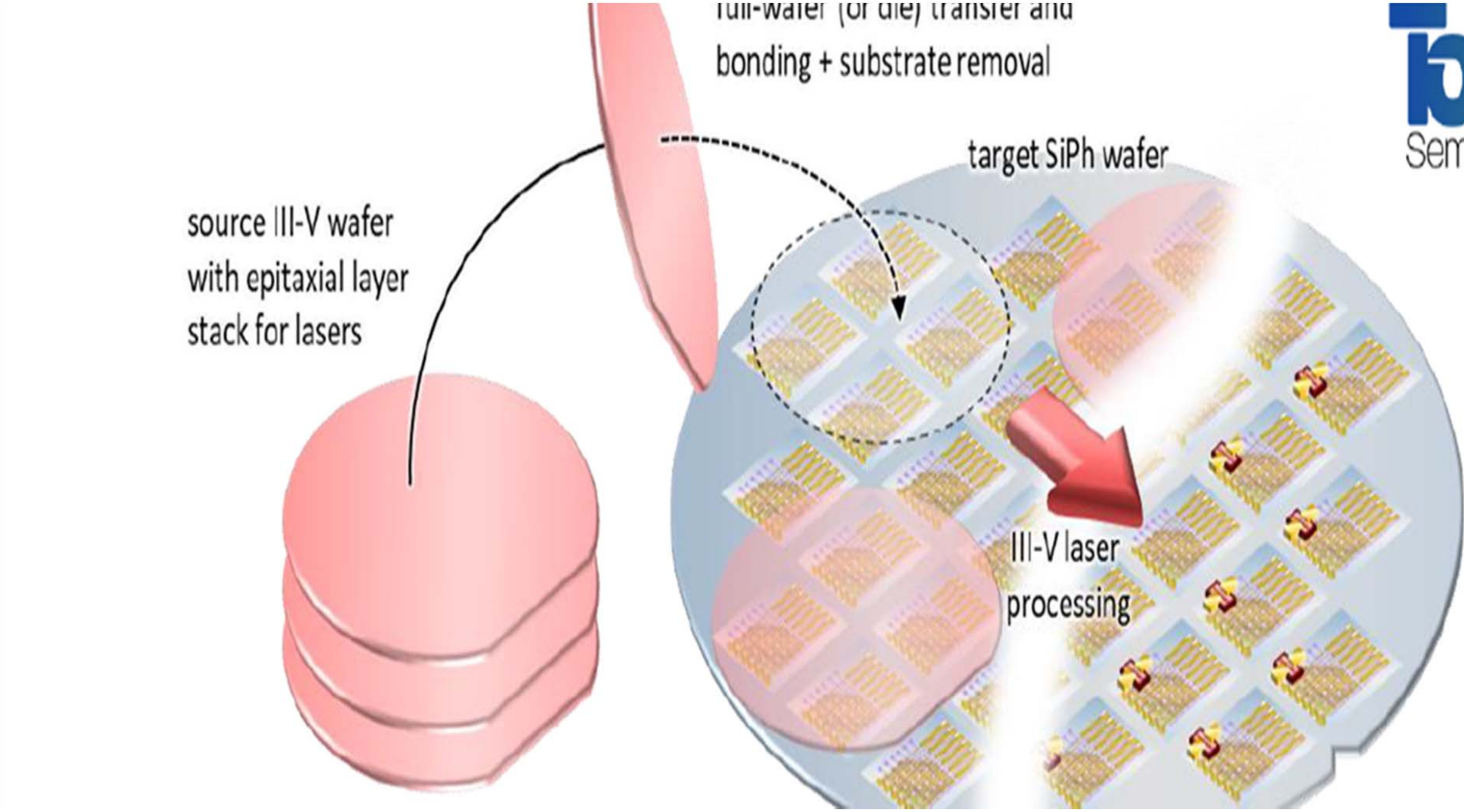




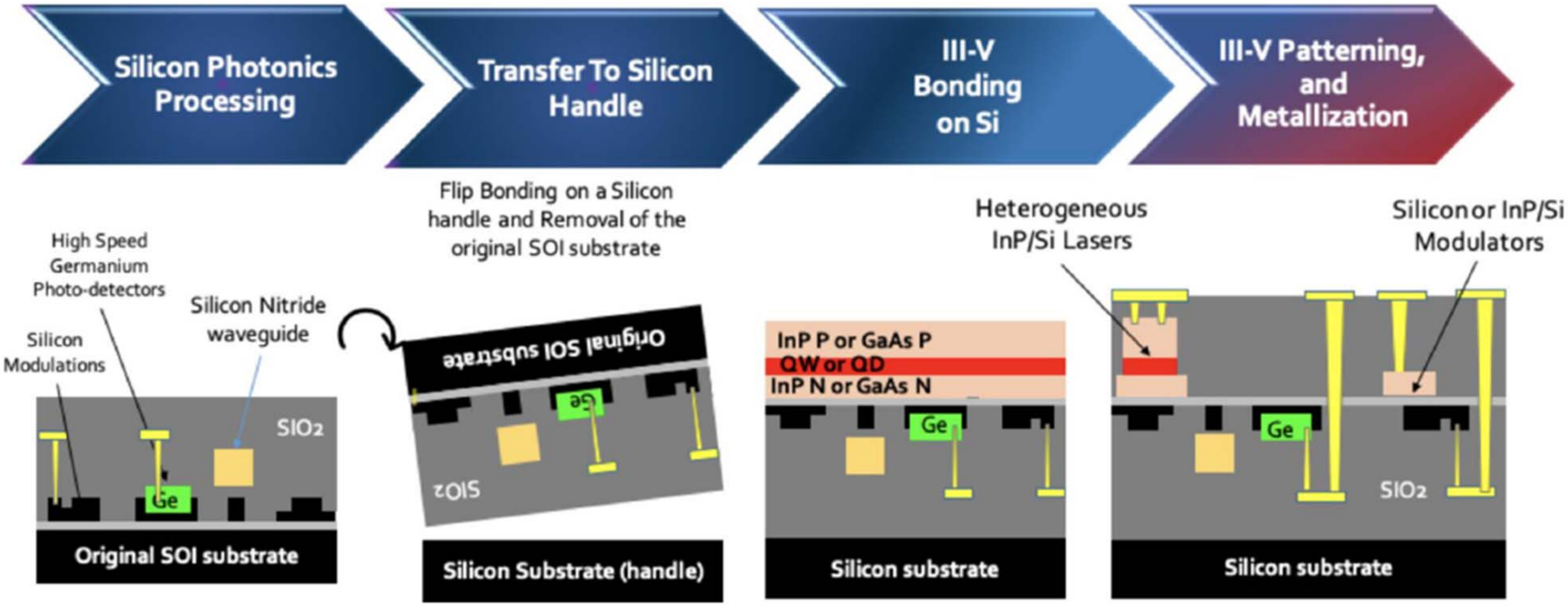
- ❑ High accuracy flip-chip laser attach through precise mechanical stops and optical alignment features

- ✓ Post fab processing to form wiring layers within the cavity and provide solder connections
- ✓ Passive *z*-alignment and seating of laser using high-precision mechanical stops inside the cavity of the PIC
- ✓ High precision bonding process for sub-micron alignment in *x* and *y* directions via optical alignment features

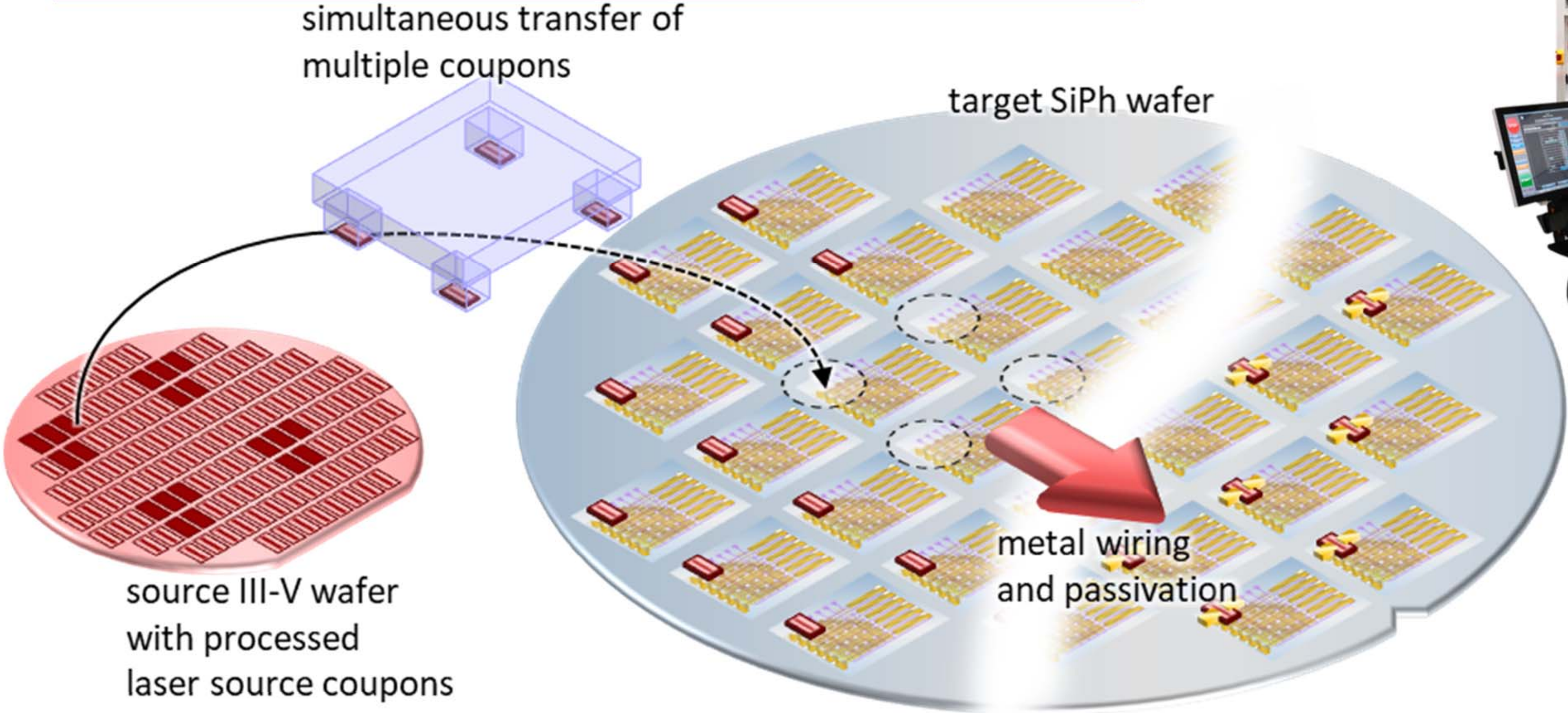
Light source integration with SiPh:
III-V/Si (die-to-) wafer bonding



Light source integration with SiPh:
Back-side III-V integration



Micro-transfer printing (MTP)



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Combines advantages of flip-chip & die-to-wafer bonding

Light source integration with SiPh:
Micro-transfer-printed III-V on Si Devices

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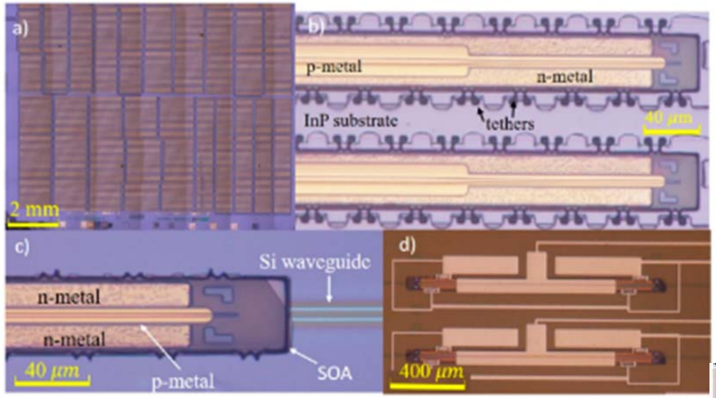
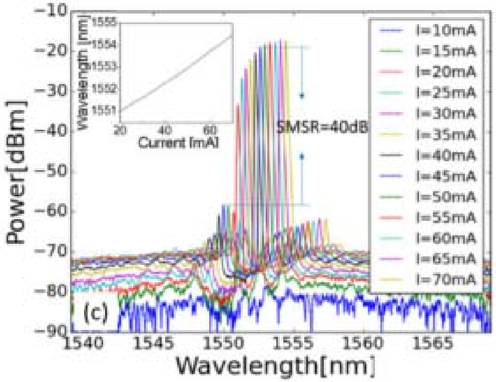
imec

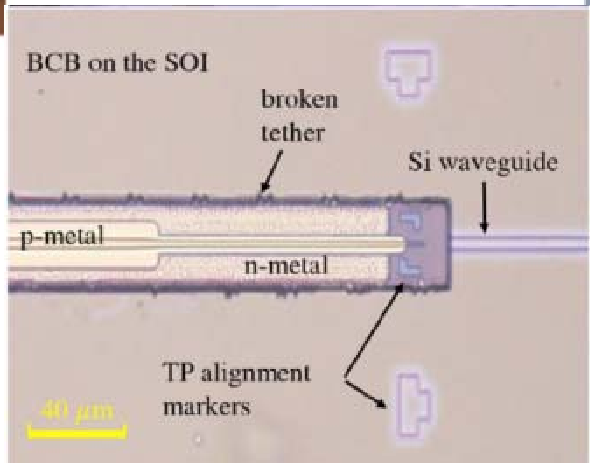
DFB lasers



Jing Zhang et al, Optics Express, 2018

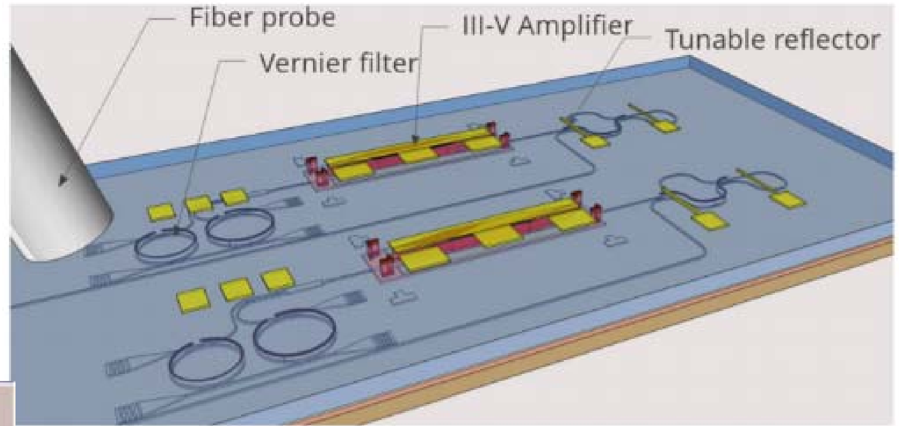


SOAs

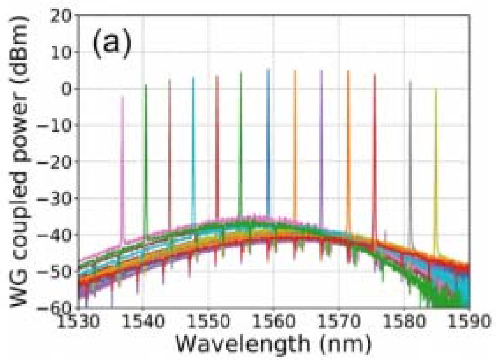


B. Haq et al, Lasers&Photonics Reviews, 2020

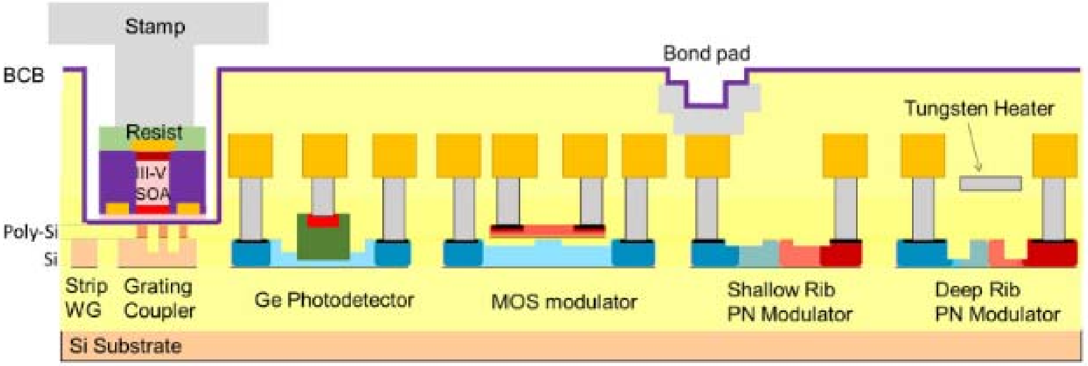
Widely tunable lasers

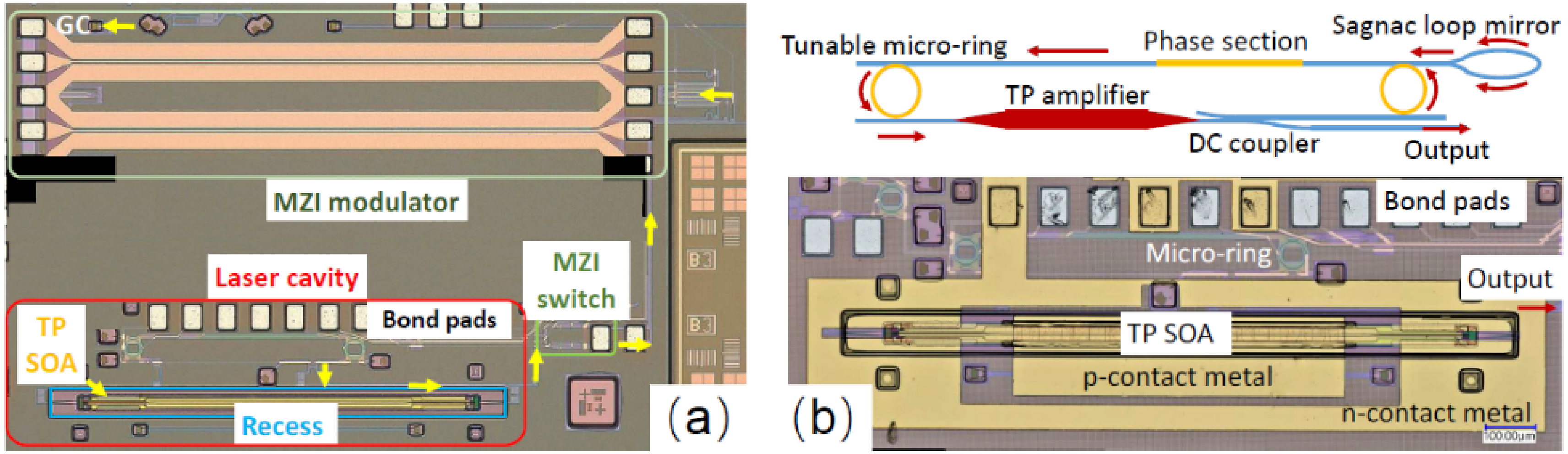


Jing Zhang et al, APL Photonics, 2019



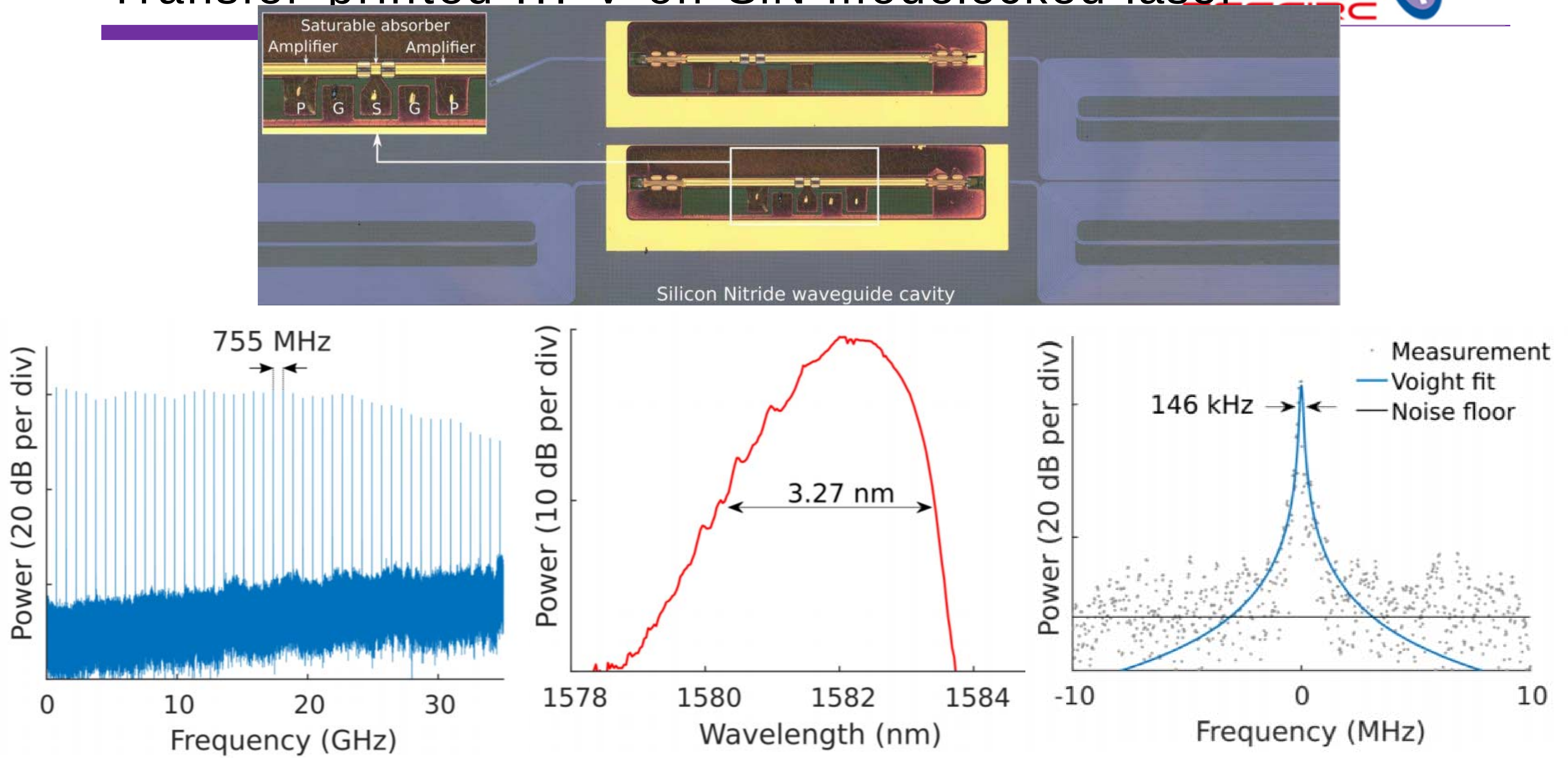
MTP Laser integration on iSiPP50G





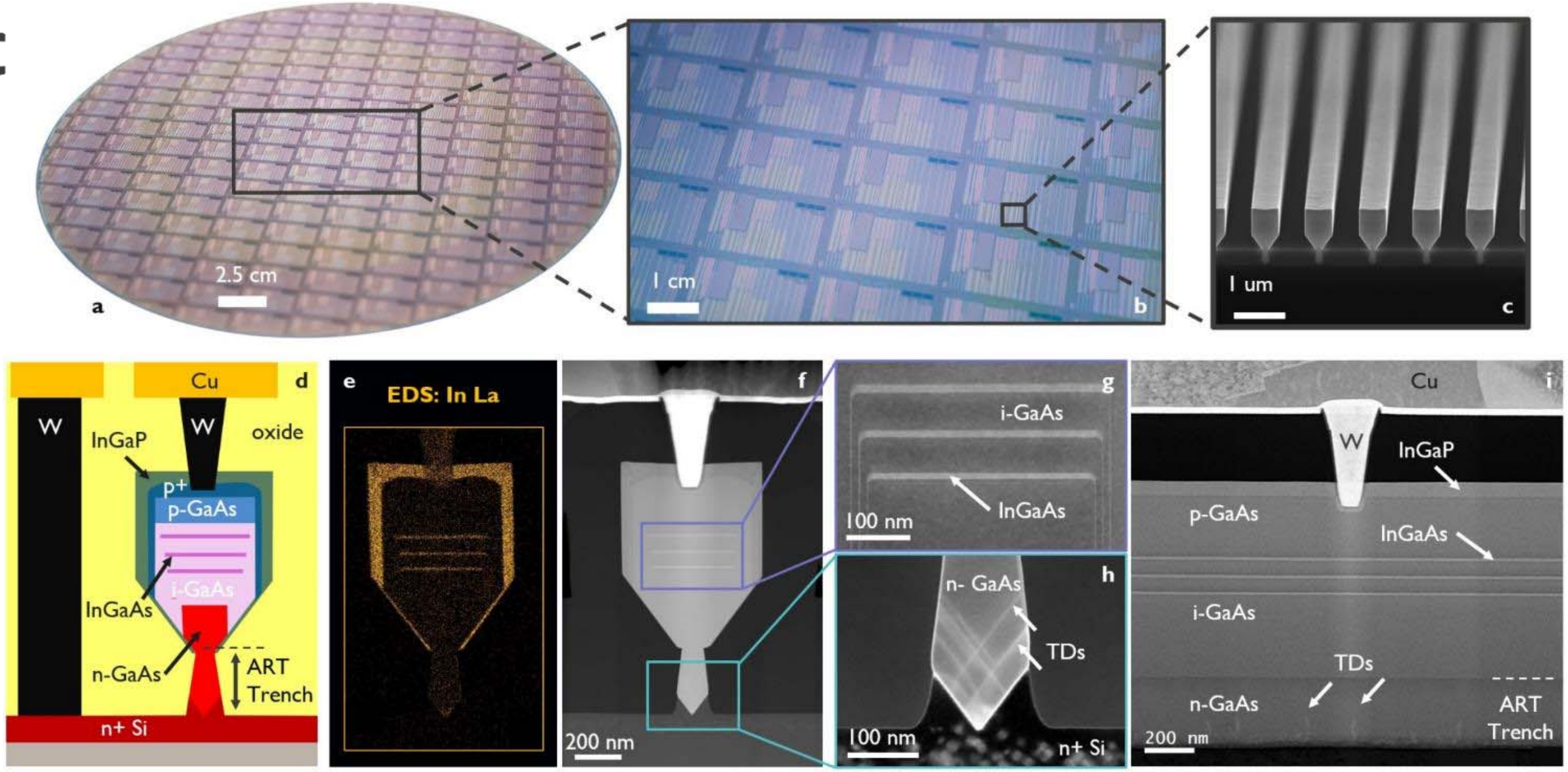
J. Zhang et al, OFC 2022

Transfer-printed III-V-on-SiN modelocked laser



S. Cuyvers et al., ECOC 2020

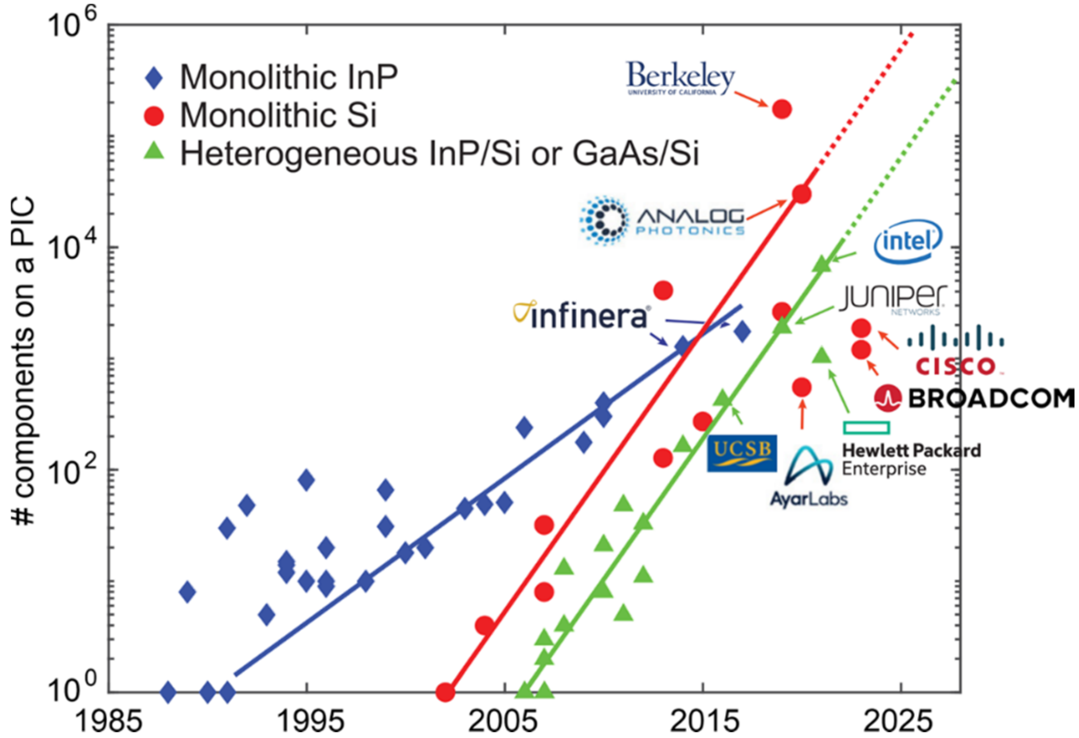
Light source integration with SiPh:
Hetero-epitaxial integration on a 300mm CMOS pilotline



GaAs nano-ridge laser diodes fully fabricated in a 300 mm CMOS pilot line:
https://doi.org/10.21203/rs.3.rs-3187756/v1

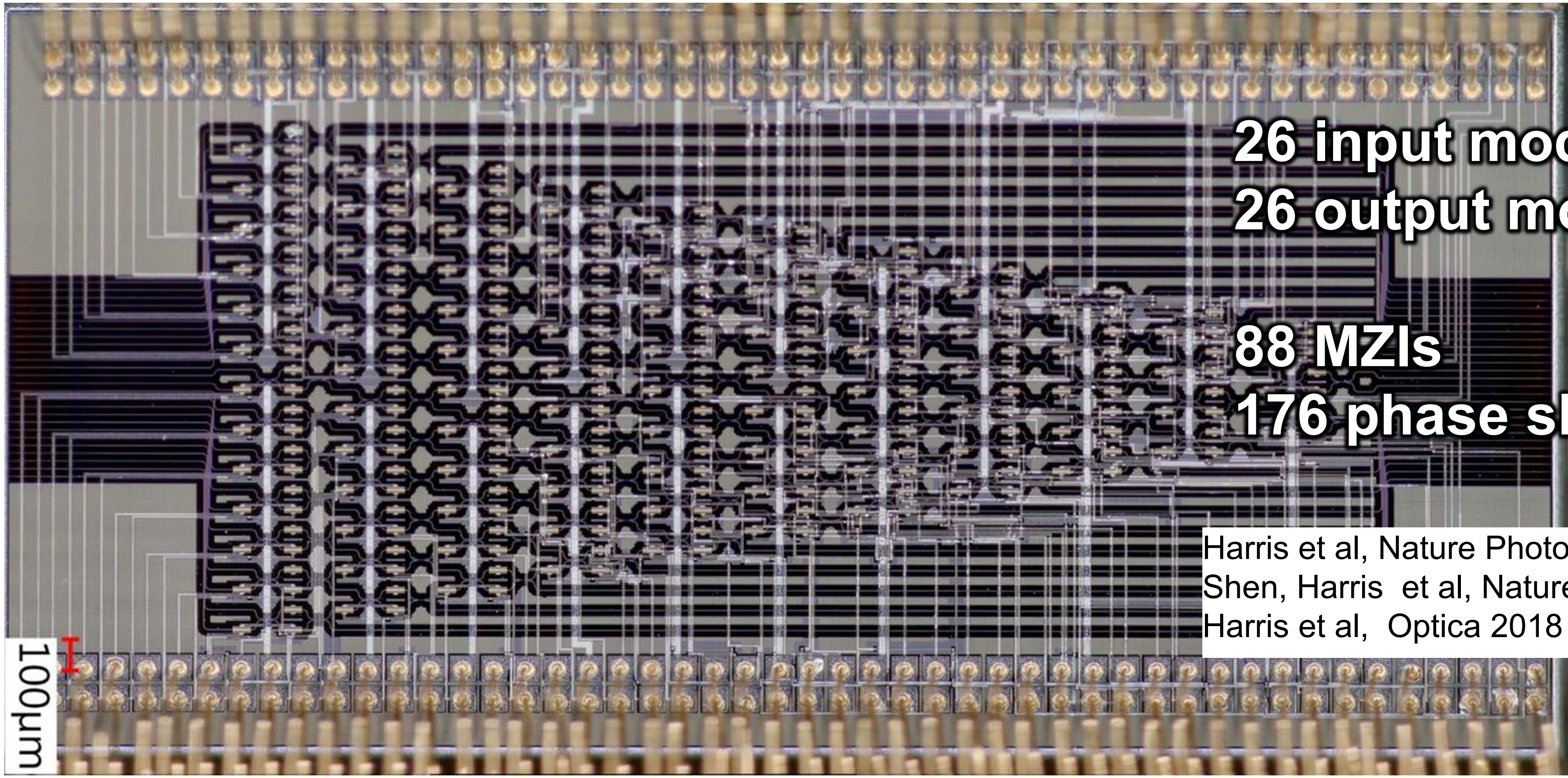
Trend 3: Large-scale photonic integration

- Growing order of integration; 10Ks of components
- photonics + electronic drivers
- different applications (AI, ML, LiDARs, Computing)
- Small chip volumes (compared to electronics)



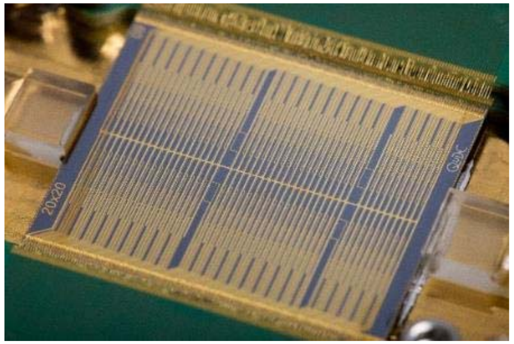
Margalit et al, APL, 2021

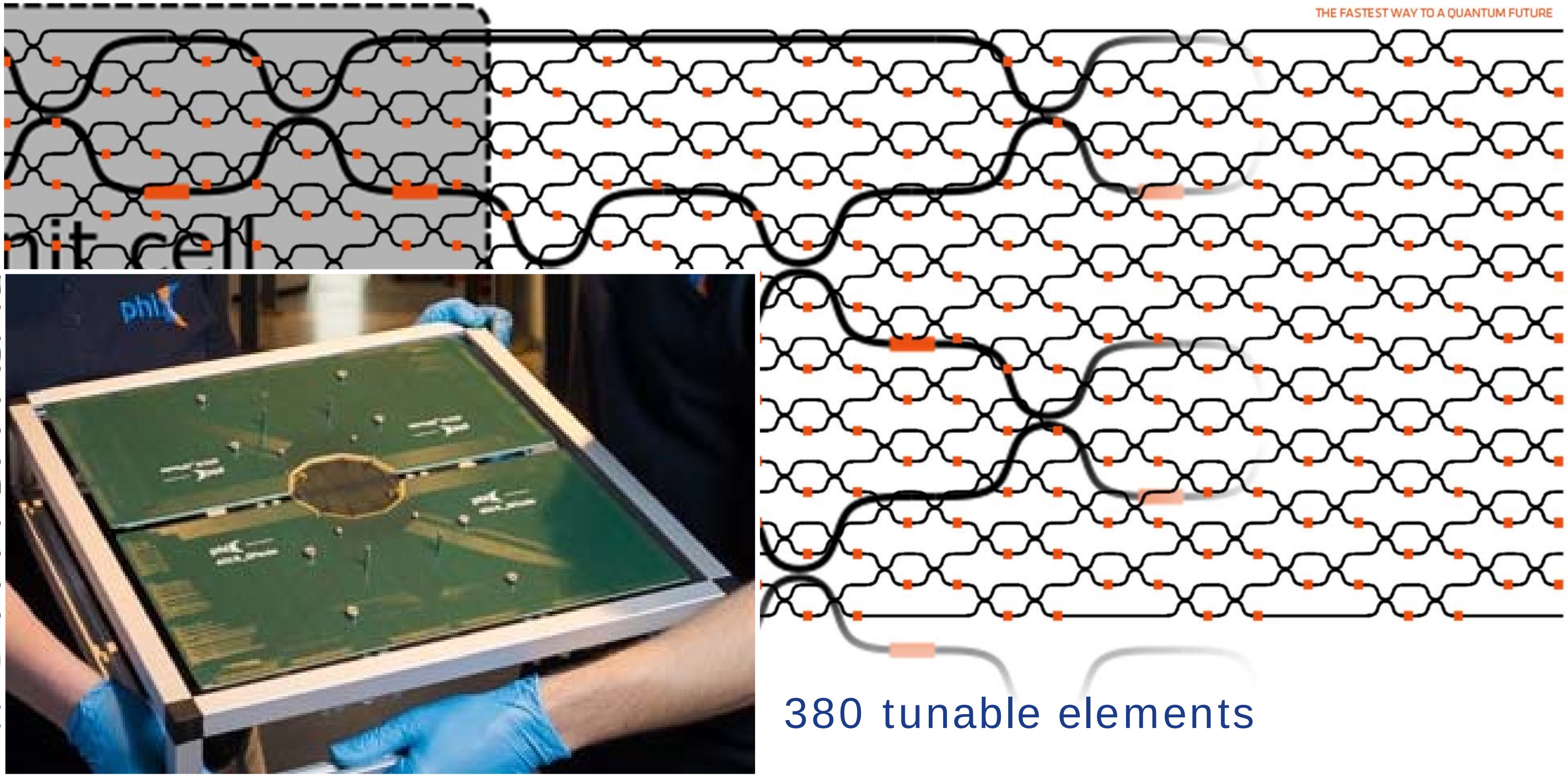
Large-scale photonic integration:
Powerful Silicon Photonic Neural Network



Harris et al, Nature Photonics 2017
Shen, Harris et al, Nature Photonics 2017
Harris et al, Optica 2018

Large-scale photonic integration:
Silicon Photonic Quantum Processor





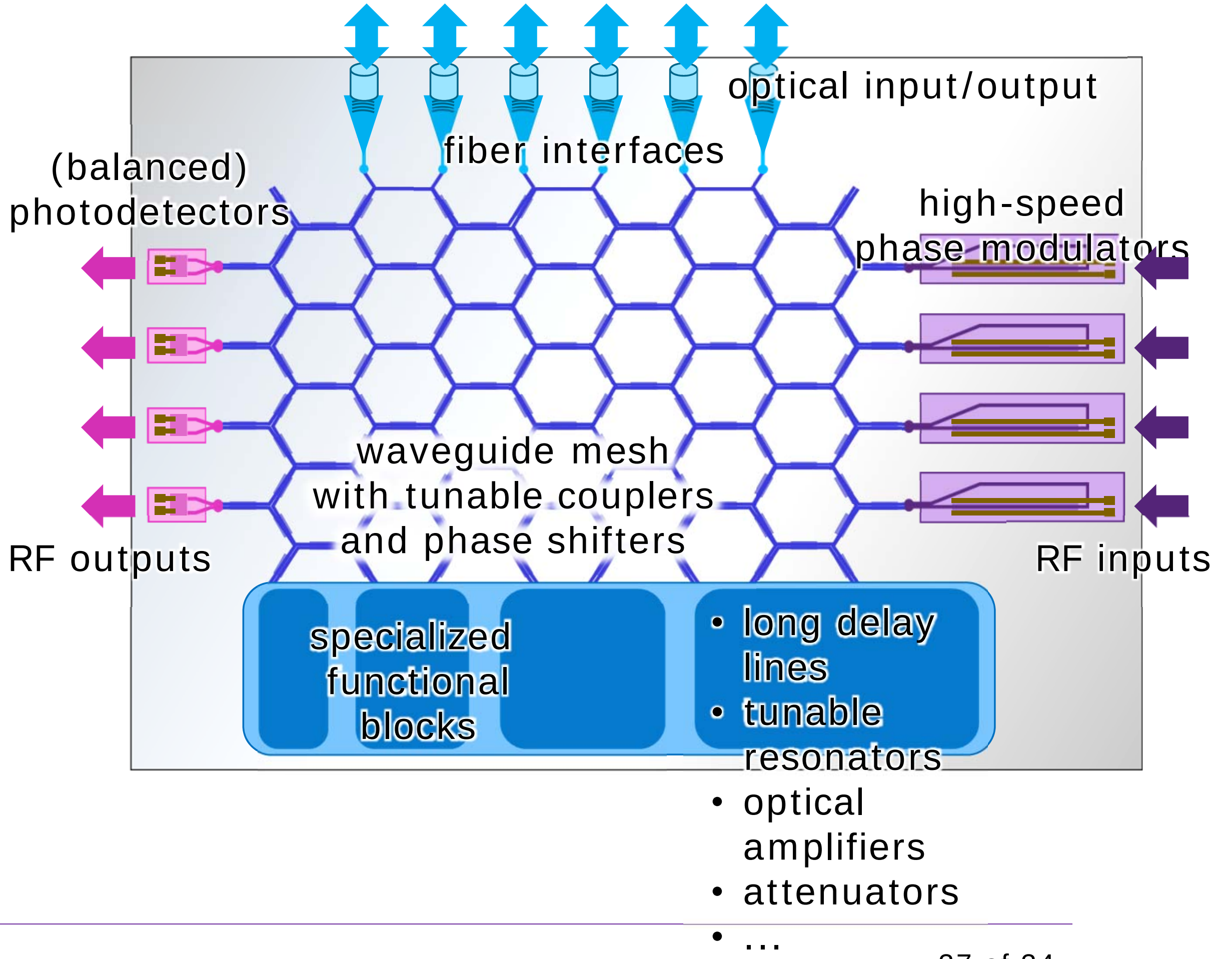
- 20 channel programmable forward-only circuit
- > 3000 wirebonds

380 tunable elements

Large-scale photonic integration:
Generic programmable processor

- Optical inputs and outputs
- RF inputs: modulators
- RF outputs: balanced PDs
- Specialized high performance blocks

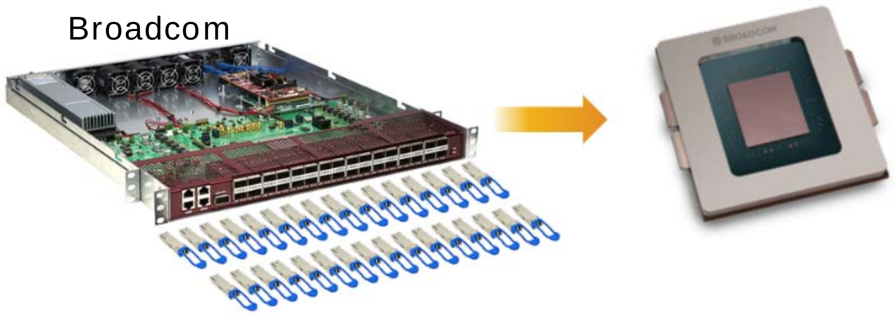
Connected by a programmable linear optical circuit

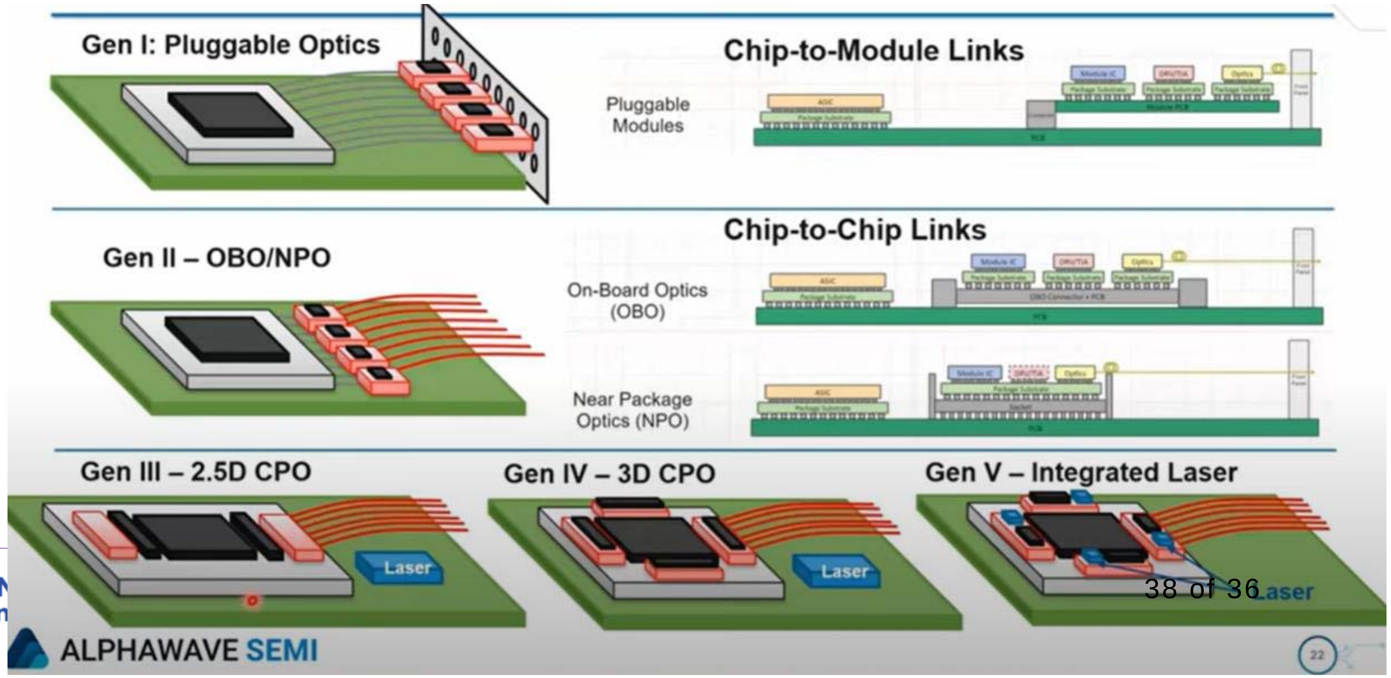


Trend 4: EIC-PIC Intimacy:

Co-packaged Optics

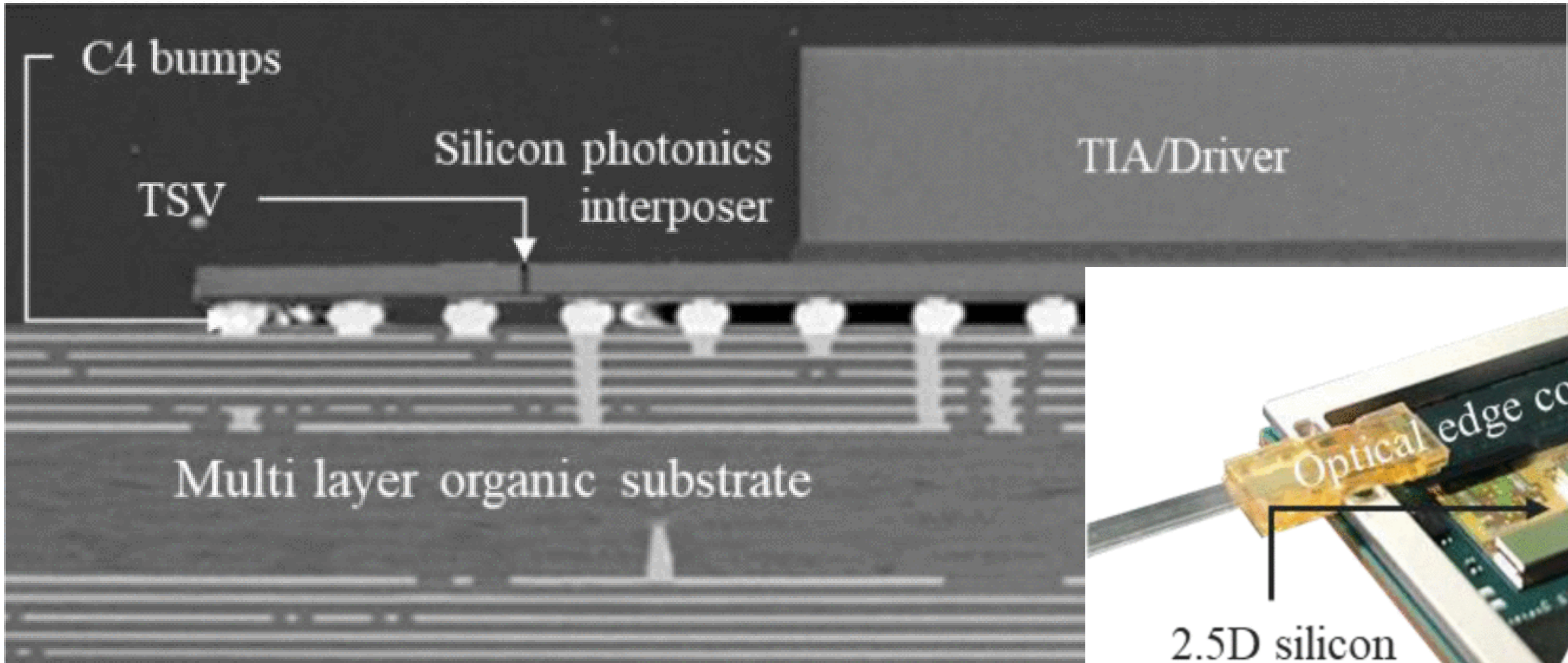
Broadcom



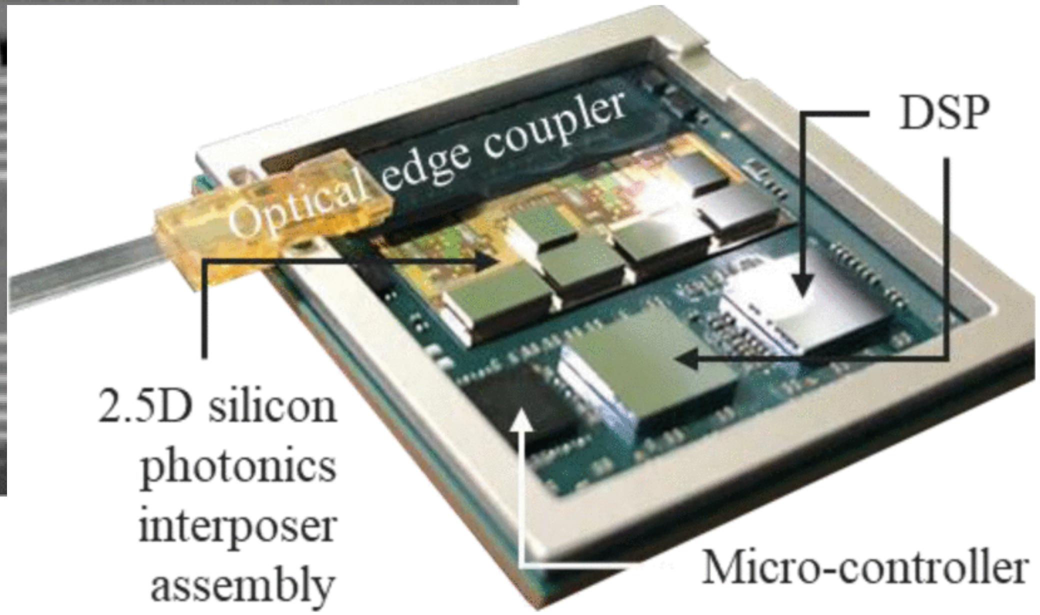


Challenges:

- **Power heat management in ASIC**
- **Complex assembly**
- **Difficult field service**
- **Restricts competition with concentrated R&D to a few companies**



DOI: 10.1109/JSTQE.2022.3214418



MARVELL™

Trend 4: EIC-PIC Intimacy:
Monolithic integration of EIC and PIC

OFC 2020 T3H

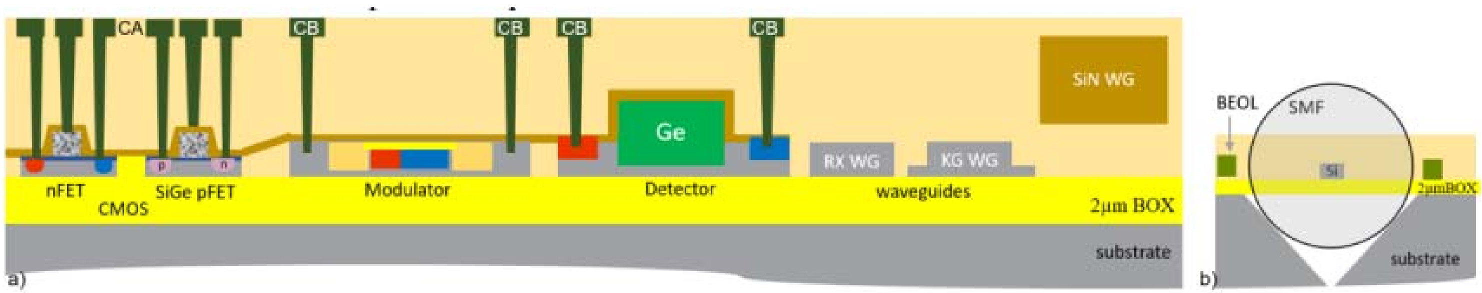


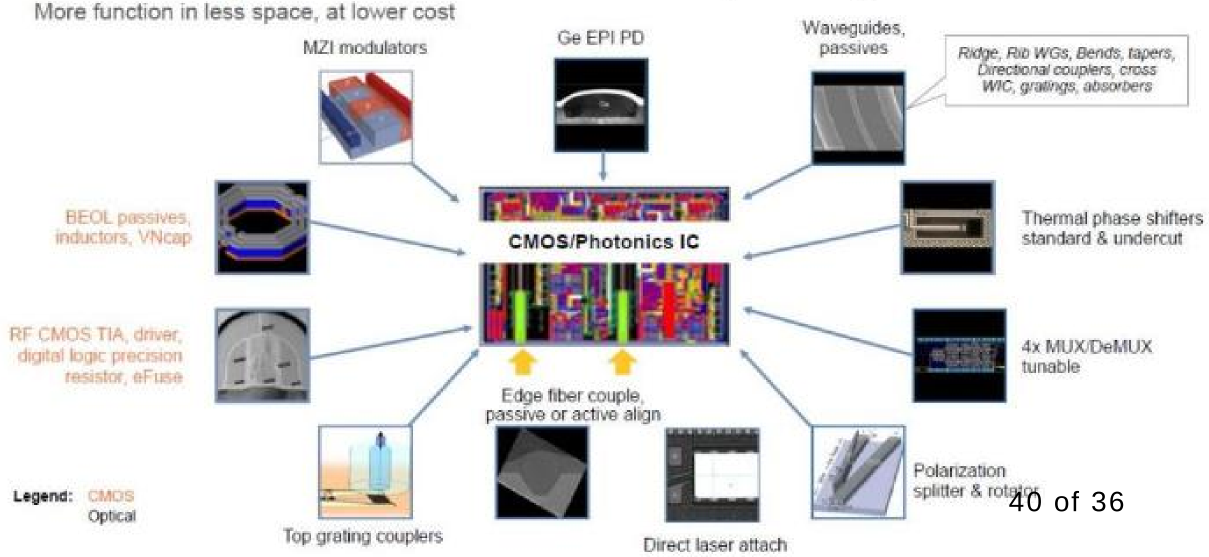
Fig. 1. (a) Cross-section showing front end and middle of line of 45CLO technology. (b) Cross-section diagram of the IOSMF with v-groove and the attached fiber.

GlobalFoundries™

Parameter	90WG Targets	45CLO O-Band
350 nm SOI (RX) waveguide loss	1.7 dB/cm	1.36 dB/cm
810 nm SOI multimode wg loss	0.8 dB/cm	0.59 dB/cm
SiN waveguide loss	n/a	0.35 dB/cm
SOI 10 µm bend loss	0.0095 dB/bend	0.007 dB/bend
WIC 50:50 coupler loss	0.09 dB/device	0.049 dB/device
PSR TE/TM output loss	0.19 /0.6 dB/device	0.22 / 0.4 dB/device
MZI 3dB BW (-2 V DV)	35 GHz	35 GHz
GePD (EPI 0.7 µm)	>0.9 A/W	0.9 A/W
GePD 3dB BW (EPI 0.7 µm)	39 GHz	50 Ghz
GePD Idark (EPI 0.7 µm)	< 40 nA	<40 nA
IOSMF Loss TE/TM (ORL)	-0.9/-1.5 (-30) dB	-0.8/-1.5 (-30) dB

The next step: GF SiPh monolithic electro-optic integration

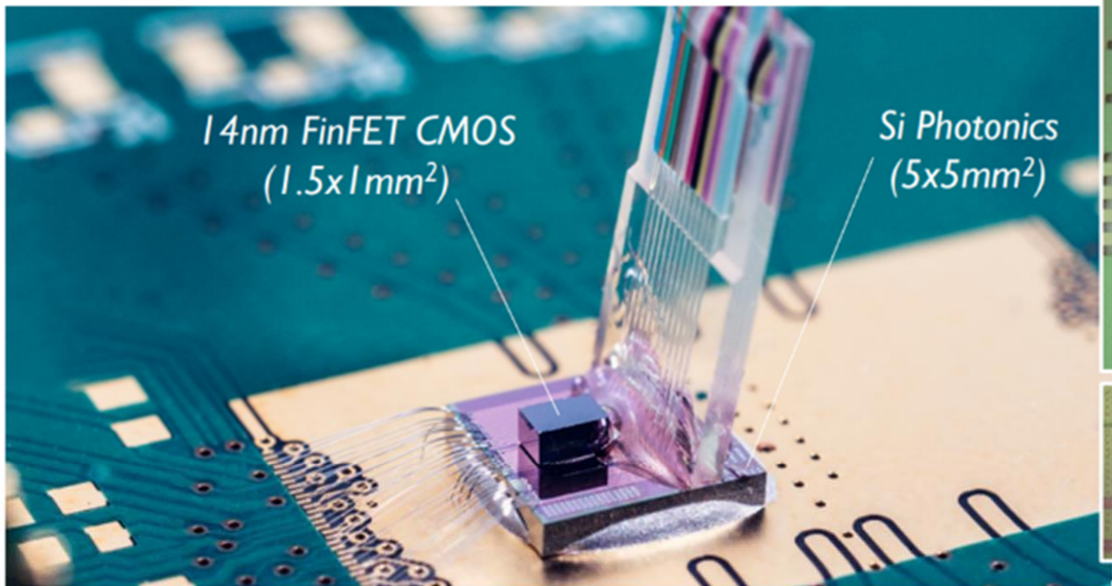
More function in less space, at lower cost



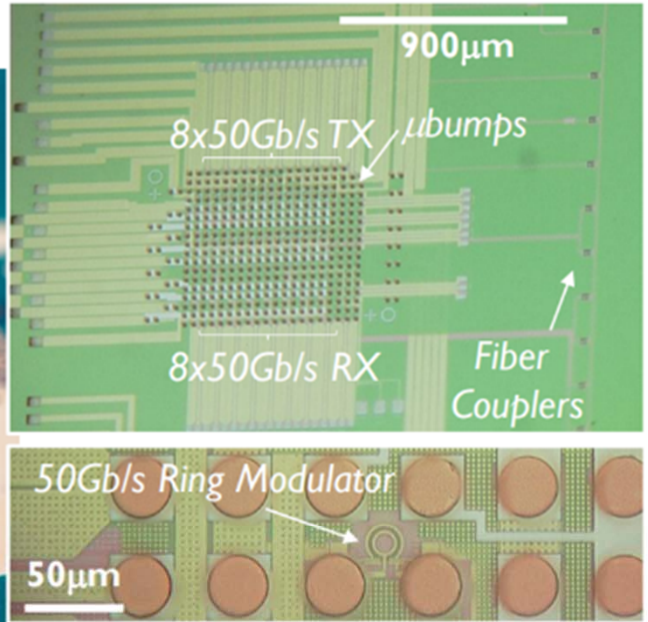
Trend 4: EIC-PIC Intimacy:
Hybrid Integration

Ultra-Dense Hybrid Integration with FinFET CMOS

8x50Gb/s CMOS-Si Photonics Transceiver Prototype



- 50Gb/s Si Modulators and Ge Photodetectors
- High-Speed Drivers and TIAs in 14nm FinFET CMOS
- Hybrid Flip-Chip integration with 50μm pitch μbumps (>1Tb/s/mm²)



2018 Symposia on VLSI Technology and Circuits:
"Hybrid 14 nm FinFET - Silicon Photonics Technology for Low-Power Tb/s/mm² Optical I/O," M. Rakowski et al., T20-5

Summary

- Silicon photonics is rapidly gaining industrial maturity
- Manufacturing mostly concentrated in US and Asia; Europe strong in R&D and provision of tools and services
- Early efforts to build manufacturing capacity in Europe
- Market dominated by transceivers for telecom and datacom
- Enormous potential for diverse markets; but not yet reality
- Heterogeneous integration is key to satisfy future needs