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FACULTEIT INGENIEURSWETENSCHAPPEN EN ARCHITECTUUR
DEPARTMENT OF INFORMATION TECHNOLOGY
PHOTONICS RESEARCH GROUP

THE NEED FOR HYBRID INTEGRATION OF NEW MATERIALS IN SILICON PHOTONICS

Dries Van Thourhout, LIMNI spring school, April 2023

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PHOTONICS RESEARCH GROUP

Research Group of Ghent University
- Faculty of Engineering and Architecture
- Department of Information Technology (INTEC)
- Associated laboratory of IMEC
- Member of the Center for Nano- & Biophotonics (NB photonics)

Technology Research
- Photonic Integration: Systems on a chip
- On silicon: "Silicon Photonics"
- Enhanced with new materials: III-V, ferro-electrics, graphene, …

Applications
- High-speed telecom and datacom
- Sensing for life sciences: visible to Mid-IR
- Optical information processing

9 Professors
16 postdocs
50 PhD students
10 support staff

20+ nationalities
6 ERC grants
4 spin-off companies
50 journal papers/year
Class 100 clean rooms

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WHAT IS SILICON PHOTONICS ?

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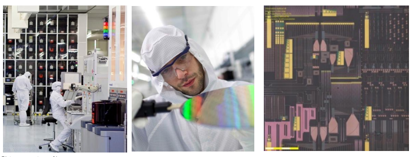
WHAT IS SILICON PHOTONICS?

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



Pictures, courtesy of imec

Enabling complex optical functionality on a compact chip at low cost

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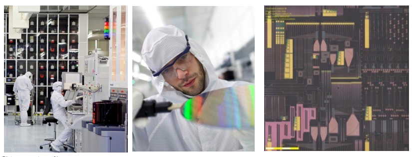
WHAT IS SILICON PHOTONICS?

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



Pictures, courtesy of imec

Enabling complex optical functionality on a compact chip at low cost

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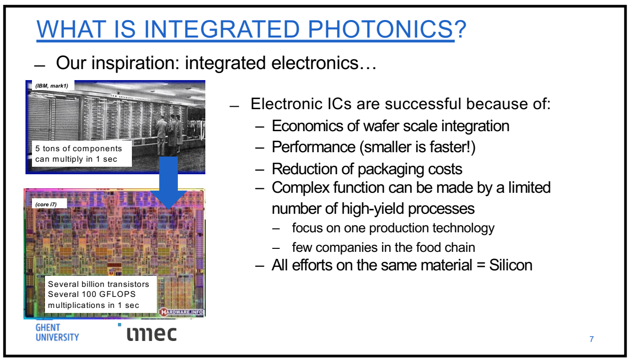
WHAT IS INTEGRATED PHOTONICS?
– Our inspiration: integrated electronics…
5 tons of components can multiply in 1 sec
Several billion transistors
Several 100 GFLOPS multiplications in 1 sec
– Electronic ICs are successful because of:
– Economics of wafer scale integration
– Performance (smaller is faster!)
– Reduction of packaging costs
– Complex function can be made by a limited number of high-yield processes
– focus on one production technology
– few companies in the food chain
– All efforts on the same material = Silicon
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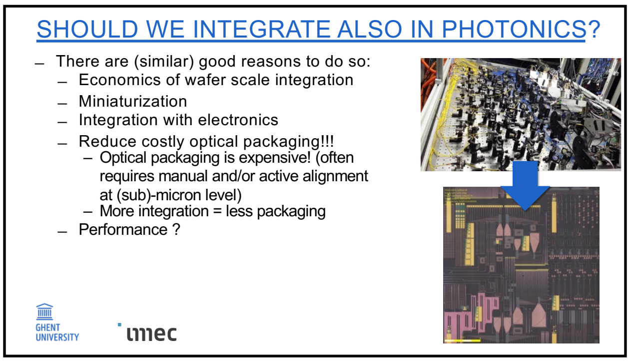
SHOULD WE INTEGRATE ALSO IN PHOTONICS?
– There are (similar) good reasons to do so:
– Economics of wafer scale integration
– Miniaturization
– Integration with electronics
– Reduce costly optical packaging!!!
– Optical packaging is expensive! (often requires manual and/or active alignment at (sub)-micron level)
– More integration = less packaging
– Performance ?
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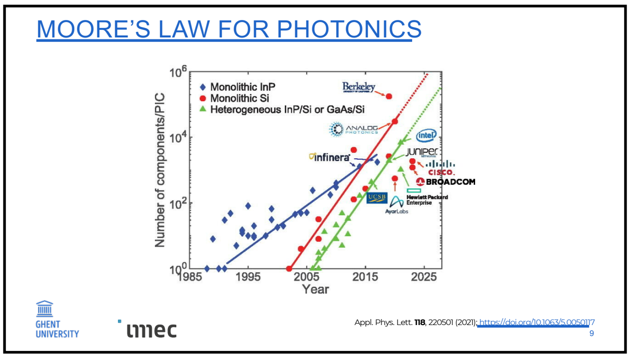
MOORE'S LAW FOR PHOTONICS
Monolithic InP
Monolithic Si
Heterogeneous InP/Si or GaAs/Si
Number of components/PIC
Year
1985
1995
2005
2015
2025
infinera
Berkeley
BROADCOM
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imec
Appl. Phys. Lett. 118, 220501 (2021); https://doi.org/10.1063/5.0050117
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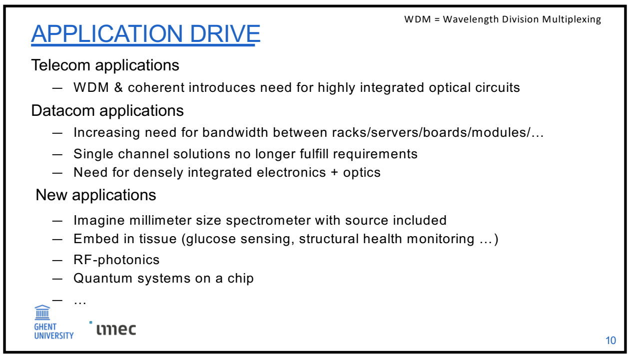
WDM = Wavelength Division Multiplexing
APPLICATION DRIVE
Telecom applications
– WDM & coherent introduces need for highly integrated optical circuits
Datacom applications
– Increasing need for bandwidth between racks/servers/boards/modules/…
– Single channel solutions no longer fulfill requirements
– Need for densely integrated electronics + optics
New applications
– Imagine millimeter size spectrometer with source included
– Embed in tissue (glucose sensing, structural health monitoring …)
– RF-photonics
– Quantum systems on a chip
– …
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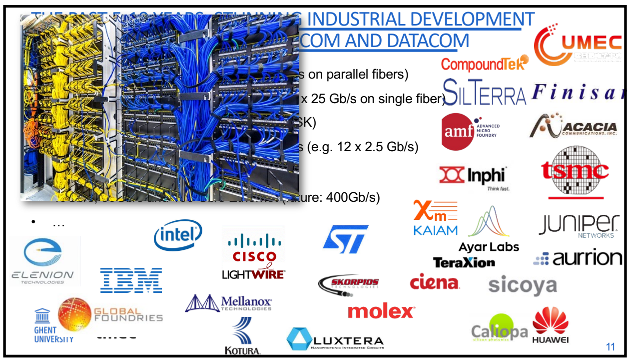
INDUSTRIAL DEVELOPMENT
COM AND DATACOM
s on parallel fibers)
x 25 Gb/s on single fiber)
SK)
s (e.g. 12 x 2.5 Gb/s)
ure: 400Gb/s)
• …
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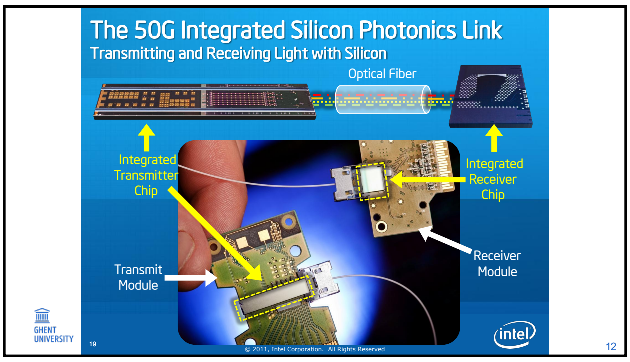
The 50G Integrated Silicon Photonics Link
Transmitting and Receiving Light with Silicon
Optical Fiber
Integrated Transmitter Chip
Integrated Receiver Chip
Transmit Module
Receiver Module
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© 2011, Intel Corporation. All Rights Reserved
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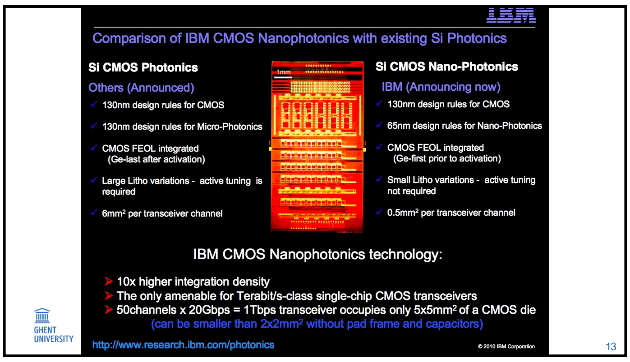

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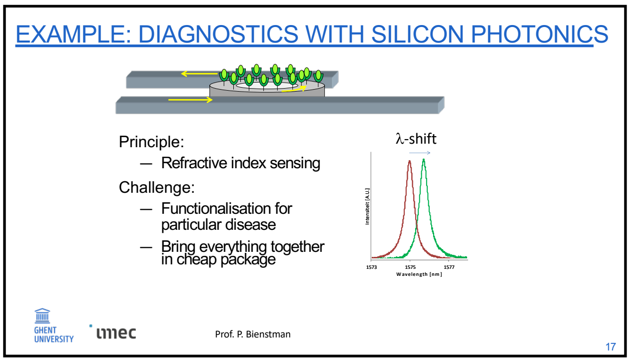

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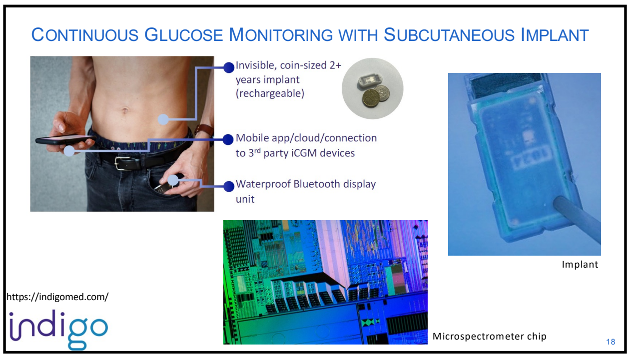

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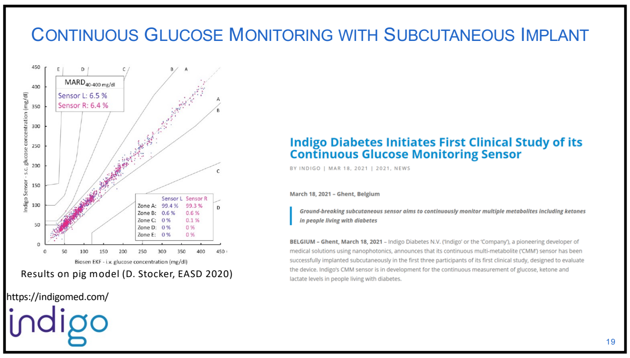

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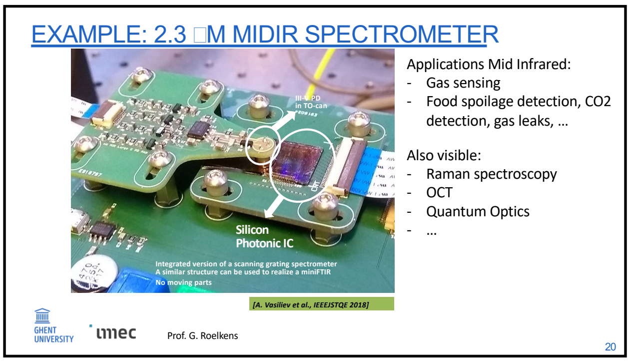

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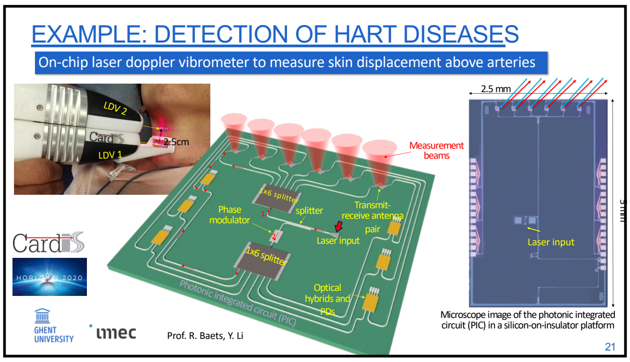

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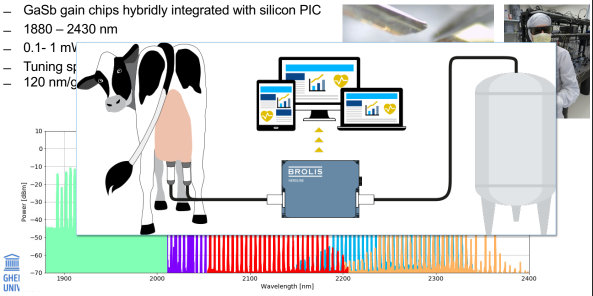
BROLIS: GaSb TUNABLE LASER TECHNOLOGY WITH SILICON PIC

- GaSb gain chips hybridly integrated with silicon PIC
- 1880 – 2430 nm
- 0.1- 1 mW
- Tuning sp
- 120 nm/g



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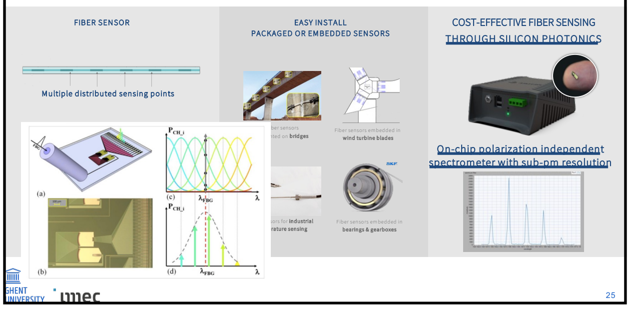
SENTEA FBG INTERROGATOR (UGENT/IMEC SPINOFF)



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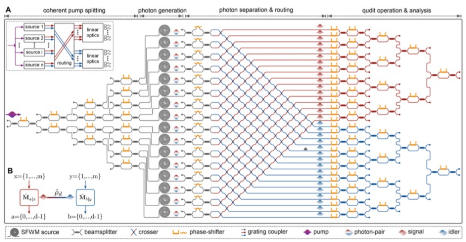
NOVEL APPLICATIONS

Quantum processor (Glasgow)



J. Wang et al., Science (2018)

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PHOTONICS ⟷ ELECTRONICS

PHOTONICS	ELECTRONICS
Many building blocks	Single building block
— Laser, Modulator, Detector Filter	— Transistor
Many technologies and materials	Single material
— Laser : III-V semiconductors	— Silicon
— Modulator : LiNbO3	
— Filter : Glass, Polymers	
High processing requirements	Relaxed processing requirements
— Analog devices	— Digital devices
— Low Yield	— High yield
No economies of scale advantage	Massive economies of scale
Many faction pushing own solution	Common ITRS roadmap

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CAN "SILICON PHOTONICS" SOLVE THIS BOTTLENECK ?

Single material platform
- Silicon transparent at telecom wavelengths
- Very high contrast : compact circuits
- Detectors (germanium), Modulators (pn-junction)

Reuse installed equipment base
- Use best equipment available
- But no capital expense …

Some standardization ongoing
- 200nm and 300nm layer thickness seem popular
- Platform building ongoing

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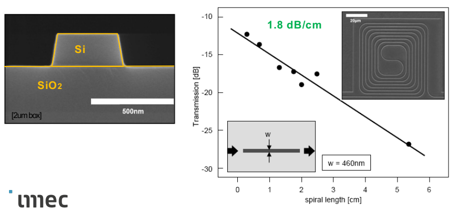
STRAIGHT WAVEGUIDE

Bogaerts e.a. , JSTQE 16, 33-44 (2010)

- Our standard waveguide: 450nm x 220nm Si
- Fabricated using 193nm DUV lithography
- In standard pilot line, on 200mm or 300mm wafer
- Starting from SOI or amorphous silicon



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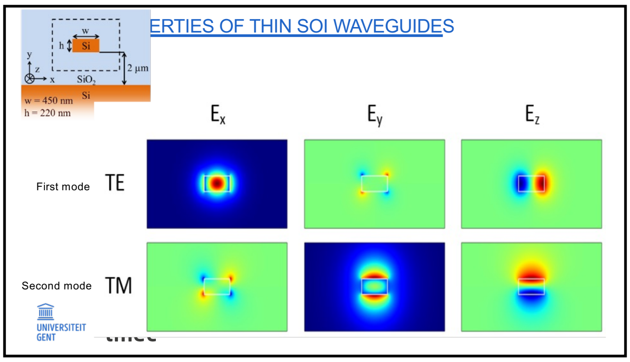

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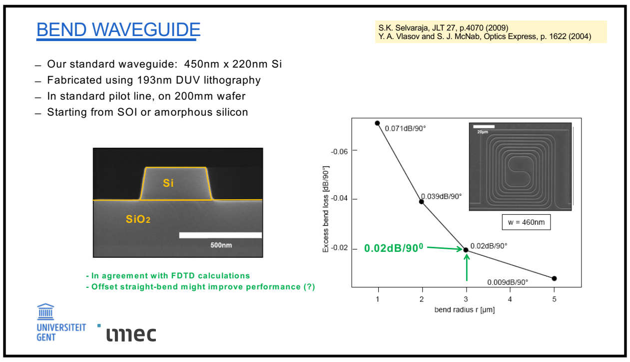

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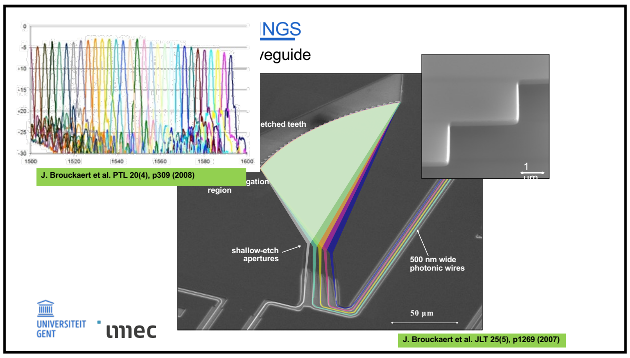

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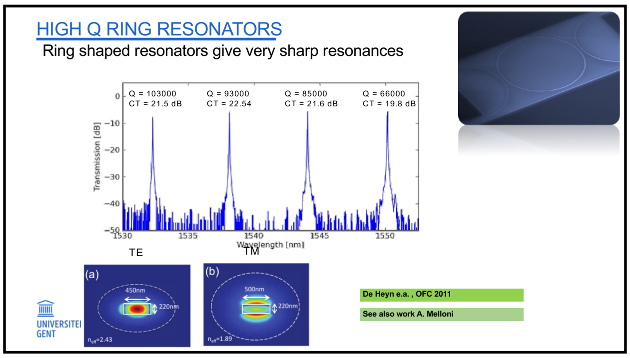

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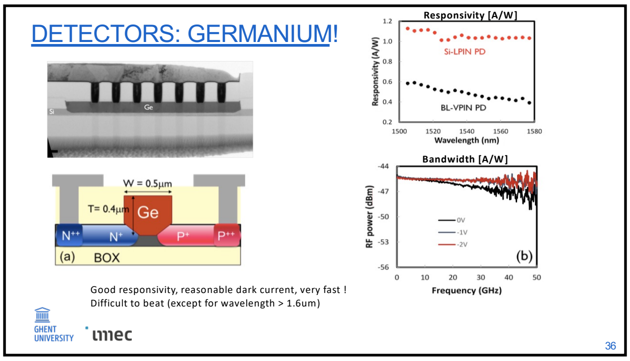

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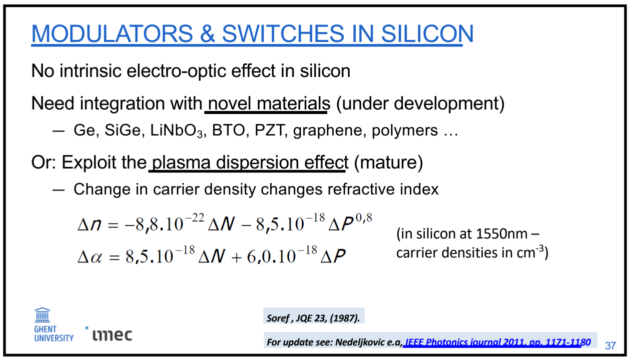

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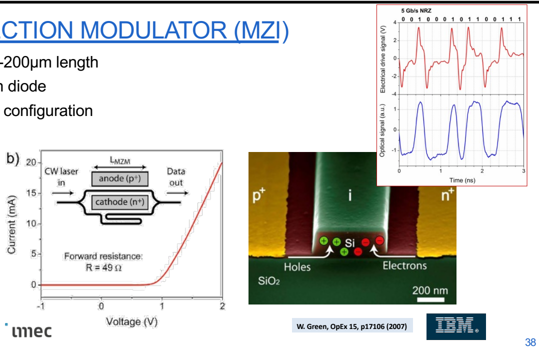
INJECTION MODULATOR (MZI)

- 100-200µm length
- p-i-n diode
- MZI configuration



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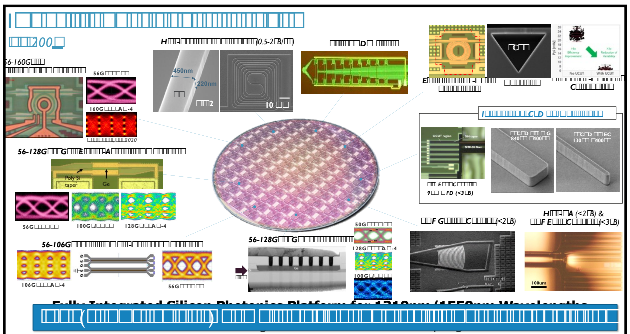

imec 56Gb/s+ (Ge)Si Modulators and Ge(Si) Photodetectors confidential

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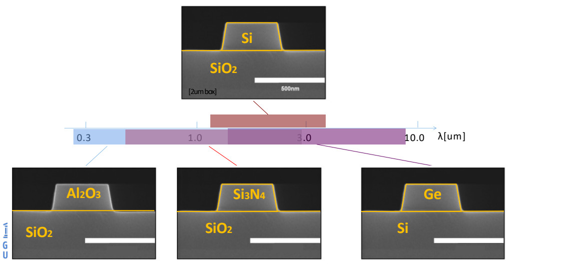
SILICON PHOTONICS: EXTENDING THE WAVELENGTH RANGE

– … without leaving the CMOS fab



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WHAT ARE REMAINING CHALLENGES ?

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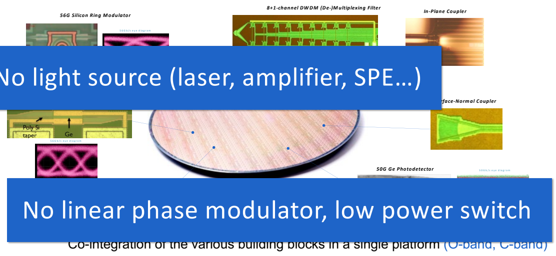
IMEC SILICON PHOTONICS PLATFORM

FULLY INTEGRATED 8X50G DWDM SI PHOTONICS TECHNOLOGY



No light source (laser, amplifier, SPE…)

No linear phase modulator, low power switch

Co-integration of the various building blocks in a single platform (O-band, C-band)

Today available on 200mm wafer size, coming soon on 300mm

95% compatible with CMOS130 in commercial foundries

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NEED FOR NOVEL MATERIALS

Silicon is great but:

- Indirect bandgap: no efficient light emission
- Cubic lattice: no second order non-linearities, no electro-optic effect

Hence need for integration with new materials:

- Direct bandgap **III-V semiconductors** for efficient light emission
- **Ferroelectrics** (PZT, BTO) for phase modulators and SHG
- **Graphene** and other **2D-materials** for intensity and phase modulators
- **Colloidal quantum dots** for light sources and single photon emitters
- **Liquid crystals** for switching
- …

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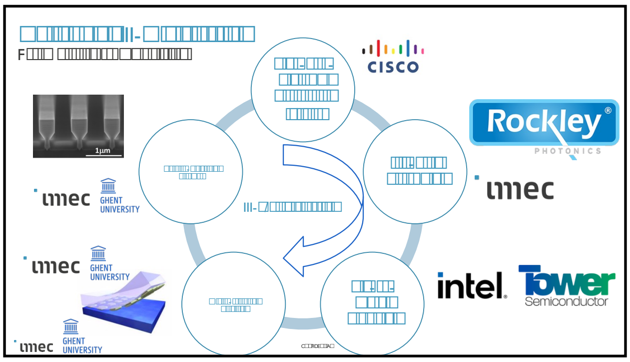

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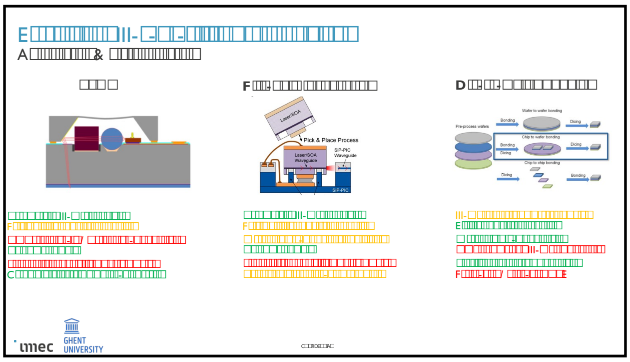

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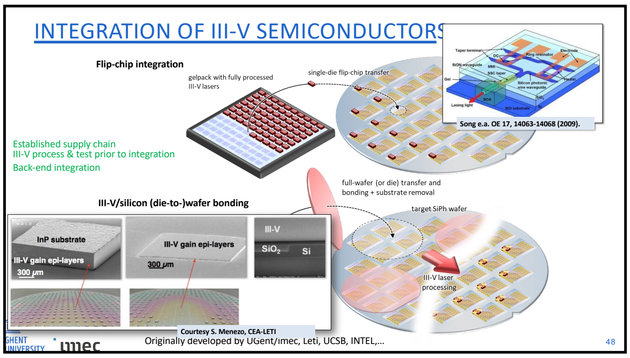

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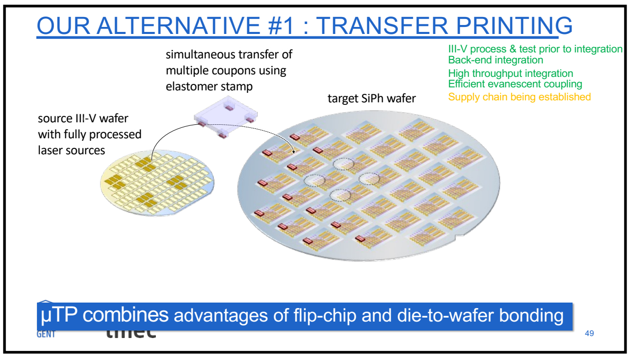

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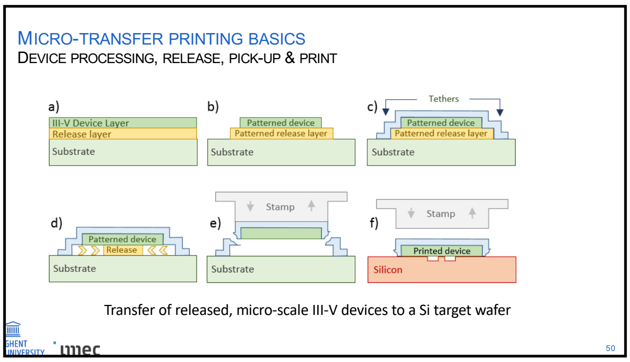

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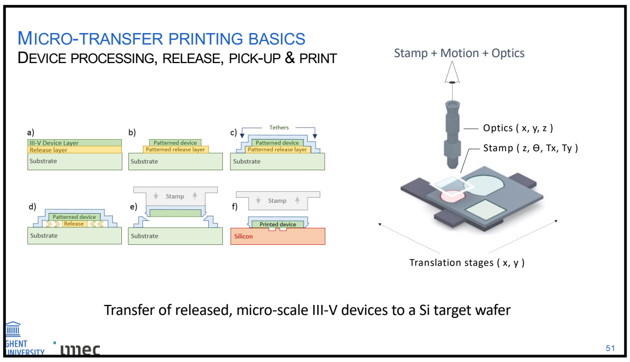

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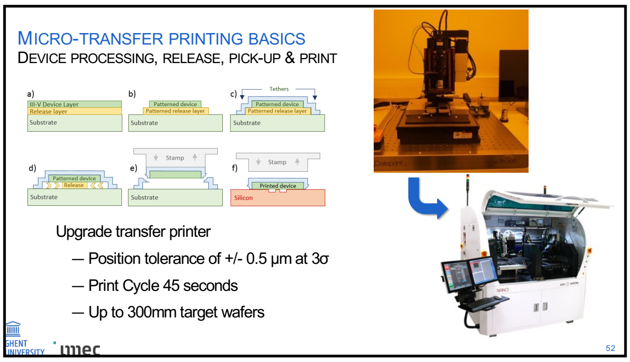

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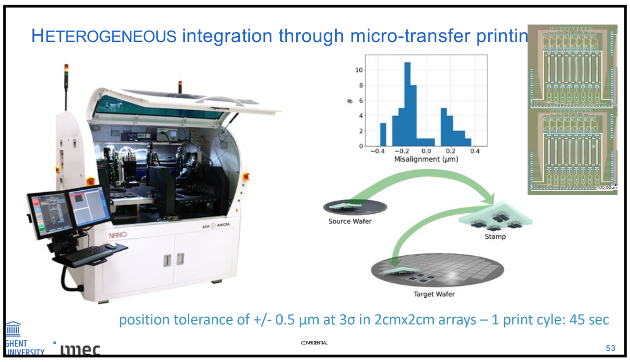

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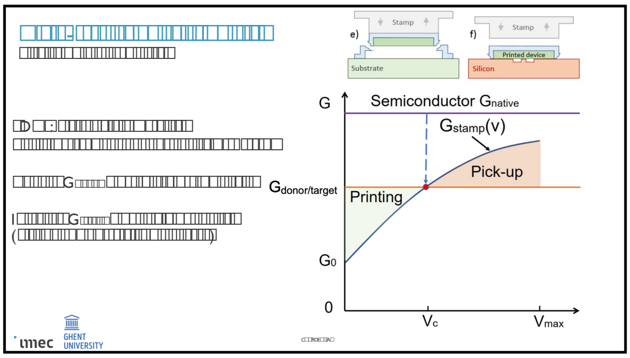

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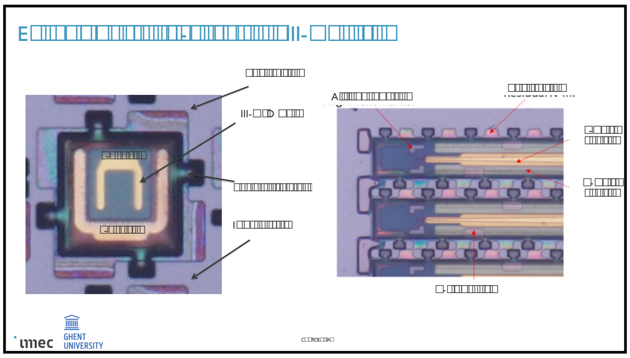

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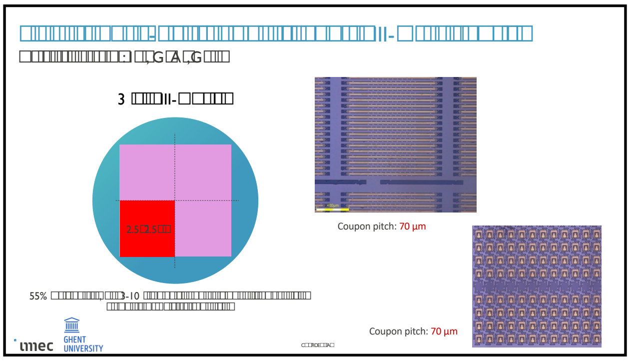

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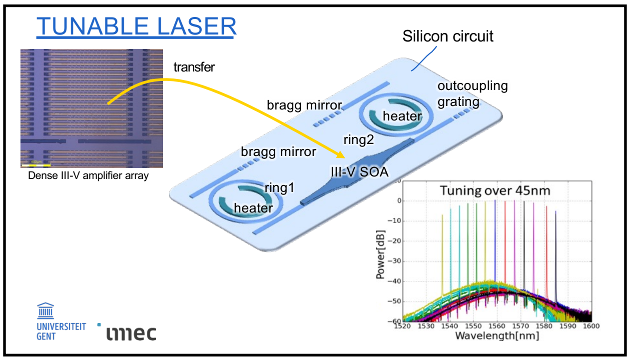

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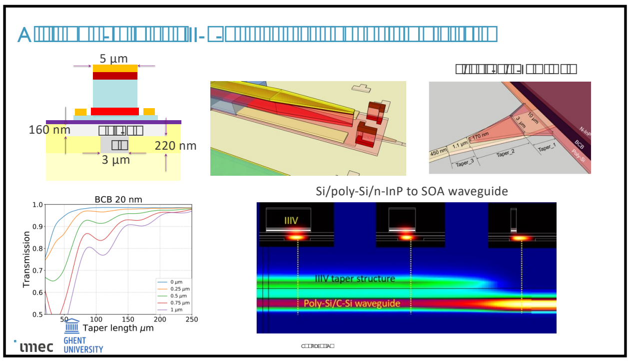

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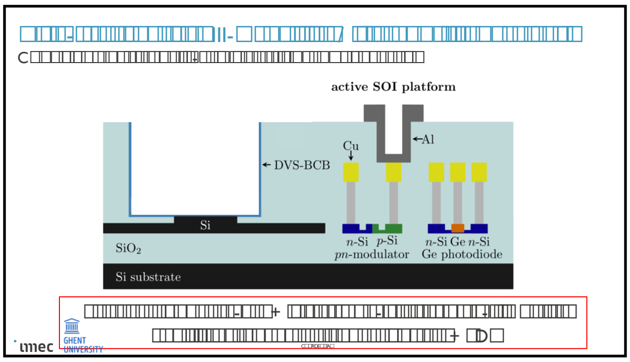

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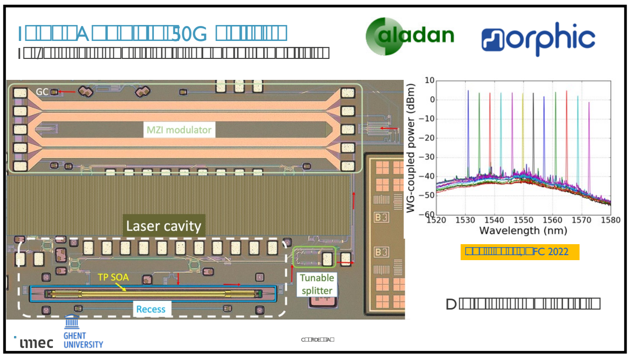

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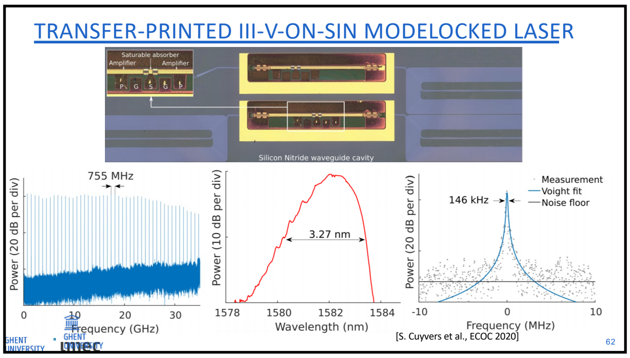

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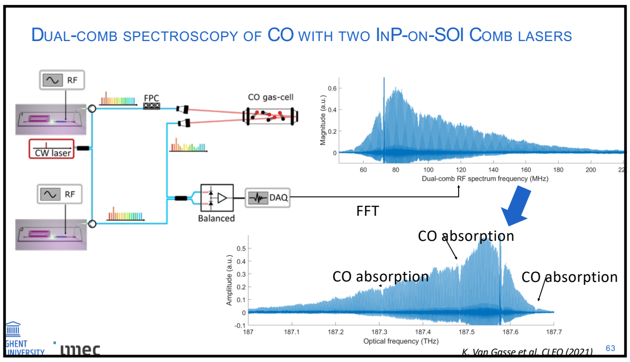

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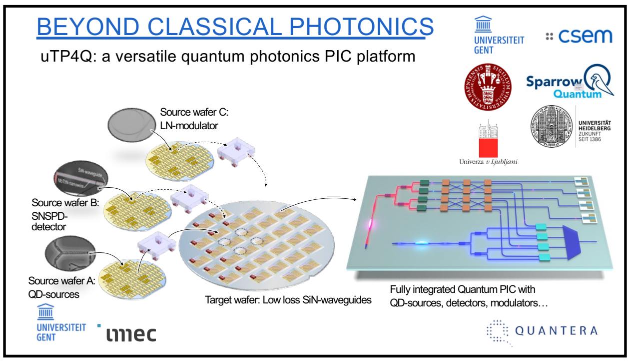

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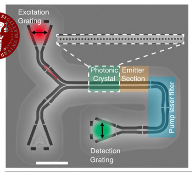

QD-single photon source demonstrated by NBI

- Record performance in terms of purity, indistinguishability and coupling efficiency to waveguide
- However: **high waveguide loss** hampers further scalability
- **Question**: can source be integrated on SiN-waveguide platform using mTP-technology ?
- **Challenge**: new material system (GaAs), thin membrane, sharp taper tips, alignment accuracy.

Midolo-group, Copenhagen

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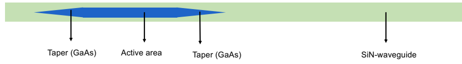
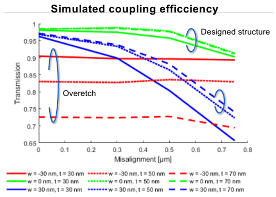
QD-SOURCE INTEGRATION THROUGH mTP

Proposed structure



Simulated coupling efficiency



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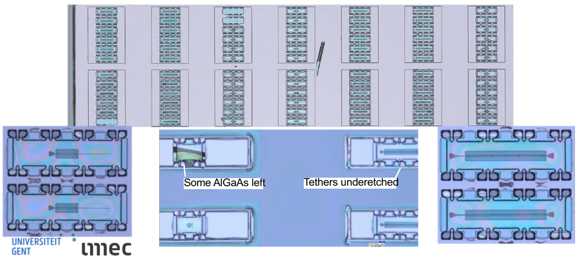
PROCESS DEVELOPMENT: UNDERETCH

Underetch: ~1 column broken coupons: 87.5 %



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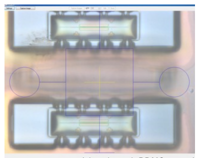
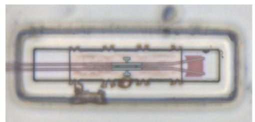
PROCESS DEVELOPMENT: PICK & PLACE

Device pick-up from source



(view through PDMS stamp)

Alignment on target



(view through PDMS stamp)

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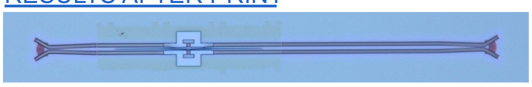
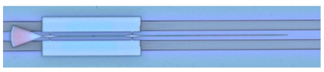
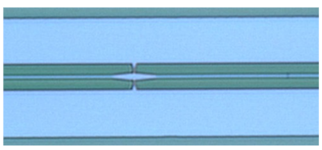
RESULTS AFTER PRINT







- Visual inspection shows good alignment
- 58/59 printed well

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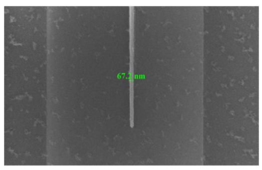
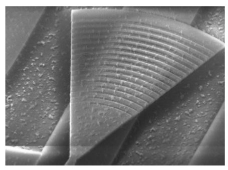
RESULTS AFTER PRINT





- SEM pictures confirm physical integrity
- Some residue left after photoresist cleaning

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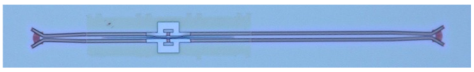
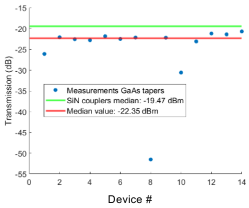
MEASUREMENT RESULTS




Jasper De Witte



Average transmission loss: 2.88 dB
- 1 dB propagation in GaAs
- 0.95dB loss/taper

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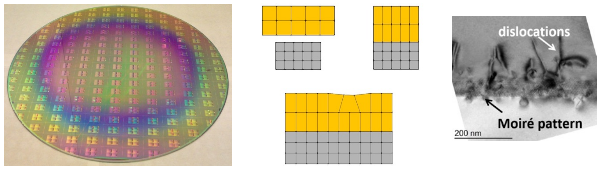
ALTERNATIVE #2: DIRECT EPITAXY ON SILICON

- Ultimate scalability: selective growth using MOCVD on 300mm wafers
- But: challenging due to lattice mismatch



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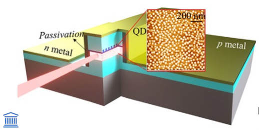

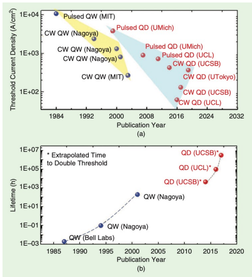

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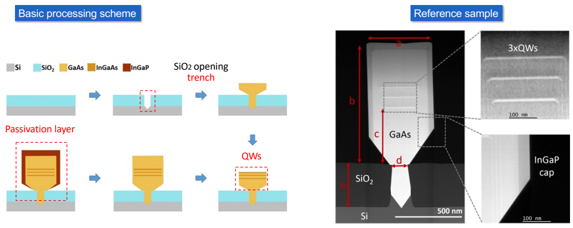
ASPECT-RATIO-TRAPPING (ART)



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Epitaxy by Bernardette Kunert, IMEC

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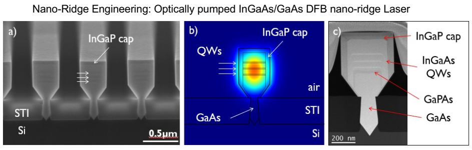
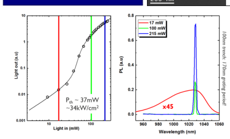
NANO-RIDGE ENGINEERING FOR III-V DEVICE

Nano-Ridge Engineering: Optically pumped InGaAs/GaAs DFB nano-ridge Laser



Y. Shi et al., Optica Vol. 4, No 12, 1468 (2017)
Y. Shi et al., Optics Express, 27, 26 (2019) 37781



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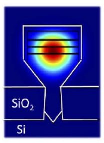
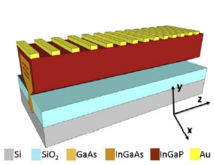
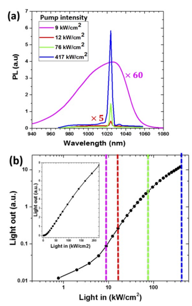
LOSS-COUPLED DFB NANO-RIDGE LASER

Metal grating deposited on top of the nano-ridge





Y. Shi et al., Optics Express Vol. 29, No 10, 14649 (2021)



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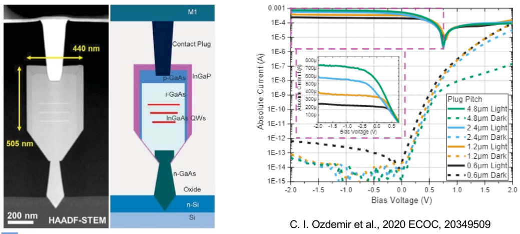
INGAAS/GAAS NANO-RIDGE PHOTODETECTOR

0.3□A D□□C□□□□□□0.65A/□ □□□□□□□□□□020□□



C. I. Ozdemir et al., 2020 ECOC, 20349509

CSW 2020: Invited talk B. Kunert, TuA2 8:00-8:30h

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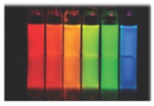
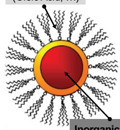
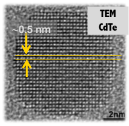
ALTERNATIVE #3: COLLOIDAL QUANTUM DOTS

- Exploit colloidal quantum dots as the active material
  - Semiconductor nanocrystals processed in solution
  - Optical properties widely tunable with size and material choice
  - Can be deposited in many ways on many substrates







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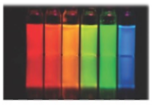
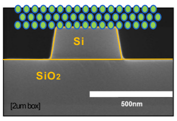
ALTERNATIVE #3: COLLOIDAL QUANTUM DOTS

- Exploit colloidal quantum dots as the active material
  - Integrated with waveguide
  - Can we demonstrate lasing from such a structure ?





(Original idea: PhD. proposal Iwan Moreels, 2004, Towards electrically injected sources on silicon)

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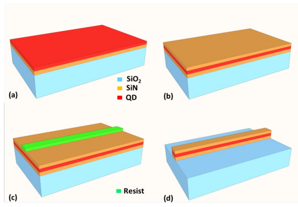
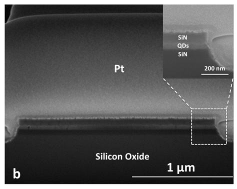
HYBRID SiN-QD PLATFORM

- Low-loss SiN-QD waveguide with uniform single layer of QDs embedded





(typically suing CdSe/cdS core/shell particles)

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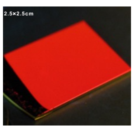
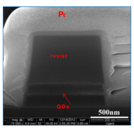
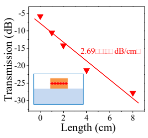
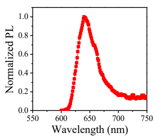
HYBRID SiN-QD PLATFORM

- Low-loss SiN-QD waveguide with uniform single layer of QDs embedded









- Chip-scale fabrication technology with dry etching process optimized for SiN-QD layers.
- Optimisation of deposition temperature and strain critical
- Demonstration of the waveguide loss of **2.7dB/cm** with preservation of QD emission.

(*Opt. Express* ***23*, 12152 (2015)**)

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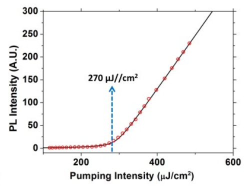
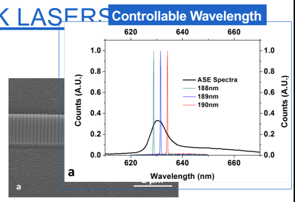
DISTRIBUTED FEEDBACK LASERS

- Nanosecond pumping





Pump: ±10ns, 1kHz, 532nm
75 nm/50nm/90nm SiN/QD/SiN
Equivalent CW-threshold: 39 kW/cm²

Gain life time ~100ps → This is ""quasi-CW operation""

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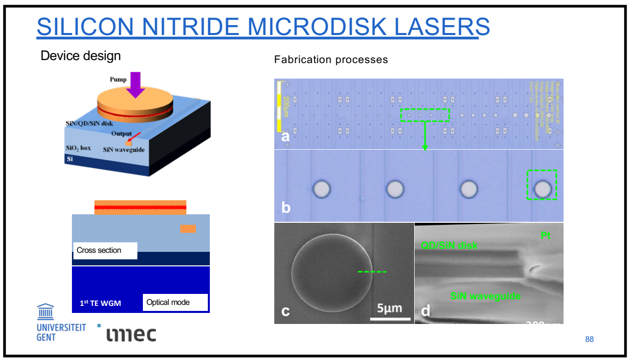

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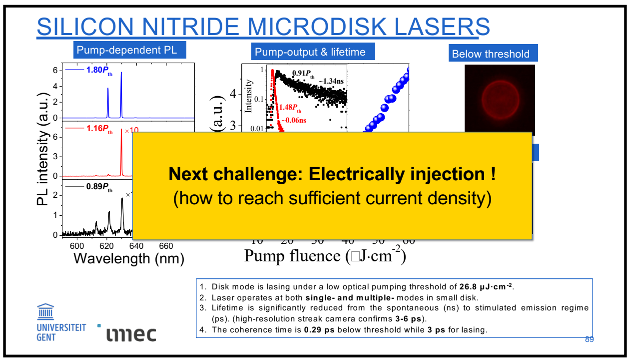

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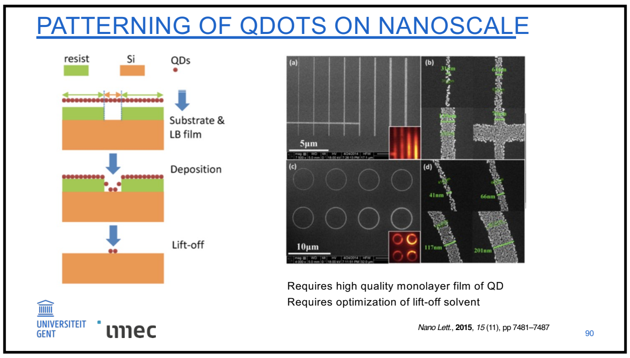

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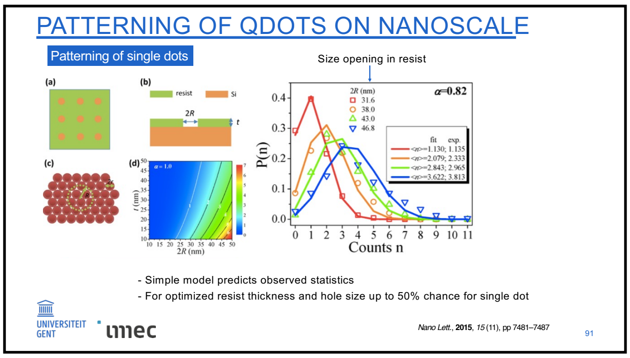

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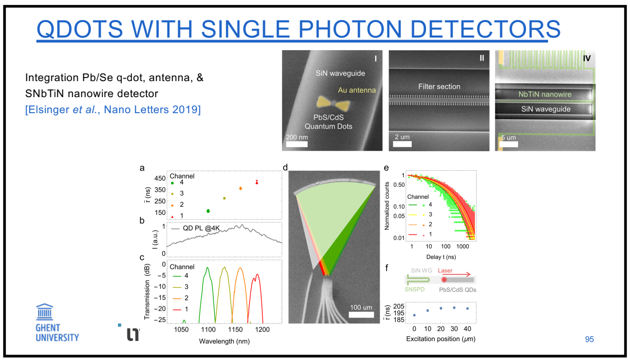

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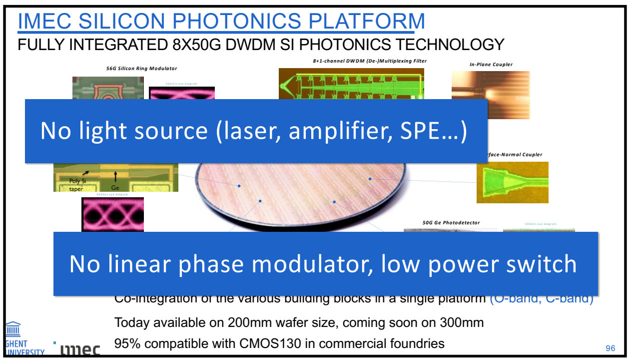

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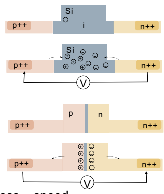
MOTIVATION

- The Silicon platform already has modulators and switches:
  - Exploiting carrier dispersion
    - Depletion (pn), injection (pin), accumulation devices
- Using native CMOS-processes
  - Highly mature
  - Very well understood, good models available
  - Very reliable processes
- BUT
  - Carrier dispersion show intrinsic trade-off between: efficiency – loss – speed
  - No pure phase modulation (AM/FM mixing)
  - Not compatible with cryogenic temperatures
  - Ge-based devices (FK): limited ratio ER/IL, limited operating wavelength range



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ER: Extinction Ratio – IL: Insertion Loss

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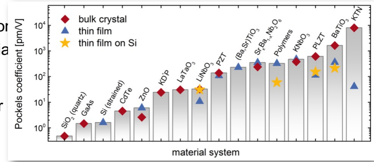
ALTERNATIVE MODULATOR TECHNOLOGIES

Phase modulators:

- LiNbO3: thin films bonded on silicon, commercially available from NanoLN (Harvard, Stanford, UCD, Sun Yat-sen & SNU …)
- BTO (Barium Titanate): epitaxially grown on silicon with STO buffer layer (IBM, Yale, imec)
- PZT: sol-gel deposition o
- EO-polymers: commercia

Amplitude modulators:

- Graphene: layer transfer
- III-V devices



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https://www.zurich.ibm.com/st/photonics/materials.html

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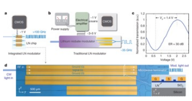
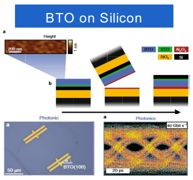
EXPLOSION IN NEW MODULATOR MATERIALS

LiNbO3 on Insulator



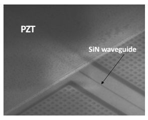
Wang e.a., Nature 2018

BTO on Silicon



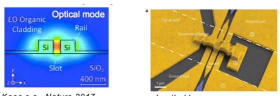
Stefan Abel et al, Nat. mat. 2018

PZT-on-anything



K. Alexander et al, Nat. Comm. 2018

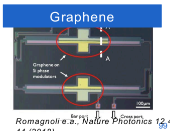
Electro-optic Polymers



Koos e.a., Nature 2017

Leuthold e.a.

Graphene



Romagnoli e.a., Nature Photonics 12,40 44 (2018)

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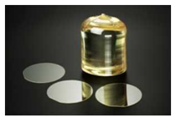
LITHIUM NIOBATE (LN)

- Till recently the main modulator technology in telecom
  - Very well understood
  - Very good linearity
  - Decent performance (reff ~30pm/V)
- But how to integrate with Silicon ?
  - LiNbO3 typically grown as bulk crystal
- Breakthrough:
  - Company NanoLN started providing thin film LN on Silicon substrates
  - Loncar-group (Harvard) demonstrated it is possible to etch low-loss WG in LN



From https://surfacinamagazine.net

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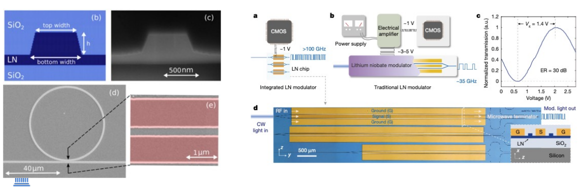
LETTER

https://doi.org/10.1038/s41586-018-0551-y

Integrated lithium niobate electro-optic modulators operating at CMOS-compatible voltages

Cheng Wang, Mian Zhang, Xi Chen, Maxime Bertrand, Amirhassan Shams-Ansari, Sethumadhavan Chandrasekhar, Peter Winzer & Marko Lončar



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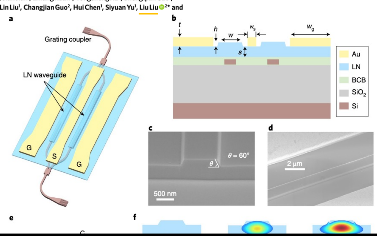
nature photonics ARTICLES

https://doi.org/10.1038/s41566-019-0378-6

High-performance hybrid silicon and lithium niobate Mach–Zehnder modulators for 100 Gbit s⁻¹ and beyond

Mingbo He, Mengyue Xu, Yuxuan Ren, Jian Jian, Ziliang Ruan, Yongsheng Xu, Shengqian Gao, Shihao Sun, Xueqin Wen, Lidan Zhou, Lin Liu, Changjian Guo, Hui Chen, Siyuan Yu, Liu Liu and Xinlun Cai

State Key Laboratory of Optoelectronic Materials and Technologies and School of Electronics and Information Technology, Sun Yat-sen University, Guangzhou, China. 2Centre for Optical and Electromagnetic Research, Guangdong Provincial Key Laboratory of Optical Information Materials and Technology, South China Academy of Advanced Optoelectronics, South China Normal University, Higher-Education Mega-Center, Guangzhou, China.



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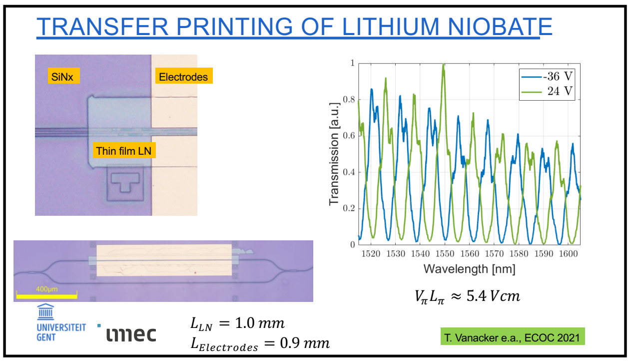

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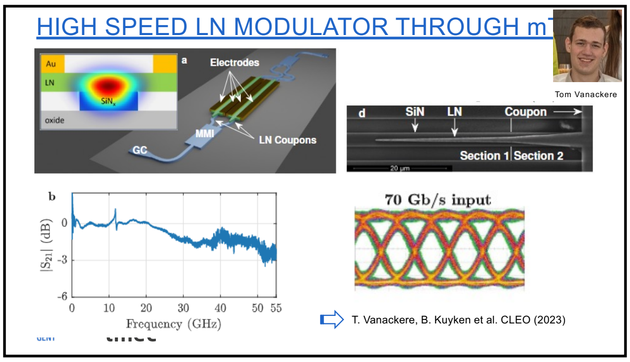

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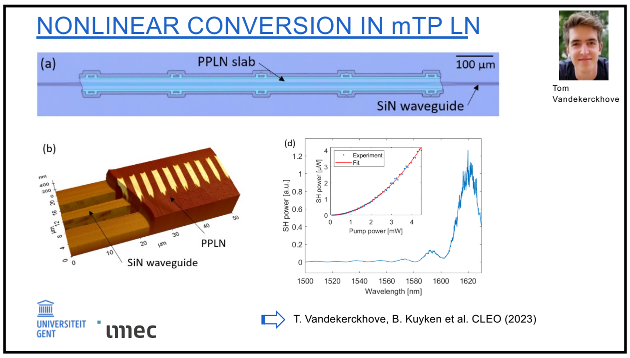

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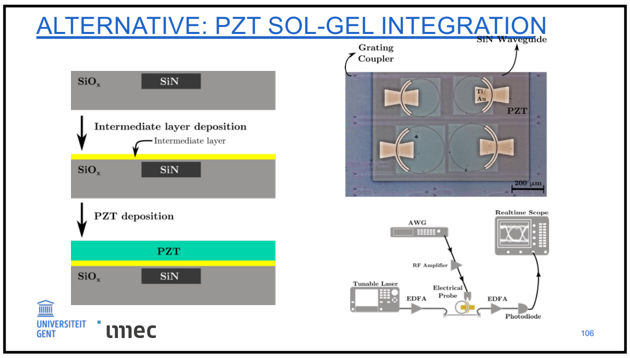

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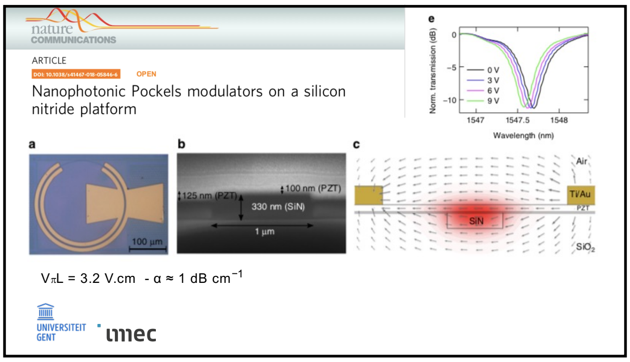

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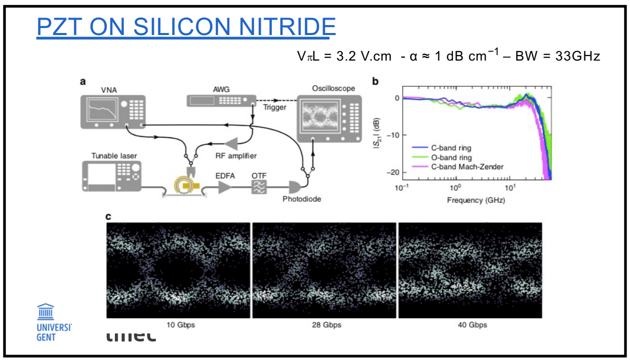

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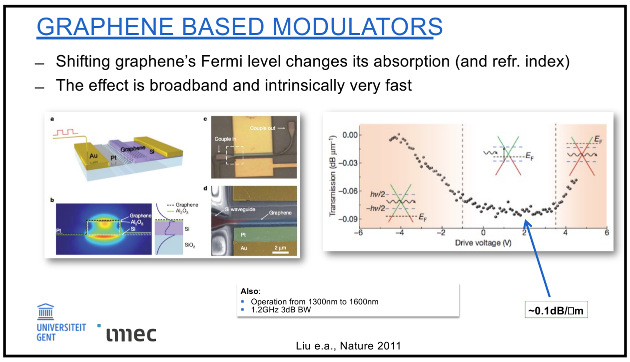

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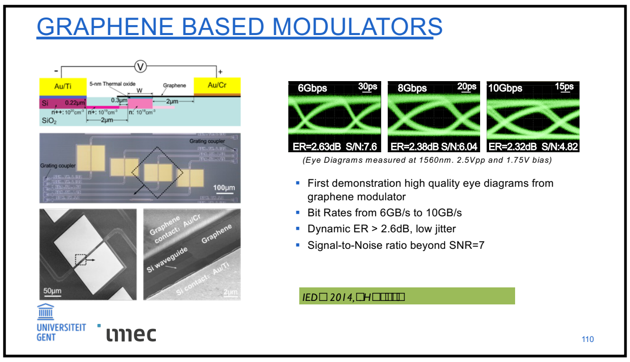

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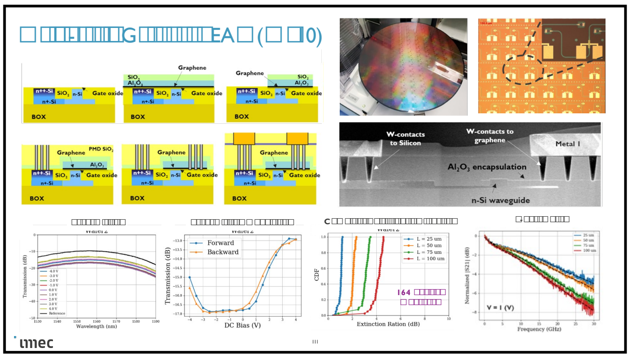

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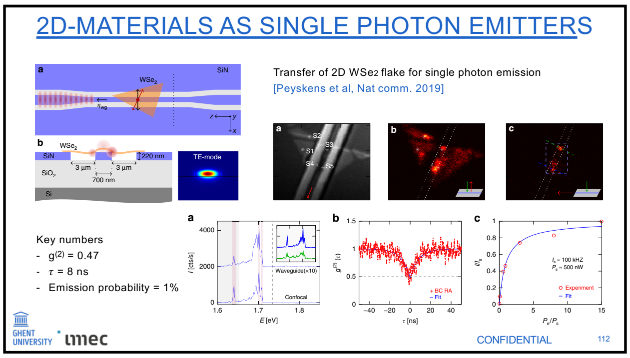

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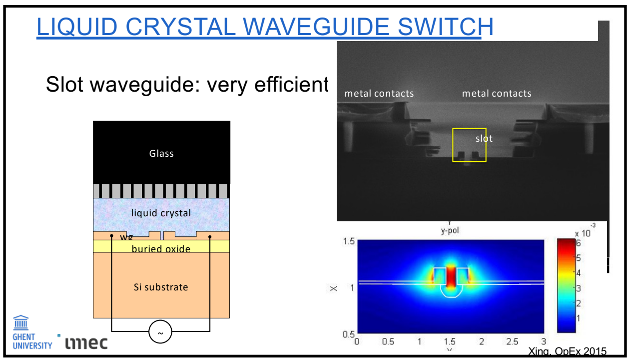

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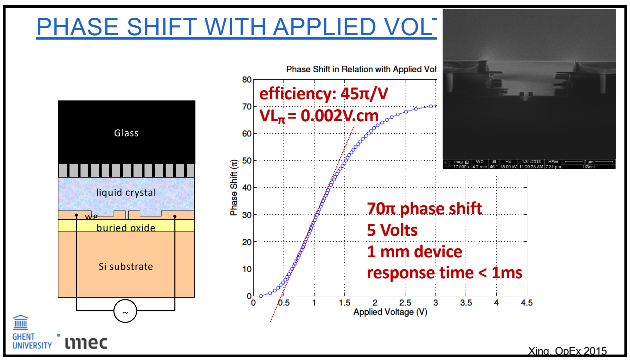

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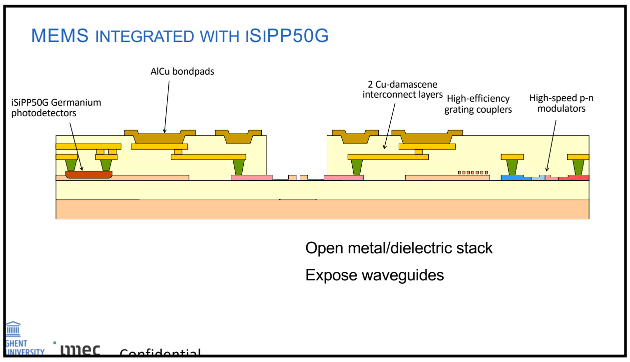

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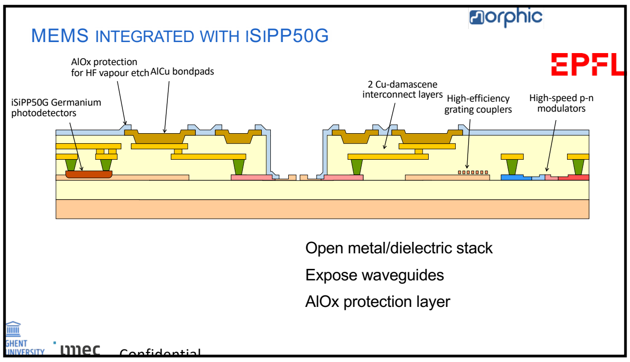

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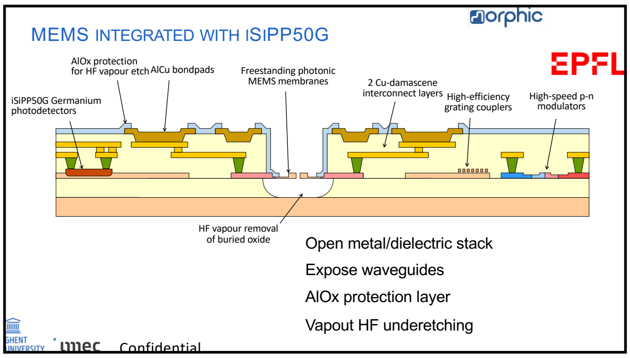

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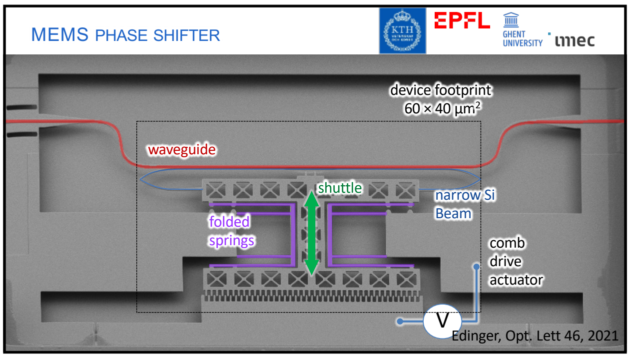

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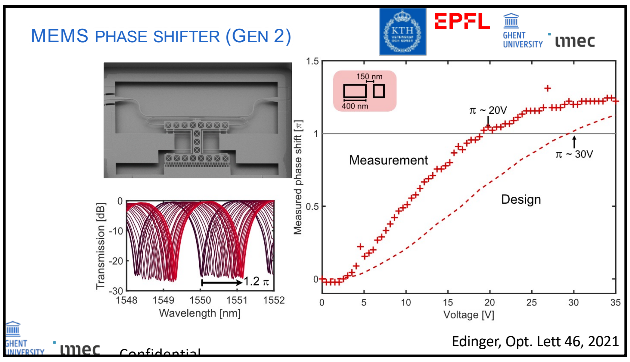

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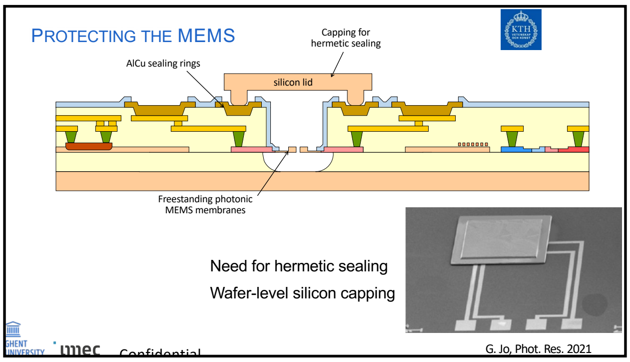

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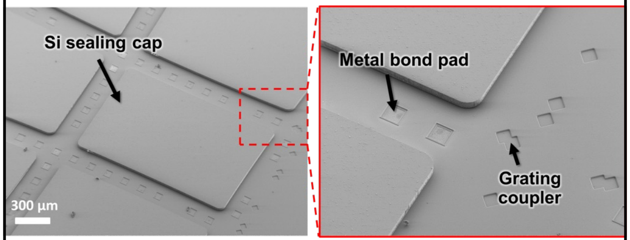
Vacuum sealing of iSiPP50G MEMS devices



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SUMMARY & CONCLUSION

Silicon Photonics is booming

- Widely used in telecom and datacom
- New application rapidly emerging (biomedical sensing, environmental sensing, spectroscopy, artificial intelligence, quantum computing…
- Available from major fabs all over the world

Remaining challenges:

- Further need for integration of new materials to enhance functionality
- Waferscale integration of lasers, phase modulators, single photon sources…

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SUMMARY & CONCLUSION

What do we have:

- Passives covering from visible up to MIR (UV is coming)
- Good detectors (Silicon & Germanium) covering λ = 400nm to 1600nm
- Reasonable phase modulators & switches based on carrier dispersion effec
- Diverse range of integration techniques for III-V direct bandgap materials (under further development)

Where can we improve further:

- Long wavelength detectors, UV-detectors
- Single photon source integration
- Ultra-fast, low power modulators
- Zero loss modulators (more stable liquid crystals ?)
- Non-volatile switches (phase change materials ?)
- Single photon emitters, efficient spin-photon interaction,…
- …

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Let me know if you have something new !

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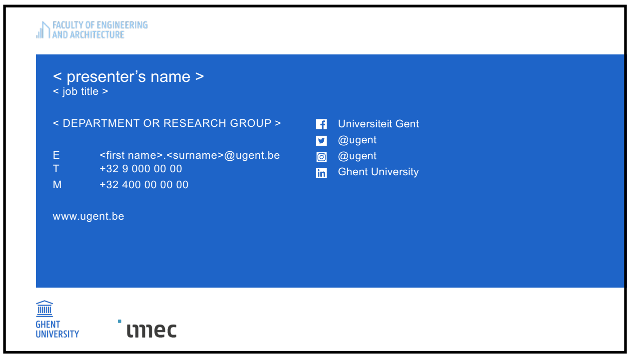
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