Silicon Photonics

Wim Bogaerts
Rusnano Forum - 27 October 2011

The Photonics Research Group

Research Group of Ghent University
- within Engineering Faculty
- within Dept. of Information Technology (INTEC)
- associated with IMEC
- member of NB Photonics

6 Professors
10 postdocs
40 PhD students
7 support staff

15 nationalities

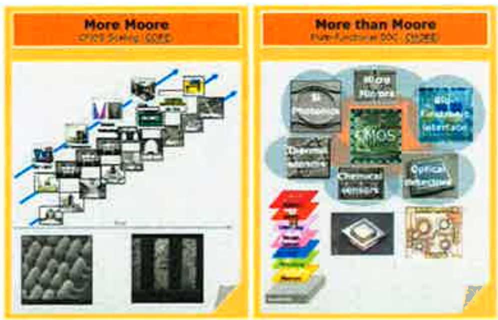
Photonics Research Group: Research Vision

1. photonic integration
   Build photonic systems on a chip
2. silicon photonics
   Use the power of silicon CMOS-technology for integrated photonics
3. heterogeneous integration
   Avoid the weaknesses of silicon through combination with other materials and nanomaterials

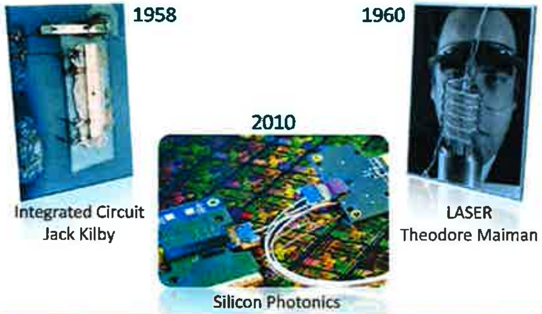
Research Vision and Focus: Applications

Leverage photonic integration to enable a variety of applications
- Core and access telecom networks
- Optical interconnect and high performance computing
- Sensors and biosensors
- Biomedical instrumentation

IMEC: More than More Moore



Photonic integration...



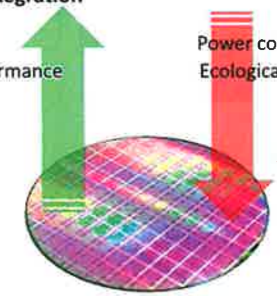
Electronic Integration

Complexity
Overall Performance
Reliability
Ergonomy

goes up

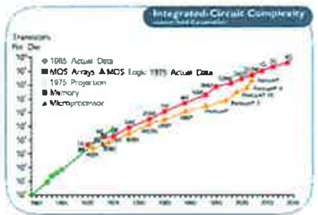
Power consumption
Ecological Footprint
Cost

goes down

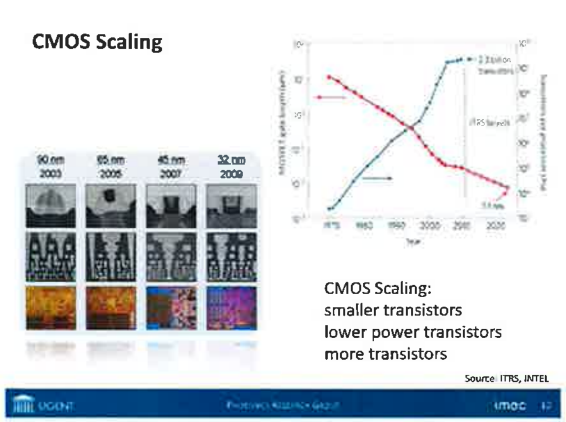


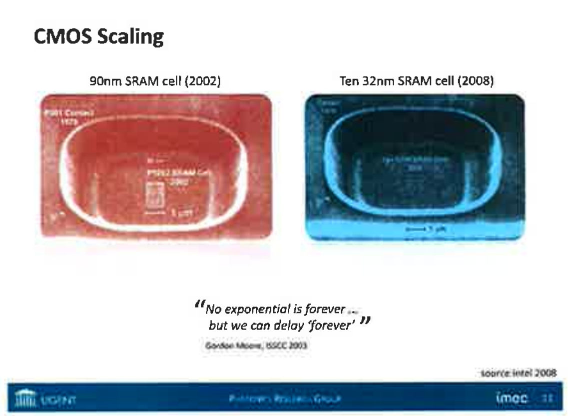
Scale, scale, scale

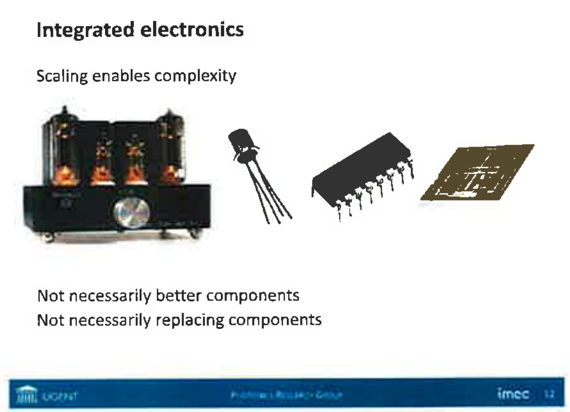
Always Mo(o)re...

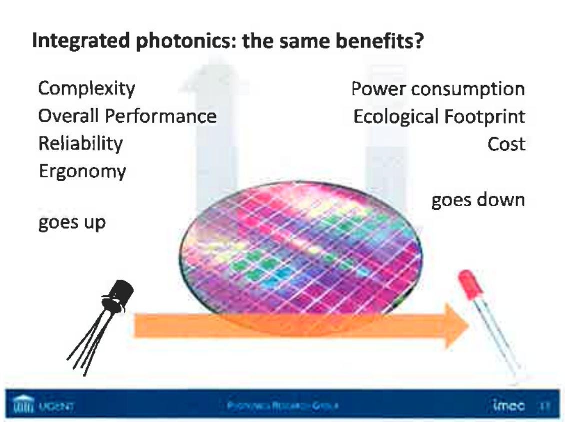


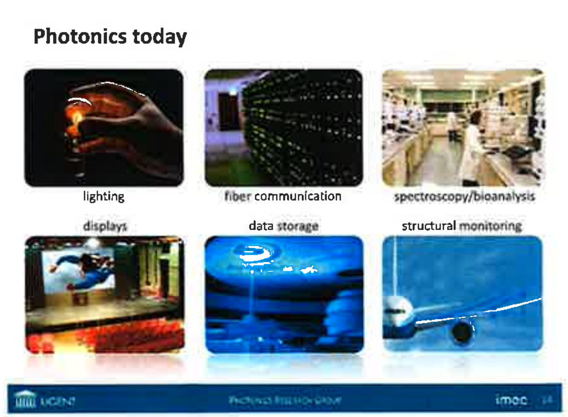
...enabled by scaling

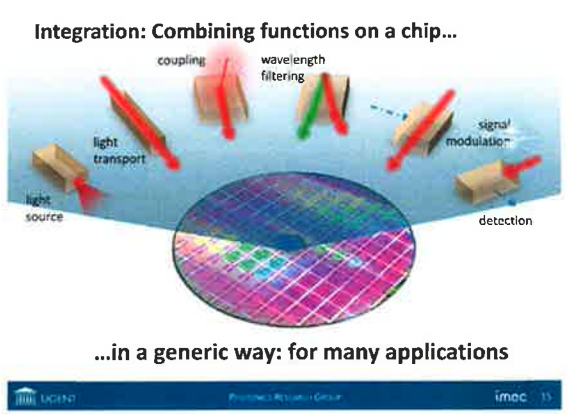

CMOS Scaling
90 nm 2003
65 nm 2005
45 nm 2007
32 nm 2009
CMOS Scaling:
smaller transistors
lower power transistors
more transistors
Source: ITRS, INTEL
UGENT
imec


CMOS Scaling
90nm SRAM cell (2002)
Ten 32nm SRAM cell (2008)
"No exponential is forever ... but we can delay 'forever'"
Gordon Moore, ISSCC 2003
source intel 2008
UGENT
imec

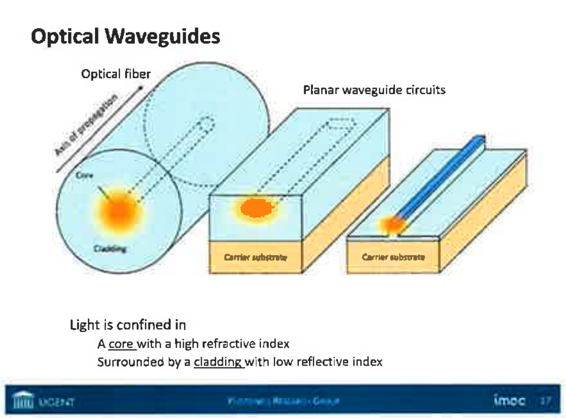

Integrated electronics
Scaling enables complexity
Not necessarily better components
Not necessarily replacing components
UGENT
imec

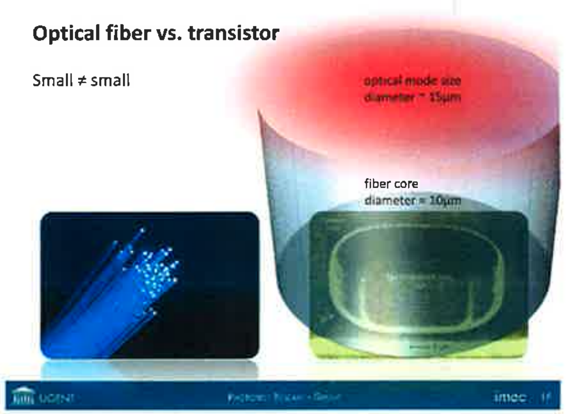

Integrated photonics: the same benefits?
Complexity
Overall Performance
Reliability
Ergonomy
goes up
Power consumption
Ecological Footprint
Cost
goes down
UGENT
imec


Photonics today
lighting
fiber communication
spectroscopy/bioanalysis
displays
data storage
structural monitoring
UGENT
imec

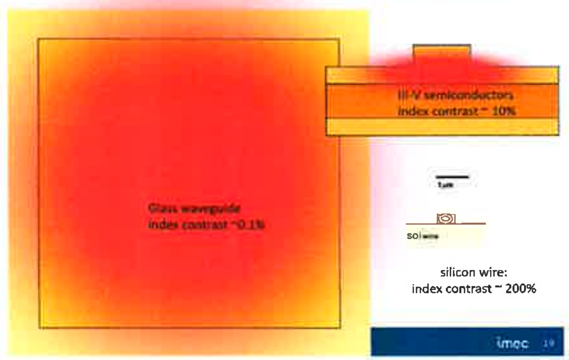

Integration: Combining functions on a chip...
coupling
wavelength filtering
light transport
signal modulation
light source
detection
...in a generic way: for many applications
UGENT
imec


Photonic Integration
solid state lighting
optical communication
lab on a chip
UGENT
imec


Optical Waveguides
Optical fiber
Axis of propagation
Core
Cladding
Planar waveguide circuits
Carrier substrate
Carrier substrate
Light is confined in
A core with a high refractive index
Surrounded by a cladding with low reflective index
UGENT
imec


Optical fiber vs. transistor
Small ≠ small
optical mode size diameter ~ 15μm
fiber core diameter ≈ 10μm
UGENT
imec

Waveguide mode sizes depends on index contrast



Higher contrast, smaller cores, tighter bends

Silica on silicon
Contrast ~ 0.01 – 0.1
Mode diameter ~ 8µm
Bend radius ~ 5mm
Size ~ 10 cm²

Indium Phosphide
Contrast ~ 0.2 – 0.5
Mode diameter ~ 2µm
Bend radius ~ 0.5mm
Size ~ 10mm²

Silicon on insulator
Contrast ~ 1.0 – 2.5
Mode diameter ~ 0.4µm
Bend radius ~ 5µm
Size ~ 0.1mm²

10000 ×

Why Silicon Photonics?

Good waveguide material
- High material contrast: 3.45 to 1.45
- Submicron waveguides and sharp bends
- Transparent for telecom wavelengths

Processing technology
- Superb infrastructure of CMOS fabs
- Germanium processing for detectors
- integration with electronics

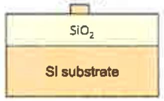
Photonic Large-scale **Integration**

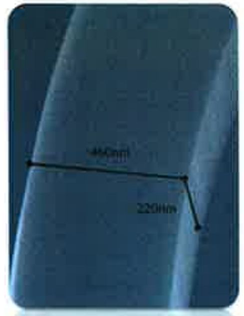
Silicon wire waveguides

High contrast: Small core, tight bends

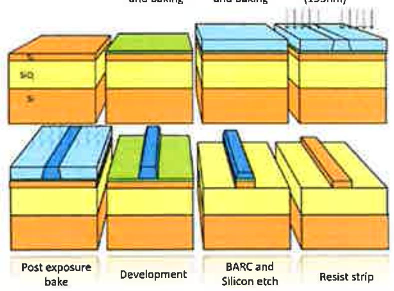
Low loss: ~ 1.5dB/cm

But sensitive to variations





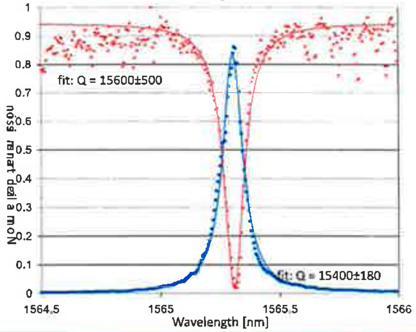
Fabrication process (waveguides)



Optical ring resonator

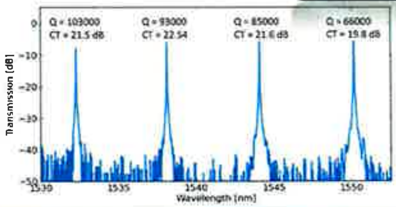
Resonance condition
$L_{optical} = L_{physical} \cdot n_{eff} = m.\lambda$

Ring resonator: Channel drop filter

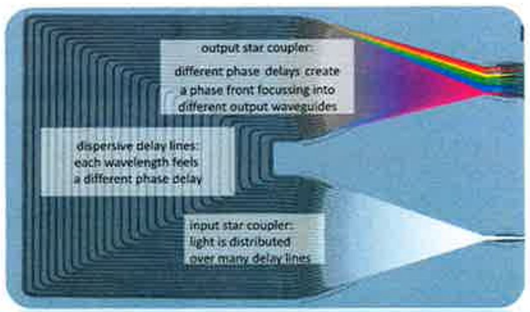


Ring resonators

High-quality rings
- Q > 30000 (TE polarization)
- Q > 300000 (TM polarization)

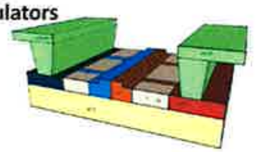


Arrayed Waveguide Grating (AWG)



Silicon Mach-Zehnder modulators

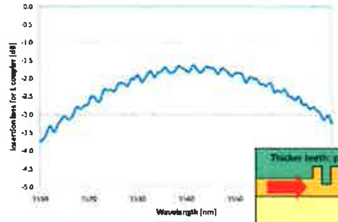
Lumped electrode (3mm long)
Operating wavelength: 1550 nm
insertion loss: 11.9 dB
Signal driving Voltage: Vpp = **2 V**

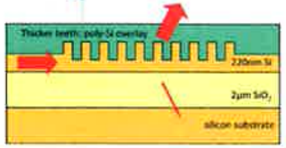


5 Gb/s, ER: 5.92 dB | 10 Gb/s, ER:4.51dB | 12.5 Gb/s, ER:3.73dB

High-efficiency grating couplers

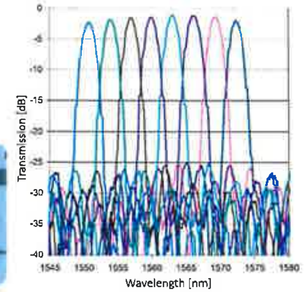
68% efficiency





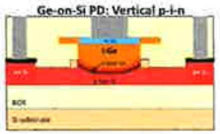
Arrayed Waveguide Grating

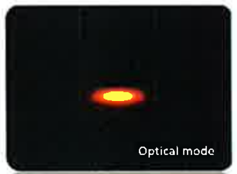
8 channels
1dB insertion loss
3.2nm channel spacing
25dB crosstalk
400 × 300 µm²



Germanium Photodiodes

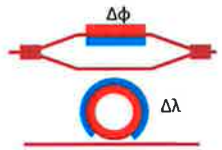
Ge epi on silicon
Integrated in waveguides





Silicon modulators

Phase shifter in an interferometer
or (ring) resonator



Phase shifter:
pn-junction in reverse bias
in the waveguide core

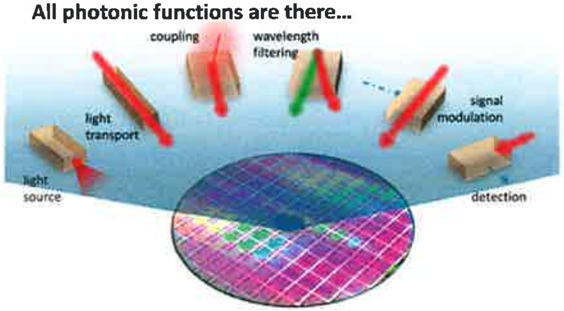
$$\Delta n = -8{,}8.10^{-22}\Delta N - 8{,}5.10^{-18}\Delta P^{0{,}8}$$
$$\Delta \alpha = 8{,}5.10^{-18}\Delta N + 6{,}0.10^{-18}\Delta P$$

in silicon at 1550nm
P, N densities in cm^{-3}

Soref, JQE 23, (1987)

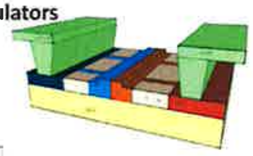
Coupling to nanophotonics

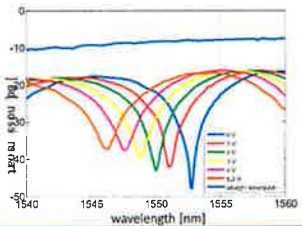
All photonic functions are there...

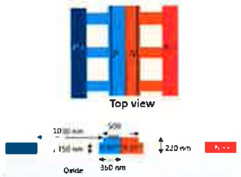


Silicon Mach-Zehnder modulators

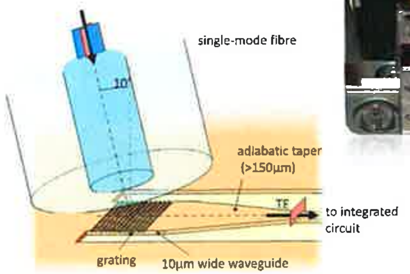
Asymmetrical MZ: ΔL = 40 µm
$V_\pi L_\pi$ =1.24 V-cm
Series resistance = 6Ω
Insertion loss = 8 dB





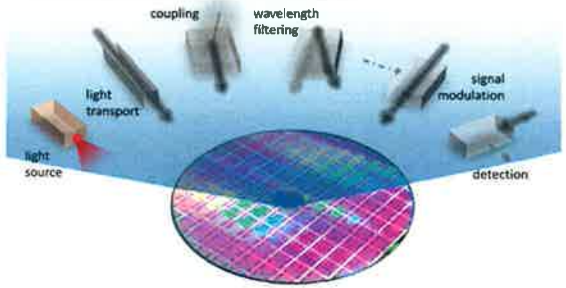


Grating Fiber Coupler



D. Taillaert, JQE 7, p949 (2002)

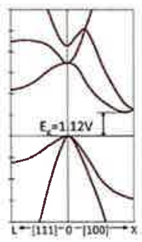
All photonic functions are there...



...except for the laser.

Silicon is a bad light emitter

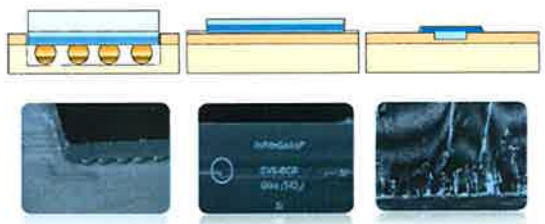
Indirect bandgap → nonradiative recombination



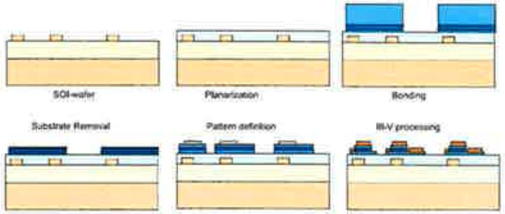
Solution: Combine with other materials

III-V lasers on Silicon

Flip-chip Bonding Epitaxy



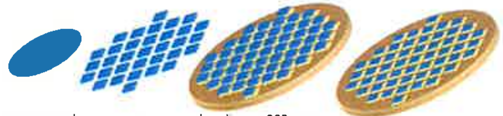
III-V integration on SOI



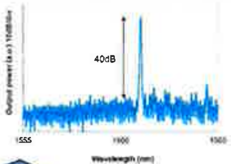
Adhesive bonding layer (DVS-BCB polymer)

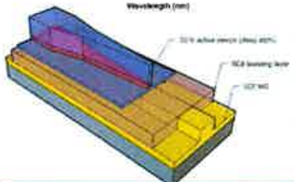
- Relaxed specs in wafer flatness
- Flexibility in bonding layer thickness (20nm -2µm)

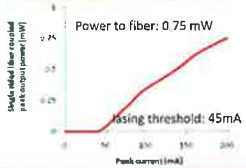
Integration of III-V on SOI



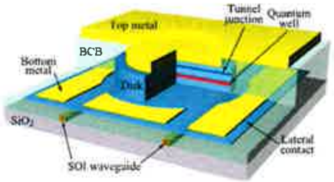
Adiabatically tapered hybrid laser

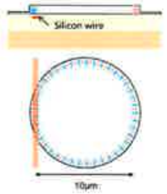






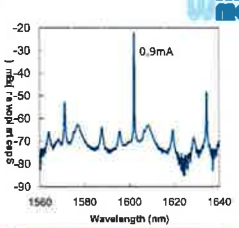
Microdisk hybrid laser





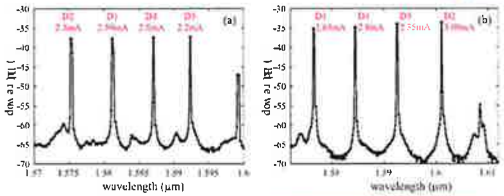
Mode fully in III-V layer: High modal gain
Ultra-compact resonator (< 10µm)

Integrated microdisk laser



Threshold current: I_{th} = 0.35mA
Voltage: V_{th} = 1.5-1.7V
CW output power: 120µW
Direct modulation: 4GHz

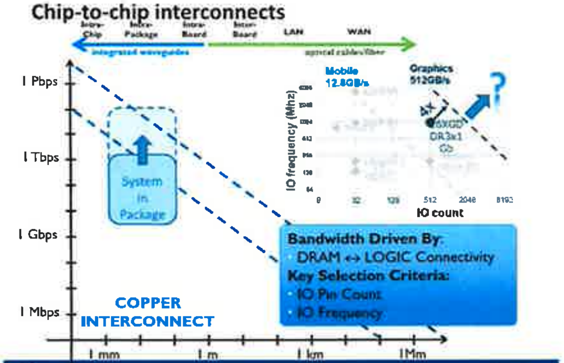
Microdisk hybrid laser



Wavelength control by changing the disk radius

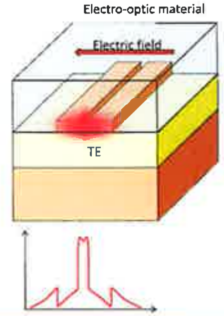
Multiwavelength laser on one waveguide

Chip-to-chip interconnects



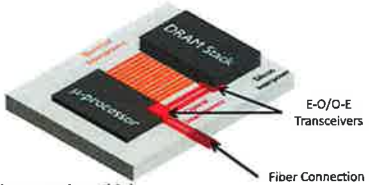
Application domains

Silicon-organic hybrid slot modulator



In the slot:
Polymers
Perovskites
nanocrystals

10Tbps Silicon E/O Interposer: integration matters.



Optical Requirements (per chip)

LASER:	8 channels @ 25mW (3dB insertion loss)
MUX:	8x1 (1dB insertion loss)
SPLITTER:	1x1000 (4dB insertion loss)
MODULATORS:	8000 (λ-selective) (3dB insertion loss)
8x1 DEMUX:	1000 (1dB insertion loss)
RECEIVERS:	8000, Sensitivity = -30dBm @ 4Gbps, @BER 10^{-12}

→ ~34,000 optical components

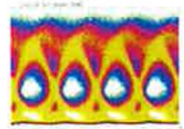
40 years of optical communication

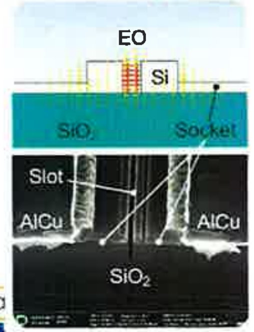
Fast and efficient modulation

Slot waveguide filled with electro-optic polymers

Modulation applied over the slot

42.7Gbit/s, Q^2=12.7dB

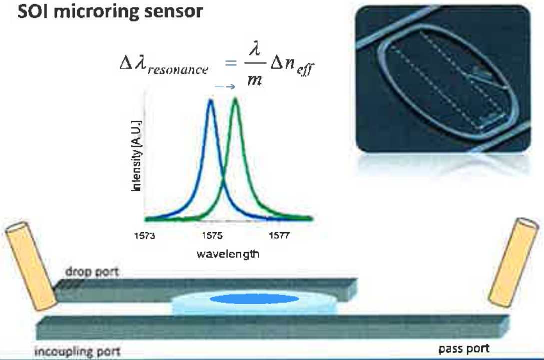




KIT design and measurements at KIT
silicon fabricated at CEA-LETI

SOI microring sensor

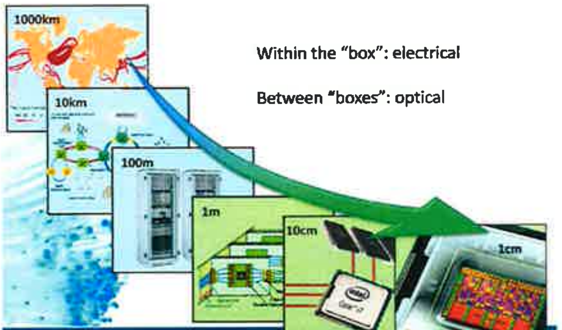
$$\Delta\lambda_{resonance} = \frac{\lambda}{m}\Delta n_{eff}$$



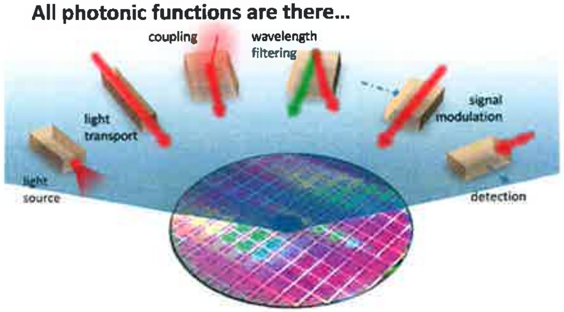
Optical Links: connecting boxes...

Within the "box": electrical

Between "boxes": optical



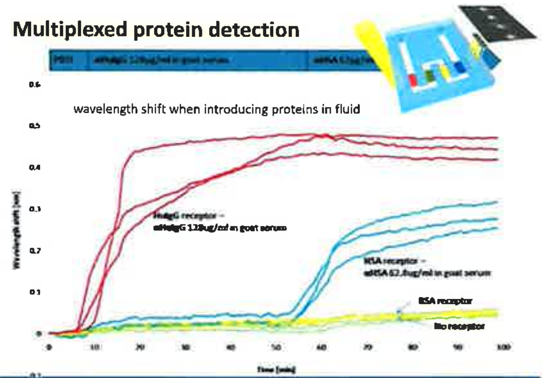
All photonic functions are there...



... with a little help from III-V.

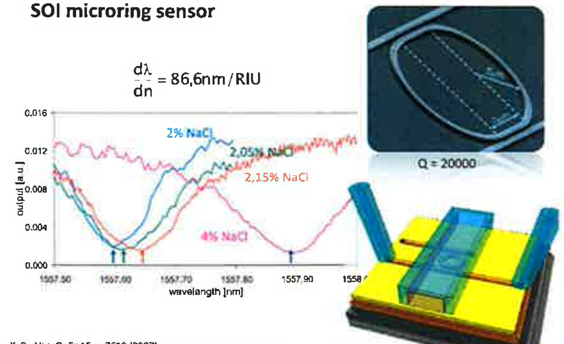
Fiber Reinforced Composites

Multiplexed protein detection



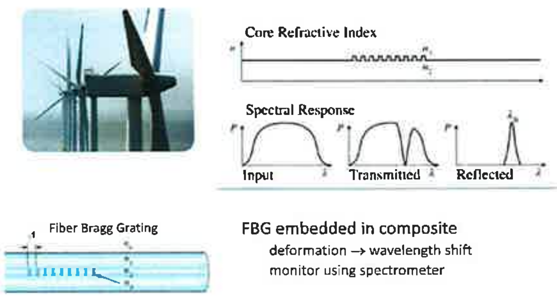
SOI microring sensor

$\frac{d\lambda}{dn} = 86{,}6nm/RIU$



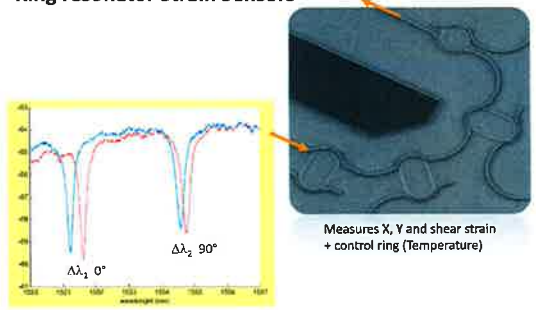
K. De Vos, OpEx 15, p.7610 (2007)

Readout for Fiber Bragg Gratings



FBG embedded in composite
deformation → wavelength shift
monitor using spectrometer

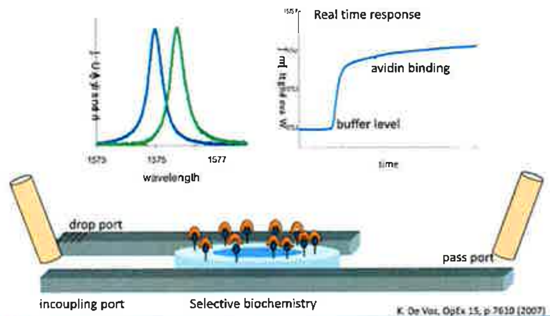
Ring resonator Strain Sensors



Measures X, Y and shear strain
+ control ring (Temperature)

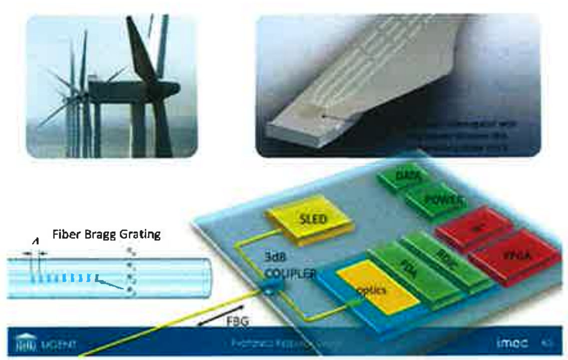
D. Taillaert, Proc.SPIE, p.661914 (2007)

Label-free biosensing

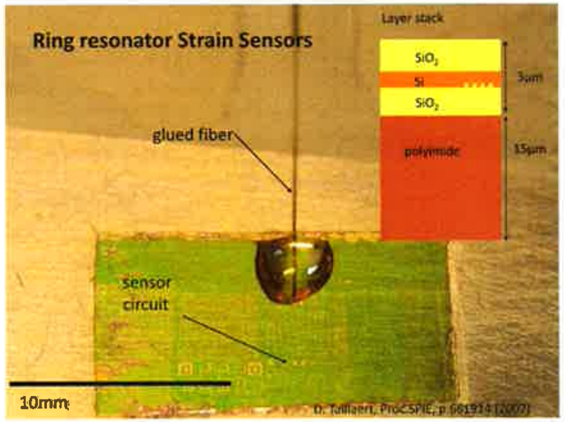


K. De Vos, OpEx 15, p.7610 (2007)

Embedded Readout for Fiber Bragg Gratings

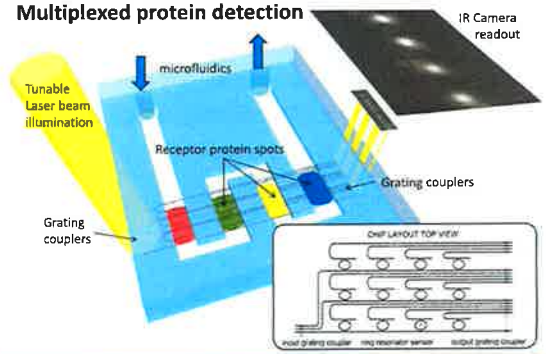


Ring resonator Strain Sensors



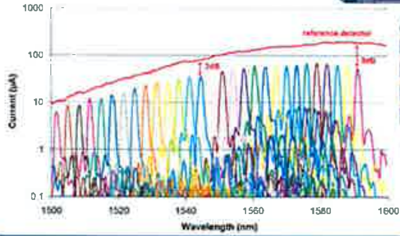
D. Taillaert, Proc.SPIE, p.661914 (2007)

Multiplexed protein detection



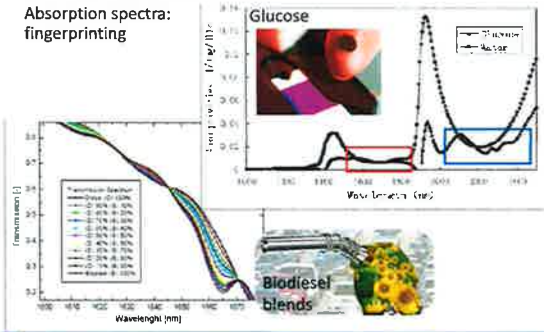
Near-infrared spectrometer

Insertion loss (on-chip): 3-5dB
Short range extinction (5nm): >15dB
Long range extinction (20nm): >20dB

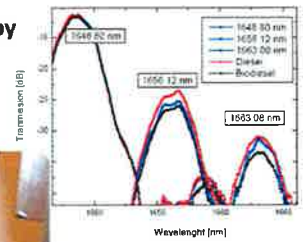



Absorption spectroscopy

Absorption spectra:
fingerprinting



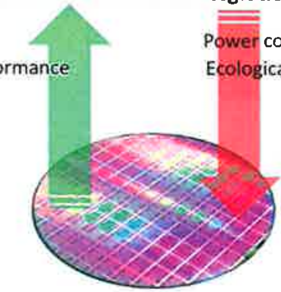
Biodiesel spectroscopy



Yes: Photonics can benefit from integration

Complexity
Overall Performance
Reliability
Ergonomy

goes up



Power consumption
Ecological Footprint
Cost

goes down

...but who will make it?

Fabless Silicon Photonics?




Fabs
Huge investment
24/7 operation
Won't invest if there are no users

Design houses
No money for technology
Based on standard Fabs
Cannot start if there are no fabs

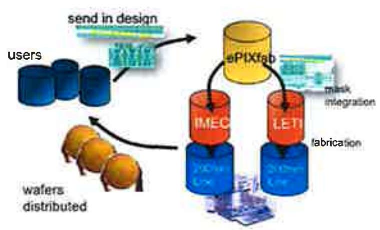
ePIXfab

Services for R&D on silicon photonics

Goals
- enable cost-effective R&D with high-end technology
- increase market take-up of silicon photonics
- open up new research areas

ePIXfab serves as a platform for the promotion and advancement of silicon photonics

MPW shuttle service



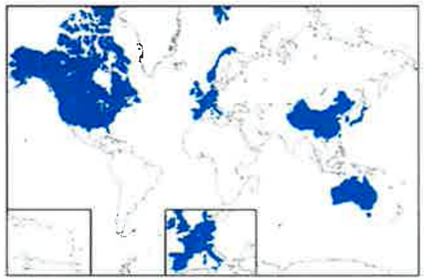
MPW service: technology

200mm pilot lines
- Continuous operation 24/7
- Trained operators, dedicated support team and development team
- Manufacturing execution system

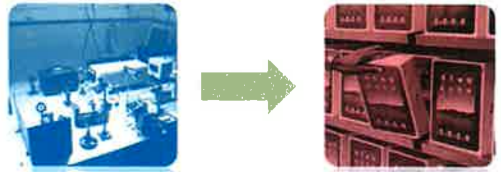
Well controlled environment
- Strict contamination control
- Statistical process control (electronics)
- Procedures

High-end tools
- Deep submicron technology (0.18→90nm)
- Wafer scale (200mm)
- 193nm deep UV lithography

ePIXfab users: a worldwide community



From the lab to the fab to the product

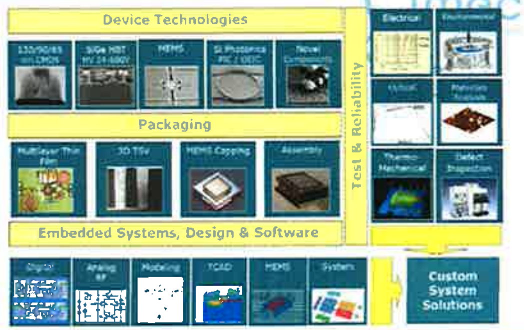


Tackle all the 'peripheral problems' : design, packaging, ...
What if you need custom fab solutions?

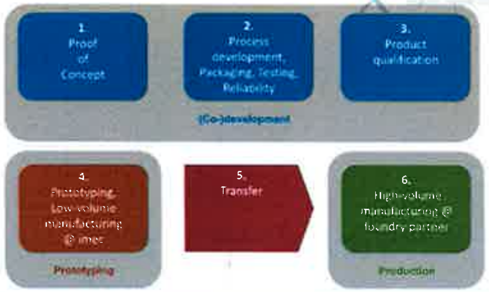
IMEC CMORE: More than Moore

IMEC has the tools
and the know-how

IMEC's CMORE Toolbox



IMEC CMORE: from concept to product



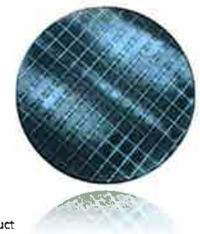
Summary: Silicon Photonics

Silicon Photonics Technology Platform
- Very large integration density
- Waveguides, couplers, modulators
- Germanium photodetectors

III-V on Silicon adds the light source

Many applications
- Interconnects, sensing, spectroscopy

Access to silicon photonics
- ePIXfab: Standardized Processes for research
- IMEC CMORE: From Proof-of-Concept to a Product



Silicon nanophotonics ...

...in a pico-scale world

UNIVERSITEIT GENT imec PHOTONICS RESEARCH GROUP

16.45-17.00	Coffee Break
17.00-17.30	«New approach for creation of nanocomposite with polymeric matrix» **Alexander Volynsky**, RAS corresponding member, Professor, Chemistry Faculty, M.V. Lomonosov Moscow State University (Russia),
17.30-18.00	«Macromolecular nanoobjects and polymeric composites on their base» **Aziz Muzafarov**, Professor, Head of Laboratory, Institute of Synthetic Polymer Materials RAS (Russia),
18.00-18.30	«Polymeric composites from micro to nano» **Vladimir Udin**, Professor, Head Laboratory, Institute of Macromolecular Compounds RAS (Russia).

Hall J
10.00-18.00

«NANOELECTRONICS AND NANOPHOTONICS» SECTION

Session 2. «Optoelectronics and nanophotonics»

- Silicon Photonics
- Colloidal quantum dots and organic light-emitting devices
- Nanoreciever network Yagi DND in the field of optics
- Spectomicroscopy of single molecules as a method for the nanodiagnostics of solid bodies.
- Methods to control the generation of electromagnetic radion with the help of nanopatterned liquid crystals.

	Moderator: **Sergey Bagaev**, RAS member, Director, Institute of laser physics RAS (Russia)
10.00-10.30	«Silicon Photonics» **Wim Bogaerts**, Professor, Interuniversity Microelectronics Center (IMEC) – Ghent University (Belgium),
10.30-11.00	«Organic emitted devices with colloidal quantum dots» **Aleksey Vitukhnovsky**, Professor, Head of the Department of Luminescence, Lebedev Physical Institute RAS (Russia),
11.00-11.30	«Photonic structures as optical nanoantennas» **Sergey Tikhodeev**, Professor, Prokhorov Institute of General Physics RAS (Russia),
11.45-12.00	Coffee Break
12.00-12.30	«New methods of highly efficient controlled generation of radiation by liquid crystal nanostructures in a wide spectral range including the THz one» **Sergey Trashkeev**, Professor, Senior Associate, Institute of Laser Physiscs SB RAS (Russia),

12.30-13.00	«Single-molecule spectromicroscopy: tool for nanodiagnostics of solids» **Andrey Naumov**, Deputy Director and Head of the Department of Molecular Spectroscopy, Institute of Spectroscopy RAS (Russia)

Session 3. «New devices and facilities in nanoelectronics and nanophotonics»

- Micro and nano-scale electromechanical devices from researchers at LETI, the major European micro and nanotechnology laboratory.
- Tunnel resonance heterojunction devices and ultrahigh-speed integrated circuits based on them, from designers at the P.N. Lebedev Physical Institute of the Russian Academy of Sciences.
- Uultraviolet lasers based on zinc oxide nanorods, from designers at the Institute for Design Problems in Microelectronics of the Russian Academy of Sciences.

	Moderator: **Alexander Orlikovsky**, Professor, RAS member; Director, Physics and Technologies Institute of the RAS (Russia)
15.00-15.30	«NEMS for sensing the world» **Jean-Philippe Polizzi**, Professor, Microsystems Program Manager, CEA-LETI/ DIHS (France),
15.30-16.00	«Development of emerging non-volatile memories and NVM technology transfer to production Fabs» **Yakov Roizin**, Professor, Director, Tower Jazz (Israel),
16.00-16.30	«Nanotransistors with ultrathin silicon and graphene channels» **Vladimir Viurkov**, Senior Associate, Physics and Technologies Institute RAS (Russia),
16.45-17.00	Coffee Break
17.00-17.30	«Tunnel resonance devices and super high-speed IS on their base» **Alexander Gorbatcevich**, Professor, Main Researcher, Lebedev Physical Institute RAS (Russia),
17.30-18.00	«Heteroepitaxial structures CdHgTe on GaAs and Si substrate for IR and terahertz detectors» **Maxim Yakushev**, Senior Associate, A.V. Rzhanov Institute of Semiconductor Physics SB RAS (Russia).