Why silicon photonics matters

Outline

An introduction to silicon photonics
Biosensing and gas sensing
Laser Doppler vibrometry and optical coherence tomography
Spectroscopy-on-a-chip

Silicon photonics: an enabler for the internet and for the life sciences

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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

Enabling complex optical functionality on a compact chip at low cost
Optical Lithography by deep UV steppers

Resolution = $k \frac{\lambda}{NA}$

Why silicon photonics

High index contrast ⇒ very compact PICs
CMOS technology ⇒ nm-precision, high yield, existing fabs, low cost in volume

High performance passive devices
High bitrate Ge photodetectors
High bitrate modulators
Wafer-level automated testing
Hierarchical set of design tools
Light source integration (hybrid/monolithic?)
Integration with electronics (hybrid/monolithic?)

Silicon photonic wires

$n_2(=3.5) > n_2(=1.45)$
Packaging photonic chips (optical, electrical, RF, thermal)

Silicon photonics chip for ultra-high bitrate communication

Industrial take-up examples in telecom/datacom

- active optical cables (e.g. 4x10Gb/s on parallel fibers)
- WDM transceivers (e.g. 4 WDM channels x 12.5 Gb/s on single fiber)
- coherent receiver (e.g. 100 Gb/s PM-QPSK)
- fiber-to-the-home bidirectional transceiver (e.g. 12 x 2.5 Gb/s)
- monolithic receiver (e.g. 16x20Gb/s)
- 40Gb/s and 50Gb/s Ethernet (future: 100 and 400Gb/s)

Testing photonic chips
Silicon photonics: extending the wavelength range

Explorative research in silicon photonics

Bring new materials in the CMOS fab:
- Transfer printing of InP (and other III-V semiconductors) on silicon
- Direct epi-growth of InP (and other III-V semiconductors) on silicon
- Integration of graphene on silicon
- Integration of electro-optic materials (PZT, BTO, ...) on silicon
- ...

Biosensors

Detect presence and concentration of
- Proteins
- Viruses
- Bacteria
- DNA
- ...

Two classes:
- Labeled: detection of label bound to biomolecule
- Label-free: direct detection of biomolecule

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Spectroscopy-on-a-chip
Multiplex sensing results

Label-free ring resonator biosensor

DNA hybridisation

Lab-on-chip concept

Concentrations down to 100 pM can be detected
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Pocket project (FP7)

- Detection of Tuberculosis biomarkers in urine
- SiN PIC-platform in visible: cheaper sources and detectors
- Cheap readout: broadband source + sensor + on-chip spectrometer
- Coordinator: UGent (P.Bienstman)
- Spin-off plans

Doppler effect

$\frac{\Delta f_{\text{opt}}}{f_{\text{opt}}} = \frac{2v_{\text{target}}}{c}$

Example:
- $v_{\text{target}} = 15$ cm/s
- $c = 30$ cm/ns
- $\Delta f/f = 10^{-9}$
- $\Delta f = 100-1000$ kHz

Selective, reversible and fast ammonia gas detection

Application: breath analysis

Microporous silica layer, pores: 2nm; porosity: 45%
Functionalized for ammonia-selectivity

Sensitivity down to 100ppb demonstrated
No interference from H$_2$O and CO$_2$

N. Yebo et al, Optics Express, 20(11), pp. 11855 (2012)
**LDV-measurement of blood pulse velocity**

Blood pulse velocity: increases when blood vessels become stiffer due to atherosclerosis

![Diagram of LDV-measurement of blood pulse velocity](image)

\[ \Delta t = 0.003 s \]

Pulse velocity: 4.5 m/s

**CARDIS project (Horizon 2020)**

Goal: develop a prototype for a point-of-care LDV device

12 LDV systems on a single photonic chip

Timeframe: 2015-2018

Budget: 3.5 Meuro

**Pulse wave velocity measurement**

- pulse wave velocity: measure for aortic stiffness, an important marker for atherosclerosis
- gold standard: carotid-femoral PWV
- not practical for general practitioner
- hence: move to local carotid PWV measurement

![Diagram of Pulse wave velocity measurement](image)
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Silicon photonics circuit for swept source OCT

Silicon chip: 0.75 × 5 mm² (waveguide loss: 0.35 dB/cm)
Reference arm with 13 cm physical length (50.4 cm optical length)
Sensitivity: −62 dB with 115 µW power delivered to the sample
Axial resolution: 25 µm (limited by bandwidth of fiber-chip grating couplers)

G. Yurtsever et al., Optics Letters 2014

Optical spectroscopy: fingerprint for molecular sensing

Probing the photon-electron coupling in molecules
Probing the photon-phonon coupling in molecules

Absorption spectra of simple molecules

NIR/MIR/FIR

UV/Visible/NIR

Fluorescence spectrum of GFP
Raman spectrum of D-glucose

Si₃N₄/SiO₂ circuit for Fourier domain OCT

Si₃N₄/SiO₂ waveguides (TriPleX) on silicon chip: 10 × 33 mm²
Waveguide loss: 0.14 dB/cm
Reference arm with 19 cm physical length
Sensitivity: −65 dB with 100 µW power delivered to the sample

G. Yurtsever et al., Biomedical Optics Express (2014)
Glucose absorption spectroscopy

Objective: Continuous Glucose Monitoring by means of subcutaneous implant

Transmission glucose + water displacement

For glucose sensing in humans (3-15 mM): Largest change in transmission is 0.5 % Required sensitivity: 0.02%

View of the chip

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Laser Doppler vibrometry and optical coherence tomography
Spectroscopy-on-a-chip
  ➔ Absorption spectroscopy for glucose detection
  Raman spectroscopy
Molecular vibrations: fingerprint for chemical composition

Some modes of vibrations of methylene group - $\text{CH}_2$

Typical vibration frequencies: several tens of THz

Glucose absorption spectroscopy: proof-of-concept

Use measured spectrum of 36 mM solution as the basic vector

Demonstrated sensitivity of 1mM

E. Ryckebeek et al, Biomedical Optics Express (2014)

Raman spectroscopy

Raman spectrum of $\text{CCl}_4$

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Absorption spectroscopy for glucose detection

→ Raman spectroscopy
Asset of waveguide based Raman spectroscopy

- Large étendue from particle cloud:
  ⇒ Resolution - sensitivity - size compromise for the spectrometer
- In a confocal microscope:
  Raman Scattering cross section

\[ P_{\text{col}} = \frac{2}{n} \frac{\lambda_0}{\rho \sigma_{\text{Raman}}} \]

Main asset

\[ \eta_{\text{Raman}} = \int d^3 \mathbf{r} \left| E_{\text{Raman}}(r) \right|^2 \frac{\rho}{\rho_{\text{pump}}} \]

Raman spectra of viruses

- MNV4 (Norovirus)
- MAD (Adenovirus)
- MHV (Coronavirus)
- SA11 (Rotavirus)


Raman spectrum of IPA on silicon-nitride waveguide

IsoPropylAlcohol

Light in

Fluid

waveguide

Light out

Counts/sec

6000

4000

2000

0

Wavenumbers (cm\(^{-1}\))

819

943

1134

1450

2080

2717

2974


Efficiency of collection >25x better than in Raman microscope

Raman signal strength

Typical molecular scattering cross-section: 10\(^{-19}\) cm\(^2\)

After propagation through 1 cm of 100% dense analyte, one photon is scattered for 10\(^{-6}\) - 10\(^{-7}\) input photons

Ways to deal with the weak signals
- use strong pumps
  - unpractical, expensive, damage
- use long integration times
  - unpractical
- surface enhanced Raman scattering (SERS) using rough gold surfaces or nanoparticles
  - poor reproducibility of spectra, probing of nm-sized volumes
- coherent anti-stokes Raman scattering (CARS)
  - nonlinear; needs two lasers or supercontinuum source
Extinction spectra of on-chip nano-antennas

Example: experimental single-rod antenna resonance as a function of height

On-chip nanoplasmonic antennas for enhanced Raman

Fabricated nanoplasmonic antennas (by e-beam lithography):
• gaps of ≈ 10 nm can be achieved
• all antennas are integrated on top of a 700 nm single-mode Si$_3$N$_4$ waveguide

Raman spectrum of NitroThymoPhenol (NTP) bound to the gold nano-antenna

Nanoplasmonic enhancement on Si$_3$N$_4$ waveguide

On-chip nanoplasmonic antennas

Fabricated nanoplasmonic antennas (by e-beam lithography):
• gaps of ≈ 10 nm can be achieved
• all antennas are integrated on top of a 700 nm single-mode Si$_3$N$_4$ waveguide

Excitation of an array of nanoplasmonic antennas on a single-mode waveguide

Pump attenuation by a single antenna: up to 25%!! → very efficient use of pump power
Conclusion

Silicon photonics:

- Mature technology in CMOS-fab, low cost in high volume
- High index contrast: miniaturisation, Purcell effect, high field confinement
- Strong industrial traction for telecom/datacom applications
- From visible to mid-IR
- Many new materials integrated on silicon
- Very large potential for:
  - lab-on-chip applications (biosensors, Raman-sensors)
  - body implants (glucose sensors)
  - point-of-care instruments (breath analysis, pulse wave velocity, OCT)

Acknowledgements

Photonics Research Group
professors P. Bienstman, W. Bogaerts, G. Marti, G. Roelens,
N. de Thomas, D. Van Thourhout

many postdocs and PhDs

IMEC CMOS process line
and ePIXfab [www.epixfab.eu]

Funding and collaborations through national and EU research projects

Collaborations:
C. Detavernier (UGent), A. Skirtach (UGent), J. Martens (KULeuven), W. Drexler (MUVienna), T. Van Leeuwen (UAmsterdam), P. Van Dorpe (imec)
# Program Photonics Event 2015 - Vision, Robotics & Mechatronics 2015

**Thursday June 4**

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**9:00-9:45**

**BRABANTZAAL**

- Opening
  - Bert Voskamp, PhotonicsNL

**9:45-10:05**

**BRABANTZAAL**

- Visit expo

**10:05-10:15**

**BRABANTZAAL**

- Exosomes enlightened
  - Edwin van der Pol, Public researcher, Academic Medical Center, University of Amsterdam

**10:15-10:35**

**BRABANTZAAL**

- Needles! Needle-free non-invasive blood analysis on premature babies
  - Niels Bouschaar, Postdoc, Twente University

**10:35-10:45**

**BRABANTZAAL**

- Visit expo

**10:45-10:55**

**BRABANTZAAL**

- Combined photoacoustic and ultrasonic modulated optical tomography for quantitative imaging
  - Alain Haavard, Researcher, Biomedical Photonics imaging group, University of Twente

**10:55-11:05**

**BRABANTZAAL**

- Blood streamline diagnosis during lung biopsy procedures using diffuse reflectance spectroscopy
  - Johan W. Stokrook, Clinical Research Scientist, PhD, candidate, Netherlands Cancer Institute, Philips Research

**11:05-11:15**

**BRABANTZAAL**

- Mosquito,Negative imaging as a diagnostic tool for severeaneous squamous cell carcinoma
  - Gigi Fantini

**11:15-11:25**

**BARONIEZAAAL**

- 10:50-11:25
  - 10:50-11:05 RoboNED DUO presentation - Robotics and Healthcare
    - Prof. dr. Tonio Borgo, Chairman of governing board at non-profit organisation Vroedencoöperatie
    - Dr. Marcel Haecken, Associate professor at Hogeschool Windesheim, Hoorn
  - 11:05-11:10 Active stereo vision of togaardkweel for robotic waste industrial 3D volume sensitivity
    - Roosdorp Van der Vliet, CEO, Photonics Engineering
  - 11:10-11:15 Sensing Vision for Drones in Civil Applications
    - Jens van de Looije, Professor Computer Vision, Centrale Esfondes Computer Vision, University of Amsterdam
  - 11:15-11:30 NTS' 125 years of experience in design and construction of optomechatronical systems
    - Theo van der Vliet, Operations Manager NTS Optie

**11:35-11:45**

**BRABANTZAAL**

- Visit expo

**11:45-11:55**

**BRABANTZAAL**

- Combined photoacoustic and ultrasonic modulated optical tomography for quantitative imaging
  - Alain Haavard, Researcher, Biomedical Photonics imaging group, University of Twente

**12:00-12:40**

**BRABANTZAAL**

- Real-time tissue diagnosis during lung biopsy procedures using diffuse reflectance spectroscopy
  - Johan W. Stokrook, Clinical Research Scientist, PhD, candidate, Netherlands Cancer Institute, Philips Research

**12:00-12:40**

**BRABANTZAAL**

- A visual inspection of the 3D concept design
  - Lars Hooger, LIR Technologies BV

**12:40-13:00**

**BRABANTZAAL**

- Visit expo

**13:00-14:30**

**BARONIEZAAAL**

- Silicon photonics: an enabler for the internet and for the life science
  - Rob Bax, Ghent University - Inno

**14:30-15:00**

**BARONIEZAAAL**

- RoboNED DUO presentation - Autonomous vehicles in agriculture settings
  - Alain Marten, Managing Director at Probota
  - Dr. Maurice Ruijter, Sr. scientist specialist, TNO Automotive and group leader of the Cooperative Vehicle Systems group

**15:00-15:30**

**BARONIEZAAAL**

- The pursuit of exceptional 3D sensor design
  - Lars Hooger, LIR Technologies BV

**15:30-16:10**

**BRABANTZAAL**

- Visit expo

**16:10-16:40**

**BRABANTZAAL**

- Workshop: Mechatronics - what's worth the cost of the technology
  - Theo Bolderman, System Architect, TEGEMA

**16:40-17:00**

**BRABANTZAAL**

- Networking drinks