SILICON PHOTONICS

PHOTONIC INTEGRATED CIRCUITS FOR TRANSCEIVERS AND LIFE SCIENCE APPLICATIONS

Roel Baets

Lasers: Science and Technology, Vilnius, August 2018

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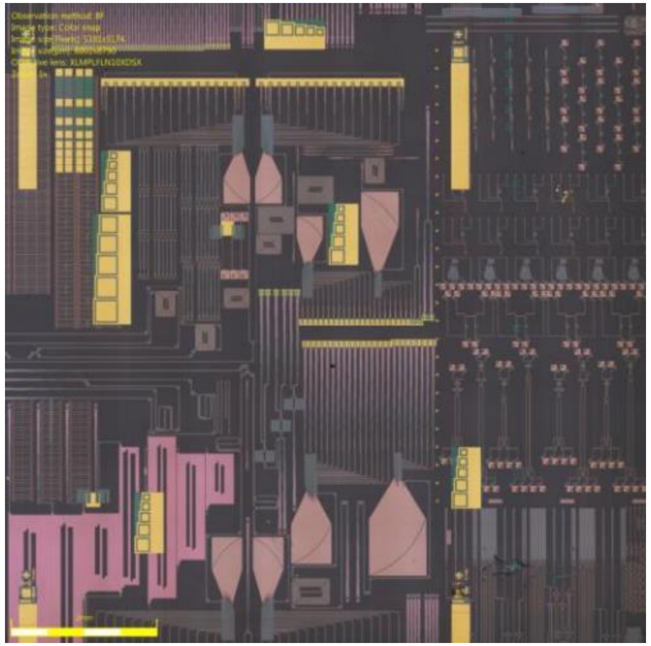
imec
embracing a better life

erc

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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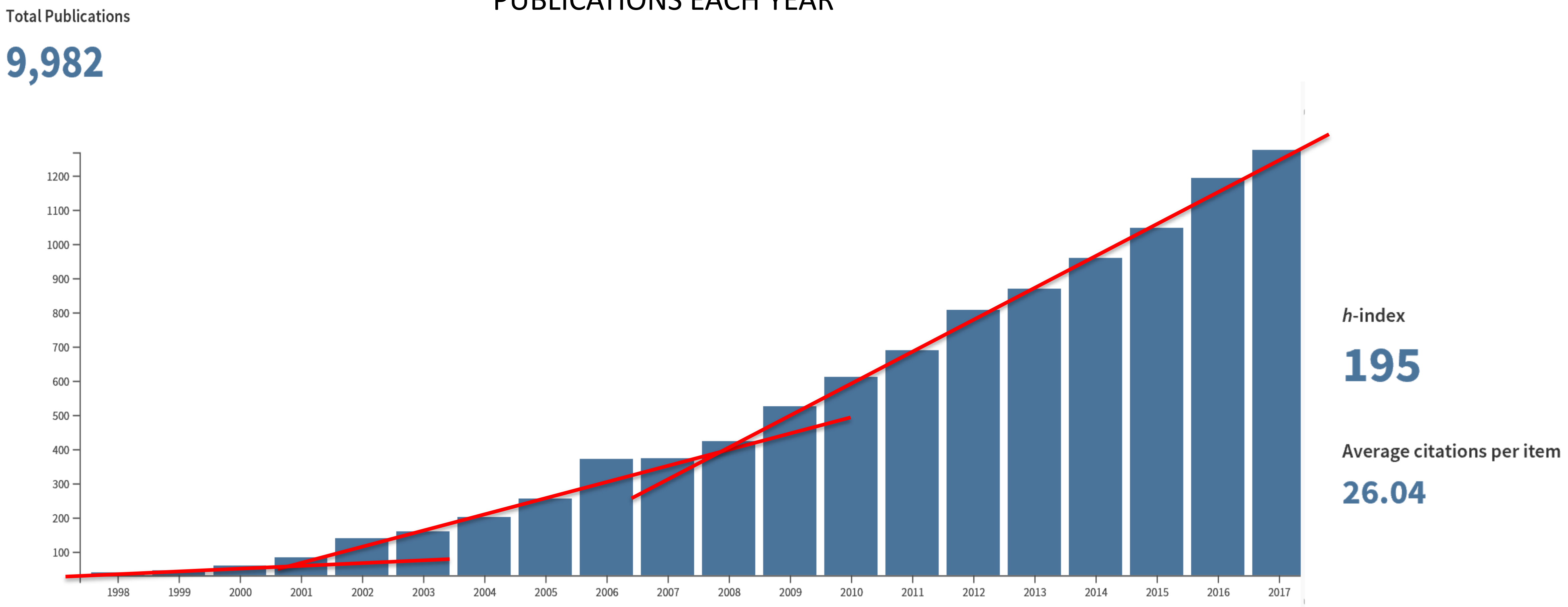
THE PAST 20 YEARS: STUNNING RESEARCH PROGRESS

Citation report for 9,982 **results** from Web of Science Core Collection
You searched for: **TOPIC:** (silicon) *AND* **TOPIC:** (photonic OR photonics) *AND* **YEAR PUBLISHED:** (1998-2017)
Indexes: SCI-EXPANDED.

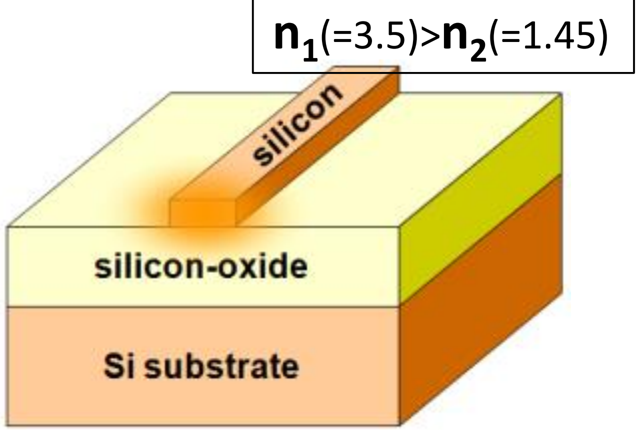
PUBLICATIONS EACH YEAR

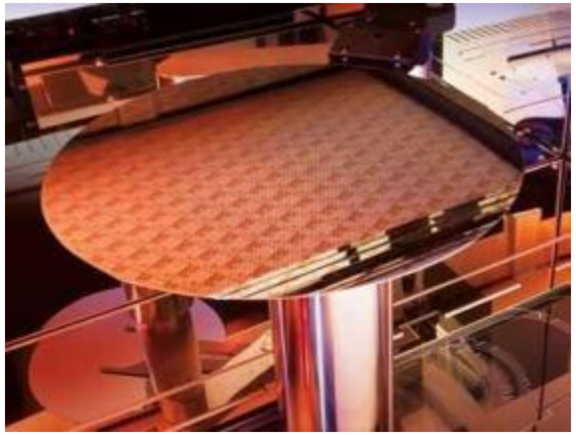


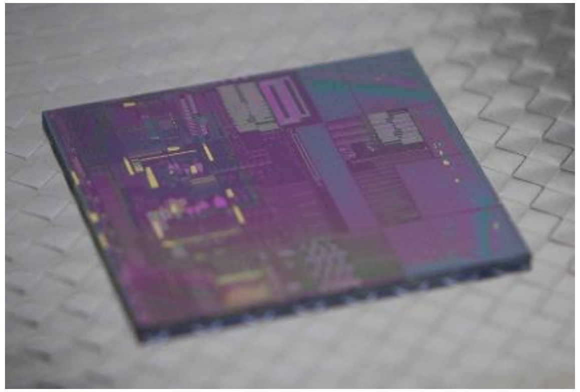
(Conferences not included)

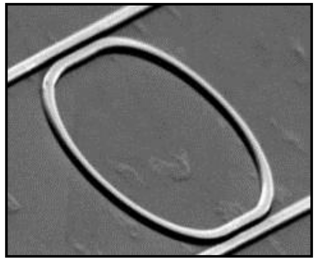
WHY SILICON PHOTONICS

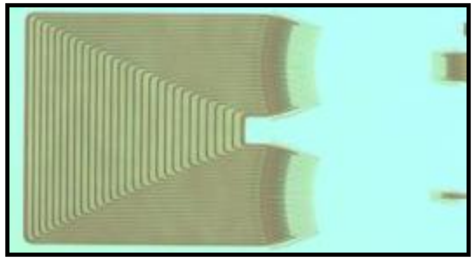
- High index contrast ⇒ very compact PICs
- CMOS technology ⇒ nm-precision, high yield, existing fabs, low cost in volume
- High performance passive devices
- High bitrate Ge photodetectors
- High bitrate modulators
- Wafer-level automated testing
- Hierarchical set of design tools
- Light source integration (hybrid/monolithic?)
- Integration with electronics (hybrid/monolithic?)

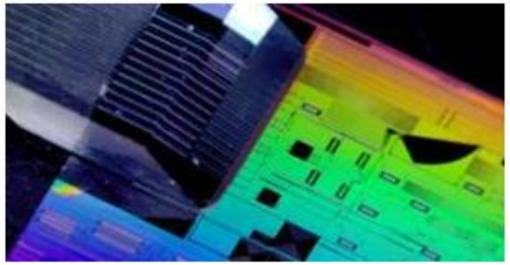






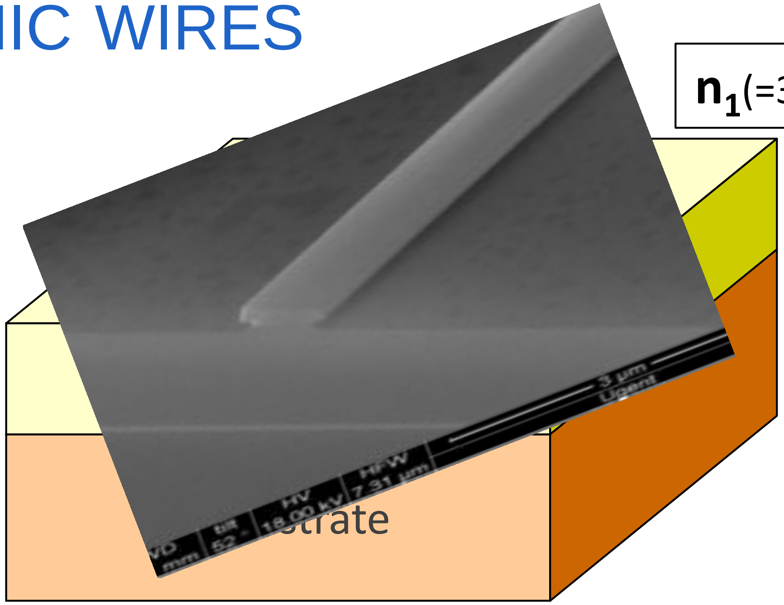


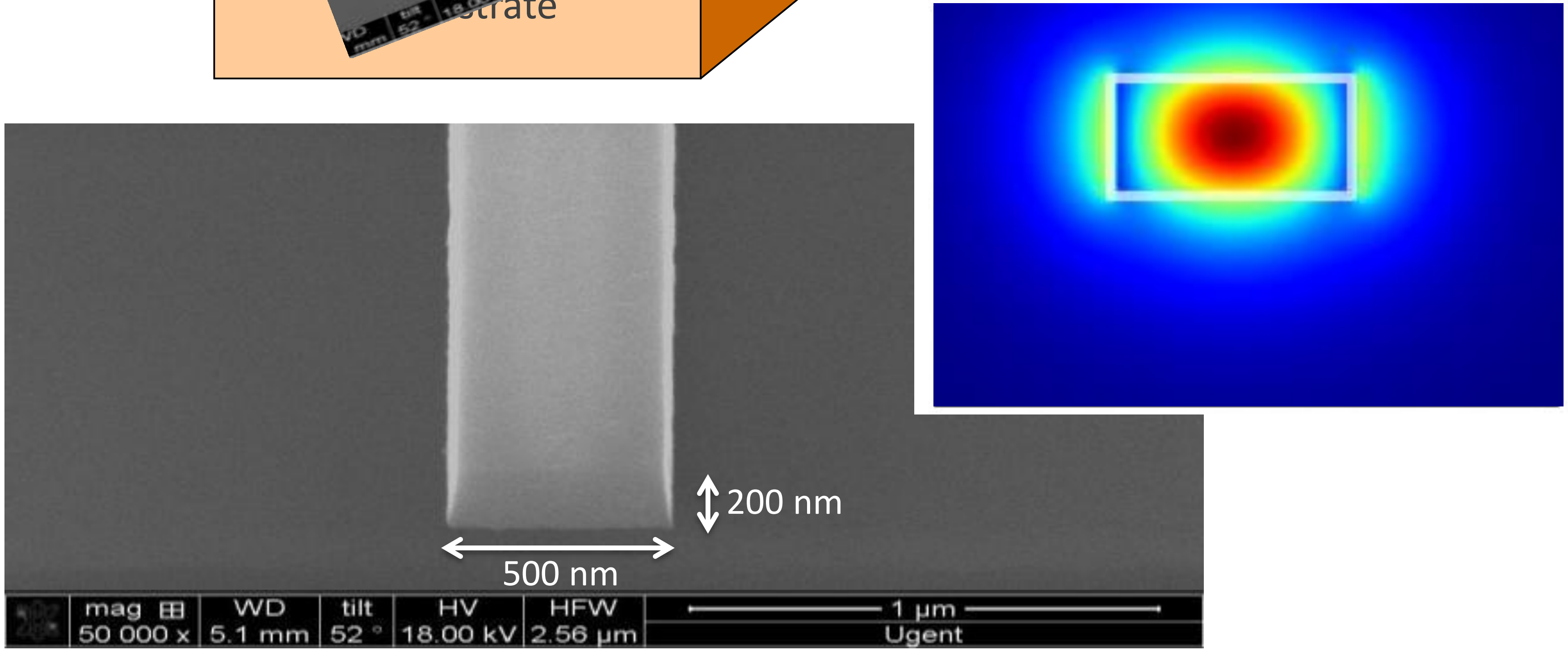




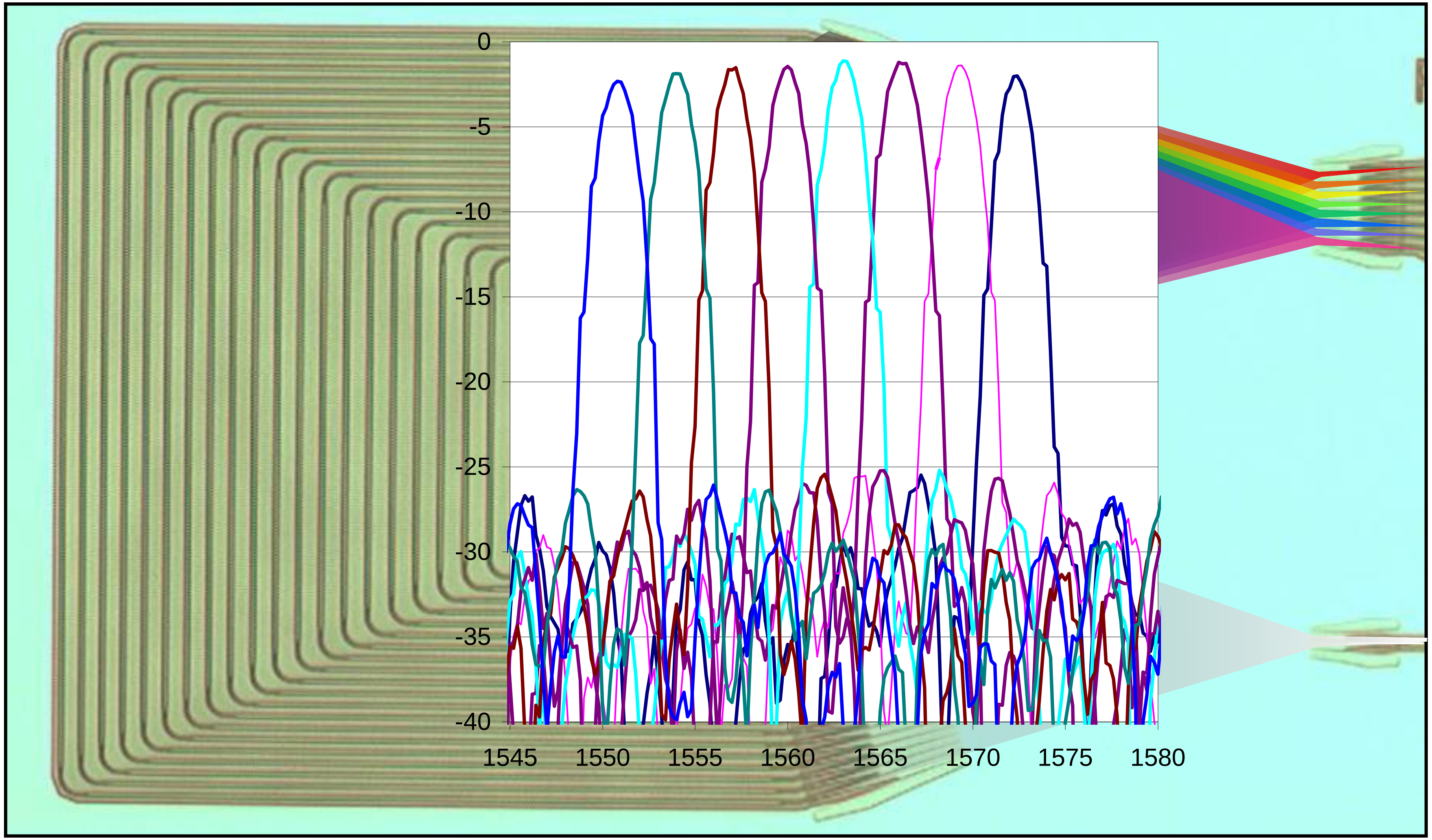
SILICON PHOTONIC WIRES

n_1(=3.5)>**n_2**(=1.45)





ON-CHIP SPECTROMETER (200 X 350 MM^2)



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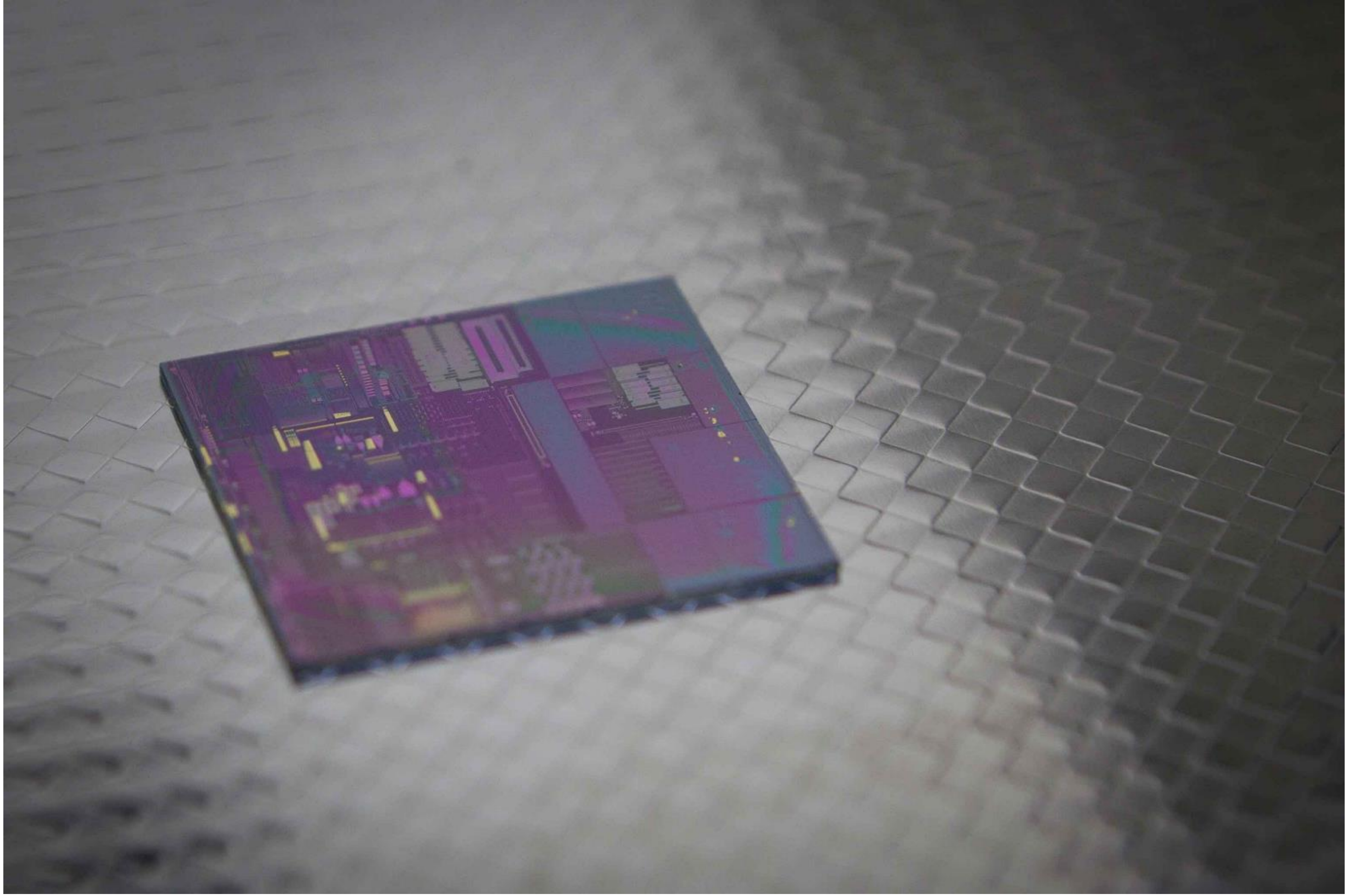
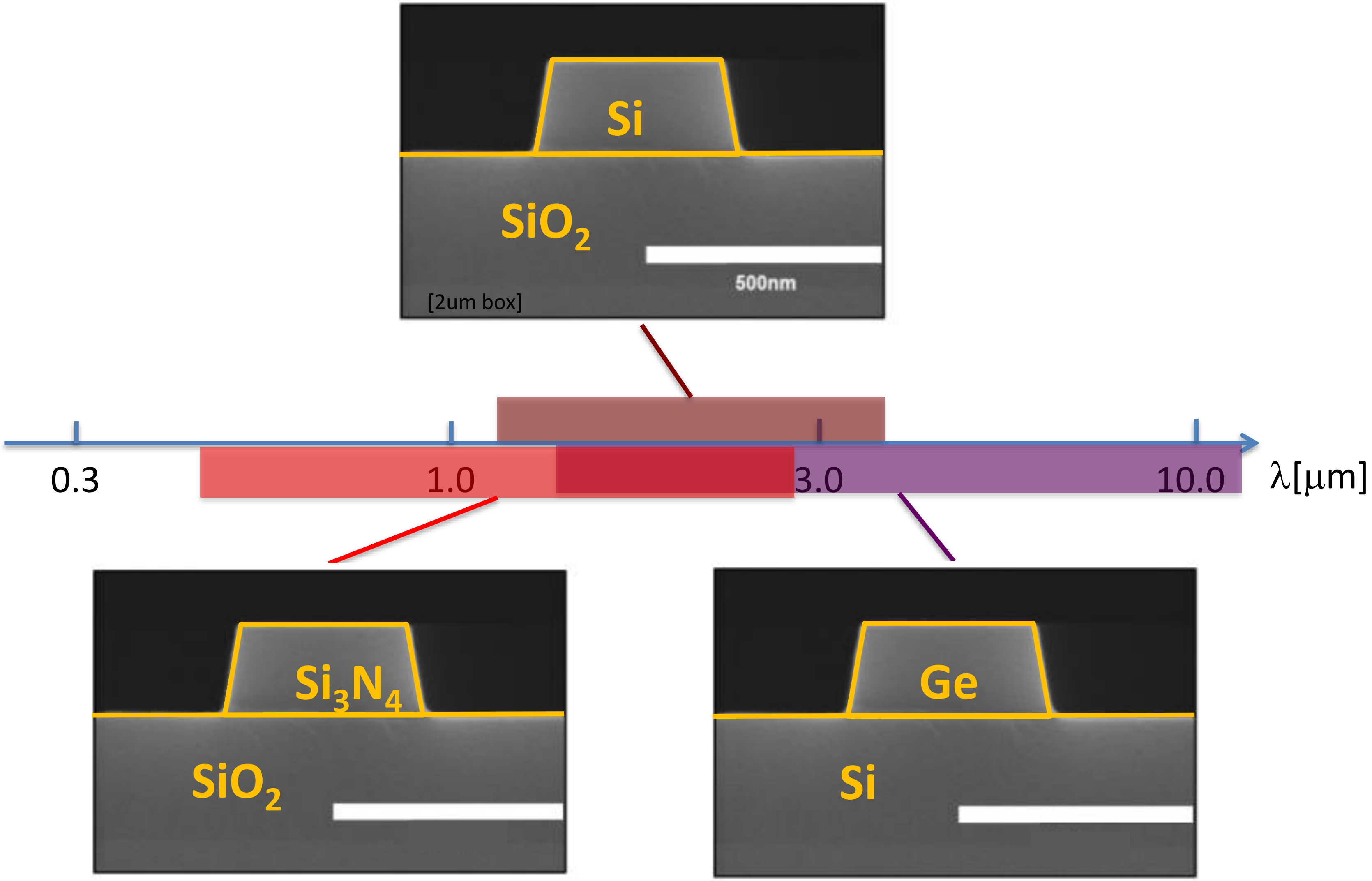


SILICON PHOTONICS: EXTENDING THE WAVELENGTH RANGE

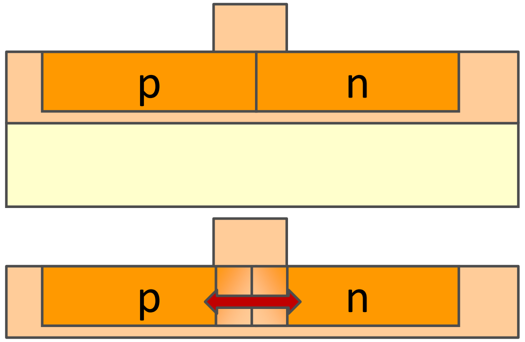
WITHOUT LEAVING THE CMOS FAB



OUTLINE

- Silicon photonics for high speed optical transceivers
- Silicon photonics for sensing and life science
- Integrated light sources

Modulator based on carrier depletion

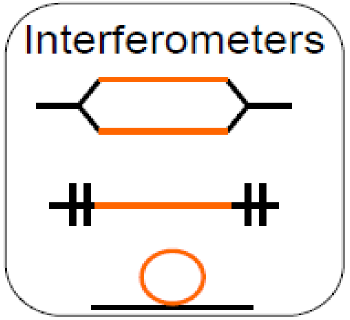


Applied voltage

Change of free electron/hole density

Change of refractive index

Change of optical phase

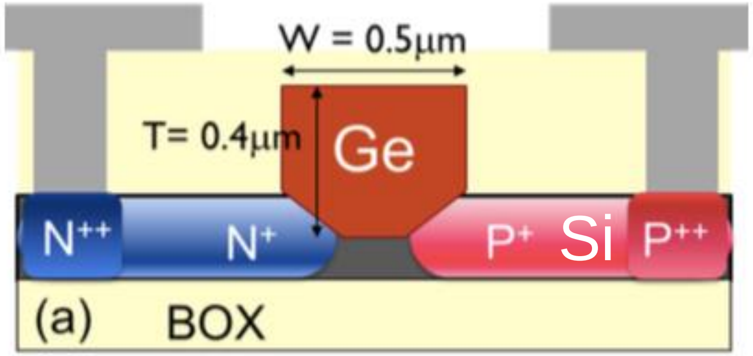


Change of optical intensity

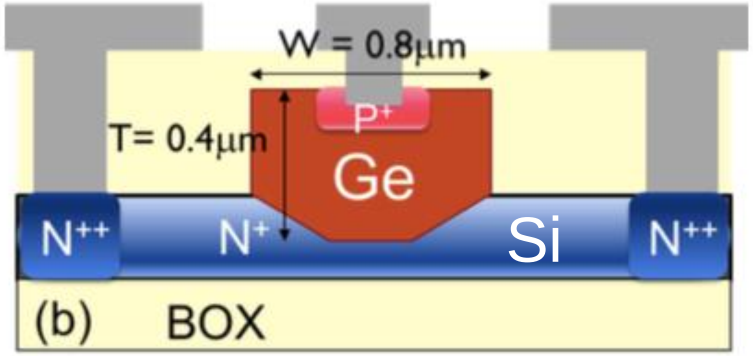
Year	Group	Electrical structure	Optical structure	Efficiency	Loss	ER	Bit rate	Vpp	Length
2007	Intel	Vertical PN junction	Mach-Zehnder	4 V cm	7 dB	–	30 GBps	6.5 V	1 mm
2009	Kotura	Lateral PN junction	Ring	1.5 V cm	3 dB	8 dB	10 GBps	2 V	$2\pi \cdot 15\,\mu m$
2010	Kotura	Lateral PN junction	Mach-Zehnder	1.4 V cm	2.5 dB	7 dB	12.5 GBps	6 V	1 mm
2011	MIT	Vertical PN junction	Microdisk	–	1 dB	5 dB	12.5 GBps	1.5 V	$\pi \cdot 3.5\,\mu m$
2011	Southampton U.	Lateral PN junction	Mach-Zehnder	2.7 V cm	15 dB	10 dB	40 GBps	6V	3.5 mm
2012	Paris-Sud U.	Lateral PIPIN junction	Mach-Zehnder	3.5 V cm	6 dB	6.6 dB	40 GBps	7 V	4.7 mm
2012	Washington U.	Lateral PN junction	Mach-Zehnder	2 V cm	5 dB	3.7 dB	20 GBps	0.63 V	5 mm
2012	Yokohama U.	Lateral PN junction	PhC-MZI	–	9.1 dB	–	40 GBps	5.3 V	90 μm
2012	I. Semicond.	Zigzag PN junction	Ring	1.7 V cm	–	3 dB	44 GBps	3 V	22 μm
2013	Colorado U.	Interleaved PN junction	Ring	–	4.5 dB	5.2 dB	5 GBps	3.6 V	$2\pi \cdot 5\,\mu m$
2013	Paris-Sud U.	Interleaved PN junction	Mach-Zehnder	2.4 V cm	4 dB	7.9 dB	40 GBps	6 V	0.95 mm
2013	IMEC/Gent U.	Lateral PN junction	Ring	-	-	11 dB	10 GBps	1 V	$2\pi \cdot 40\,\mu m$
2014	MIT	Vertical PN junction	Microdisk	–	1 dB	8 dB	44 GBps	2.2 V	$\pi \cdot 4.8\,\mu m$
2014	McGill U.	Lateral PN junction	Michelson	0.7 V cm	3 dB	3.3 dB	25 GBps	4 V	500 μm
2014	Valencia U.	Vertical PN junction	–	0.4 V cm	4.7 dB	–	–	–	–
2014	A*STAR	Lateral PN junction	Mach-Zehnder	1.65 V cm	7.65 dB	5.66 dB	28 GBps	1.3 V	5.5 mm
2014	Delaware U.	Lateral PN junction	Ring	2.2 V cm	7 dB	6.2 dB	40 GBps	4.8 V	$2\pi \cdot 7.5\,\mu m$

GE PHOTODIODES

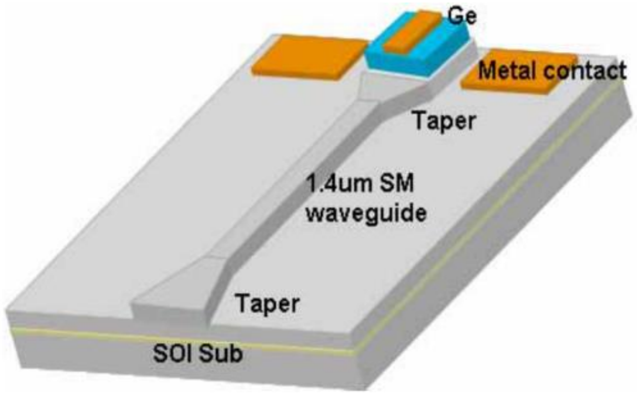
Lateral PIN



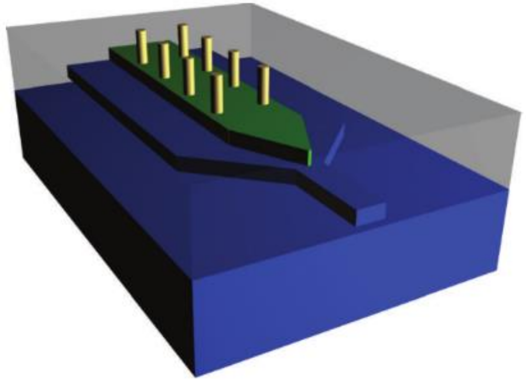
Vertical PIN



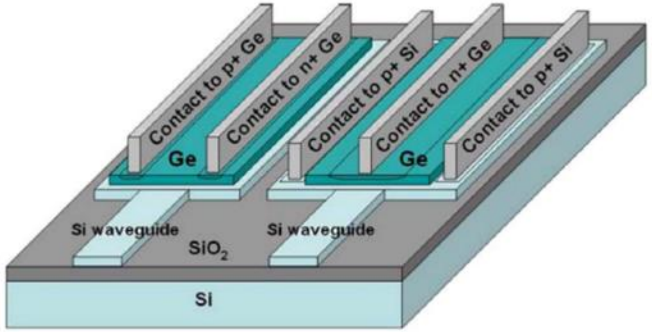
GE PHOTODETECTORS: STATE OF THE ART



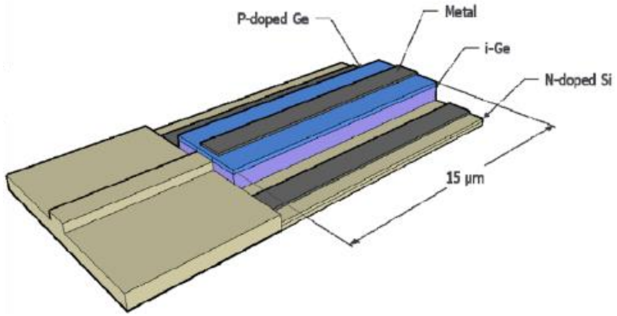
Intel, 2005.



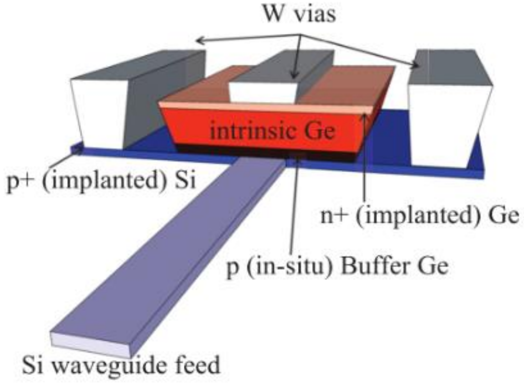
Luxtera, 2008.



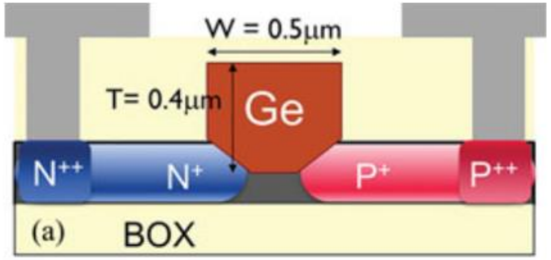
IME, 2008.



IEF, 2009.



Sandia Lab., 2011.

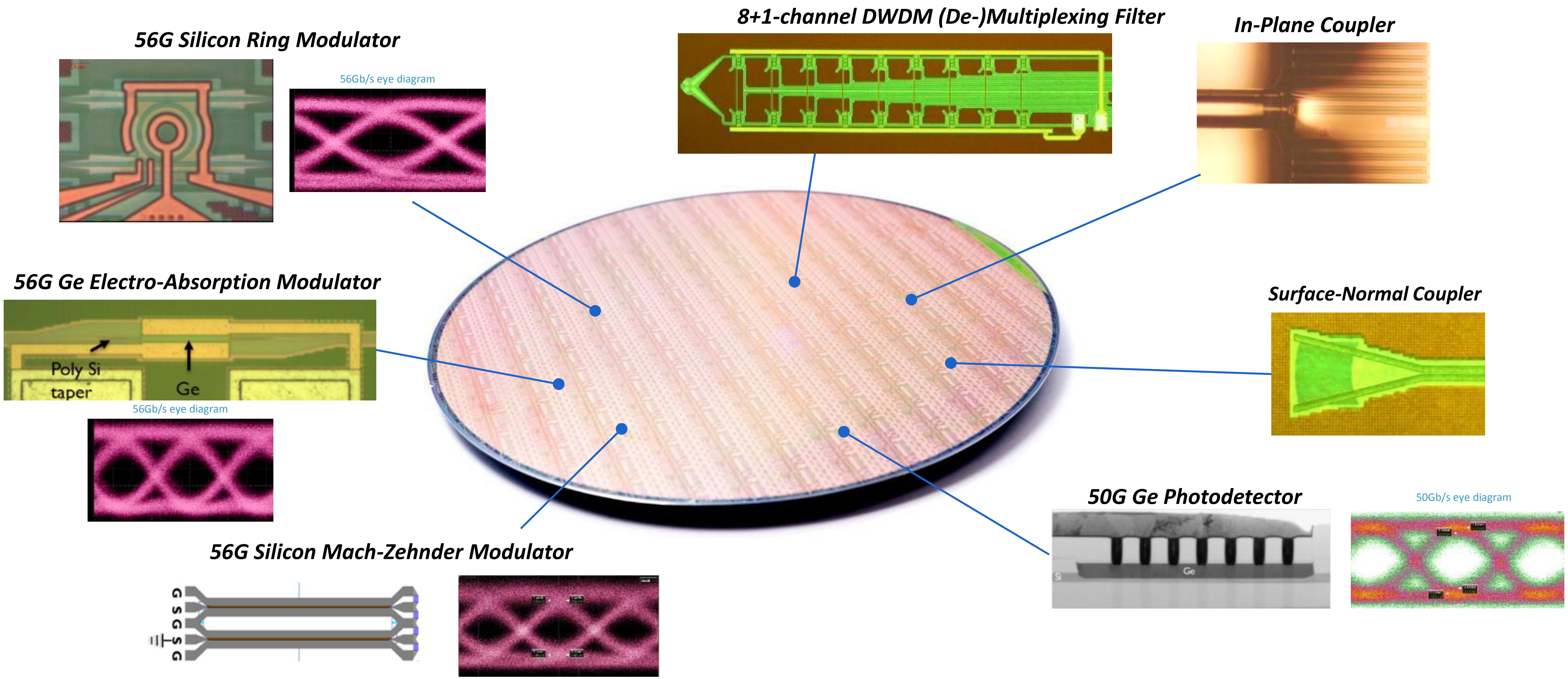


IMEC, Gent Univ., 2015.

Main characteristics of all detectors:

- ✓ **Bandwidth > 40GHz**
- ✓ **Low dark current < µA**
- ✓ **High responsivity > 1A/W @ 1550nm**

IMEC STATE-OF-THE-ART SILICON PHOTONICS PLATFORM



Co-integration of the various building blocks in a single platform

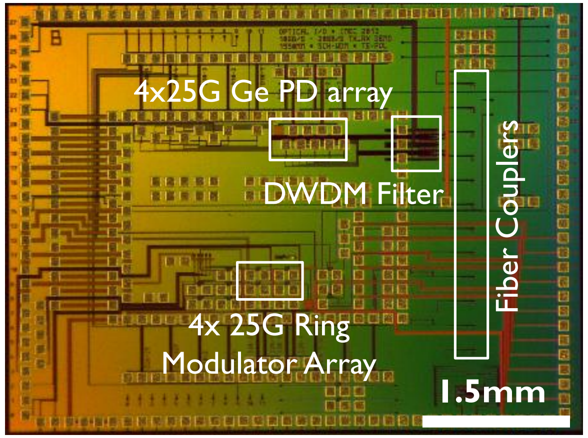
Today available on 200mm wafer size, coming soon on 300mm

95% compatible with CMOS130 in commercial foundries

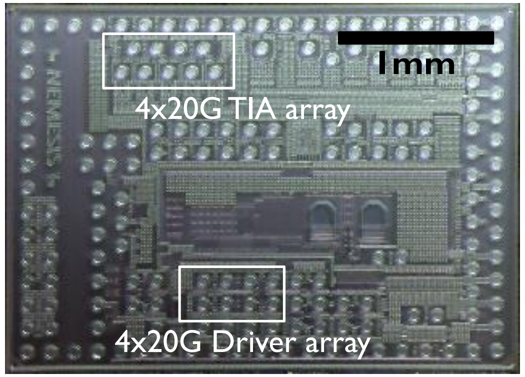
HYBRID CMOS SI-PHOTONICS TRANSCEIVER DEMO

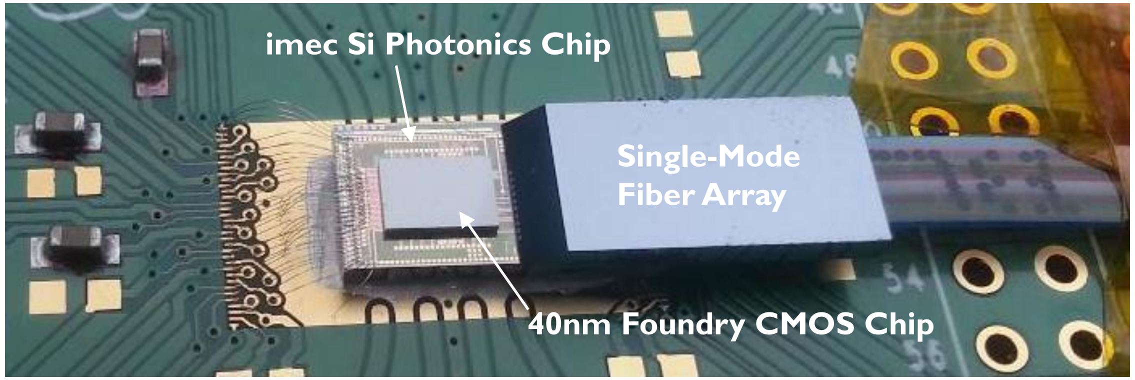
Putting it all together

imec Silicon Photonics Chip



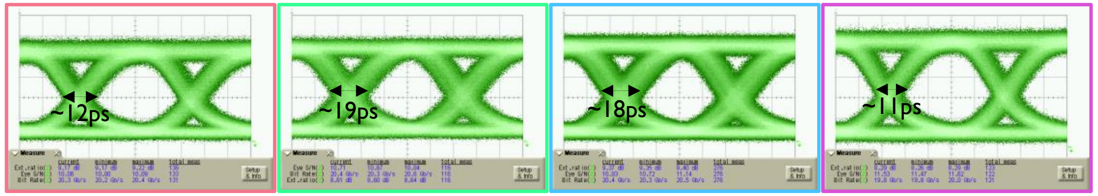
40nm Foundry CMOS Chip



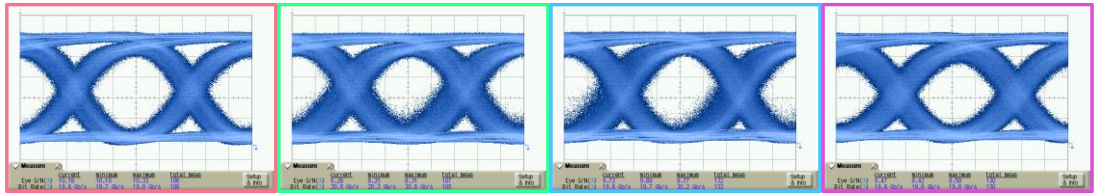


Hybrid CMOS Si-Photonics Transceiver Module

Transmitter Eye Diagrams (4x20G)



Receiver Eye Diagrams (4x20G)



4x DWDM Wavelength Channels
Each operational at 20G
~ 2mW/Gbps power efficiency*

***Excluding laser and thermal control power**
(Rakowski, ISSCC 2015)

THE PAST 5-10 YEARS: STUNNING INDUSTRIAL DEVELOPMENT IN SILICON PHOTONICS, DRIVEN BY TELECOM/DATACOM

- active optical cables (eg PSM4: 4x28 Gb/s on parallel fibers)
- WDM transceivers (eg 4 WDM channels x 25 Gb/s on single fiber)
- coherent receiver (eg 100 Gb/s PM-QPSK)
- fiber-to-the-home bidirectional transceiver (eg 12 x 2.5 Gb/s)
- monolithic receiver (eg 16x20Gb/s)
- 40Gb/s, 50Gb/s and 100 Gb/s Ethernet (future: 400Gb/s)
- …

CompoundTek tsmc SilTerra amf ADVANCED MICRO FOUNDRY Finisar ACACIA COMMUNICATIONS, INC. Inphi Think fast. Xm KAIAM Ayar Labs JUNIPER NETWORKS aurrion TeraXion sicoya ciena ELENION TECHNOLOGIES TOWERJAZZ The Global Specialty Foundry Leader intel IBM CISCO LIGHTWIRE SKORPIOS TECHNOLOGIES GLOBALFOUNDRIES Mellanox TECHNOLOGIES molex LUXTERA NANOPHOTONIC INTEGRATED CIRCUITS Caliopa silicon photonics HUAWEI

OUTLINE

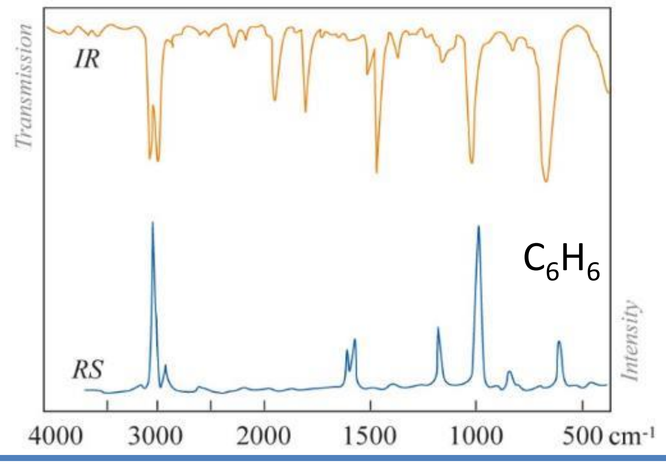
Silicon photonics for high speed optical transceivers

Silicon photonics for sensing and life science

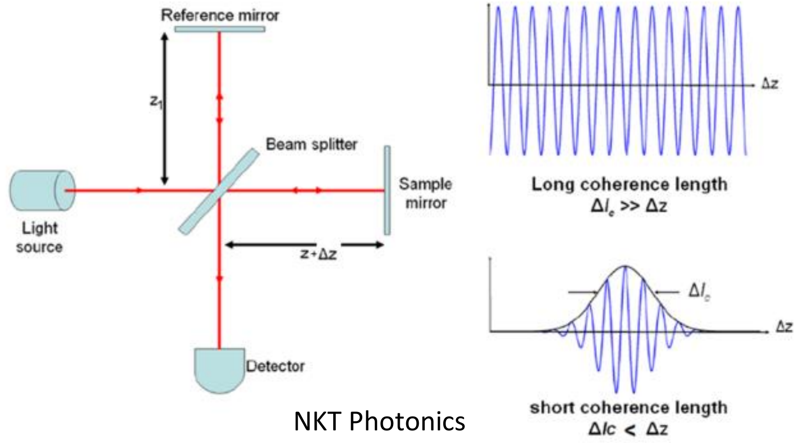
Integrated light sources

Sensing Applications enabled by silicon Photonic ICs

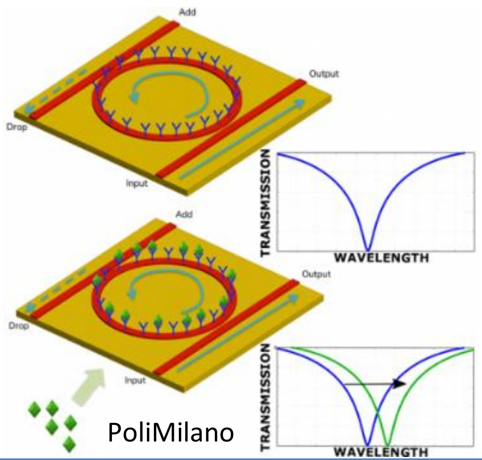
Vibrational spectroscopy (absorption, Raman)



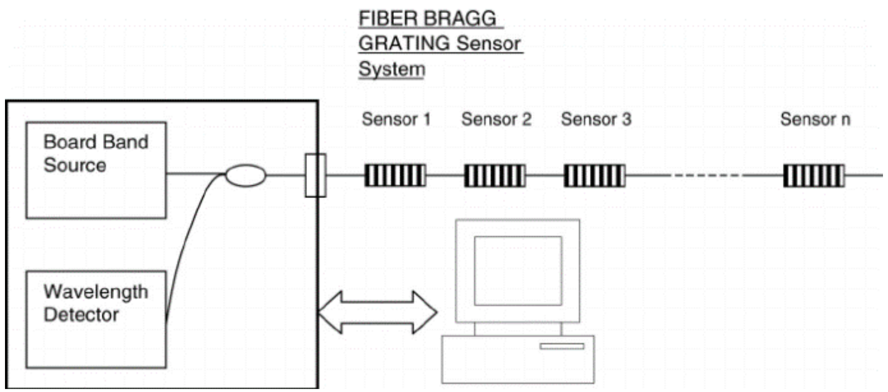
3D imaging (Lidar, OCT, LDV)



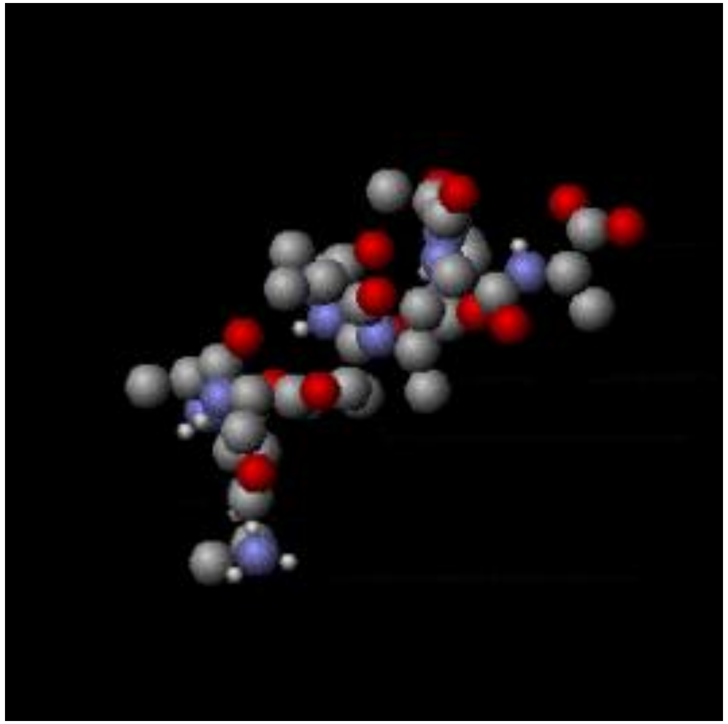
Refractive index sensing (biosensing, gas sensing)



Fiber sensor readout (FBG, Brillouin, Raman)



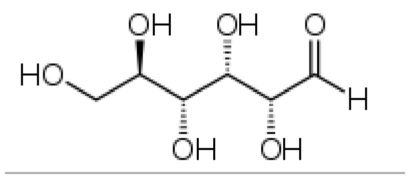
VIBRATIONAL SPECTROSCOPY: FINGERPRINT TECHNIQUE FOR CHEMICAL ANALYSIS



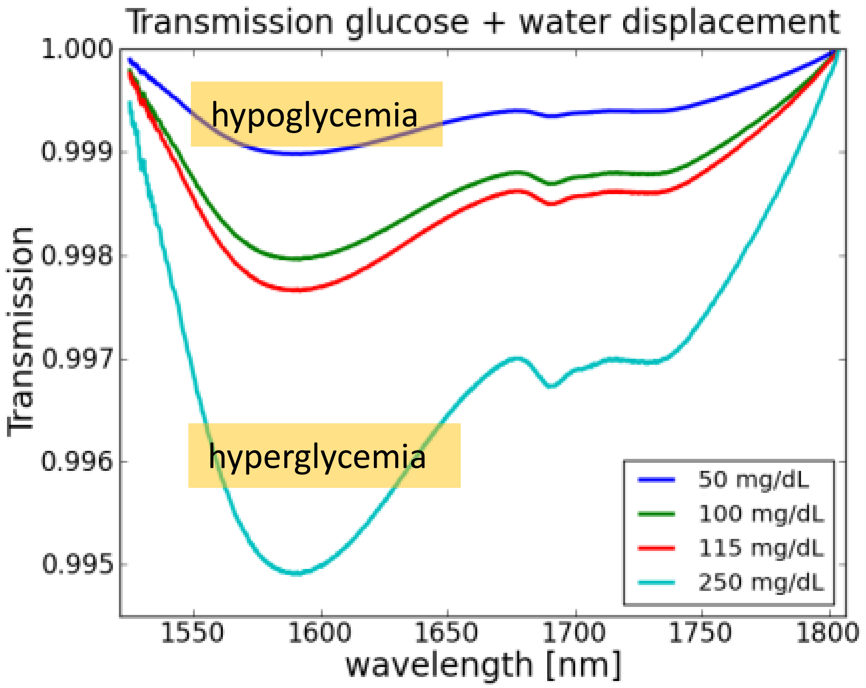
Infrared absorption spectroscopy
Very sensitive
"Poor"/expensive sources and detectors
Less compatible with biology

Raman spectroscopy
Very insensitive (but there are tricks)
Mainstream sources and detectors
More compatible with biology

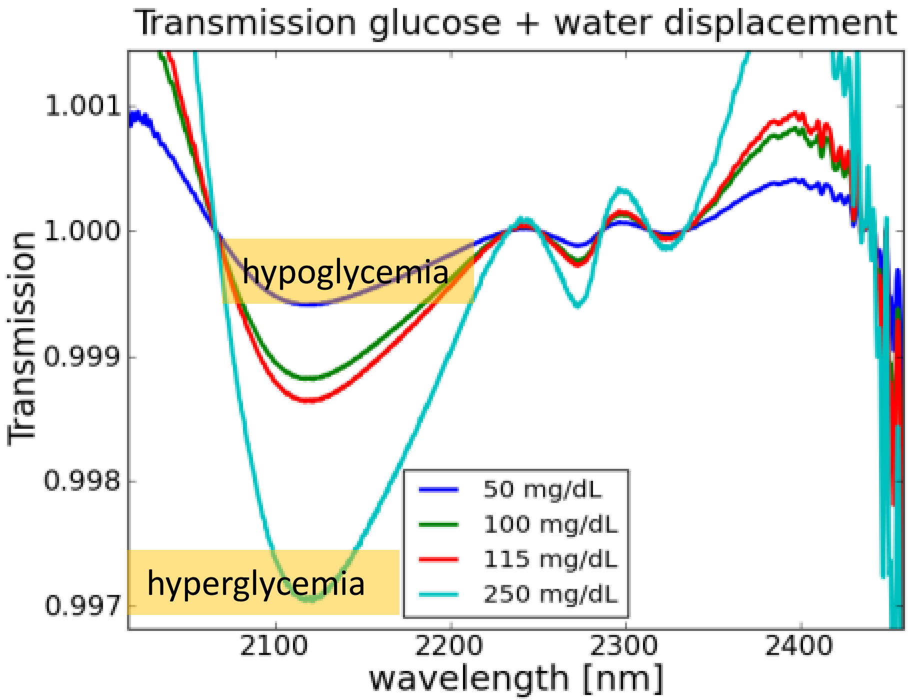
GLUCOSE ABSORPTION SPECTROSCOPY



Objective: Continuous Glucose Monitoring (CGM) by means of **subcutaneous implant**



First overtone band: 1500 - 1800 nm



Combination band: 2000 - 2500 nm

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

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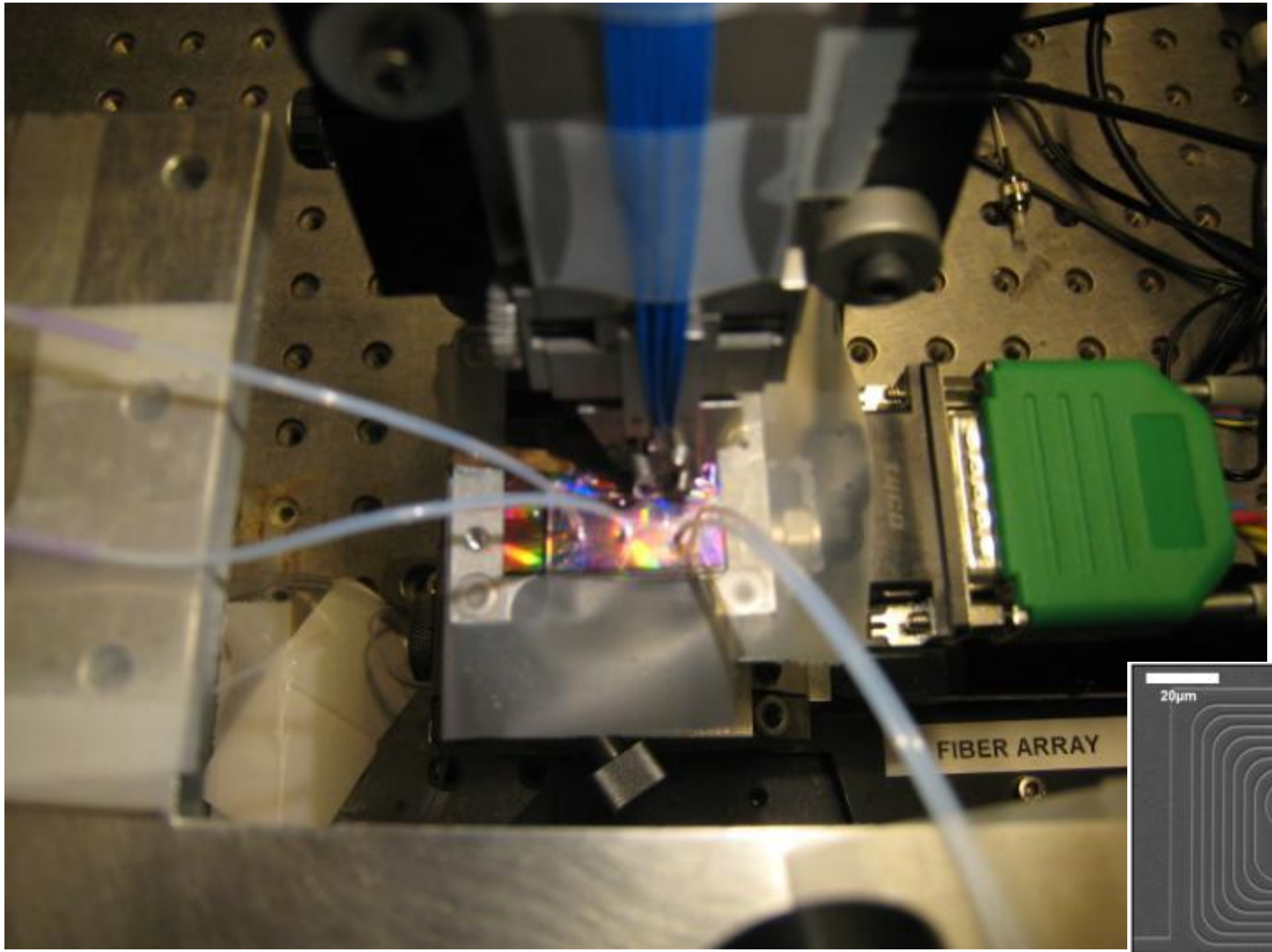
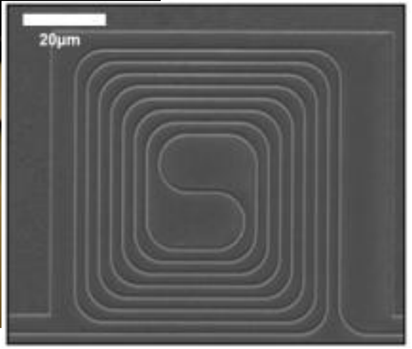
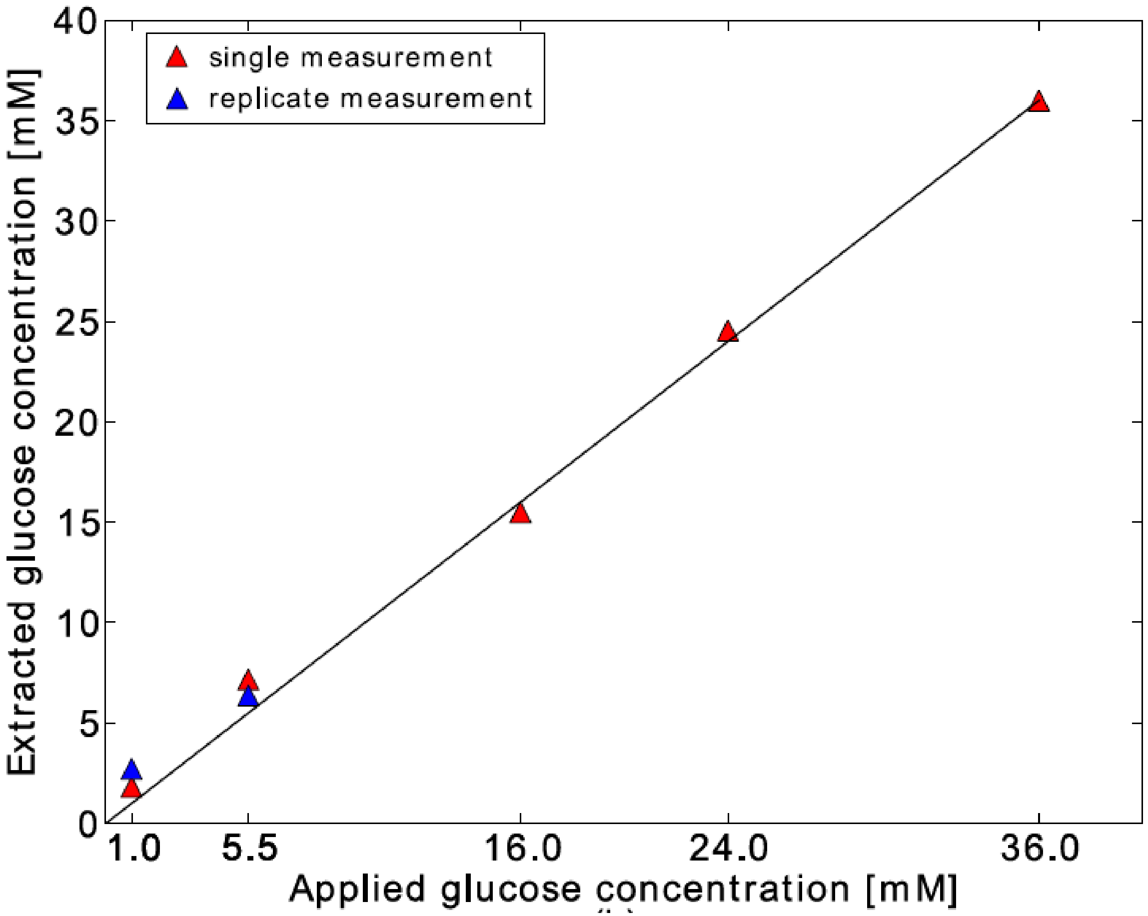
Proof-of-concept demonstration in the lab





GLUCOSE ABSORPTION SPECTROSCOPY: PROOF-OF-CONCEPT

Use measured spectrum of 36 mM solution as the basic vector

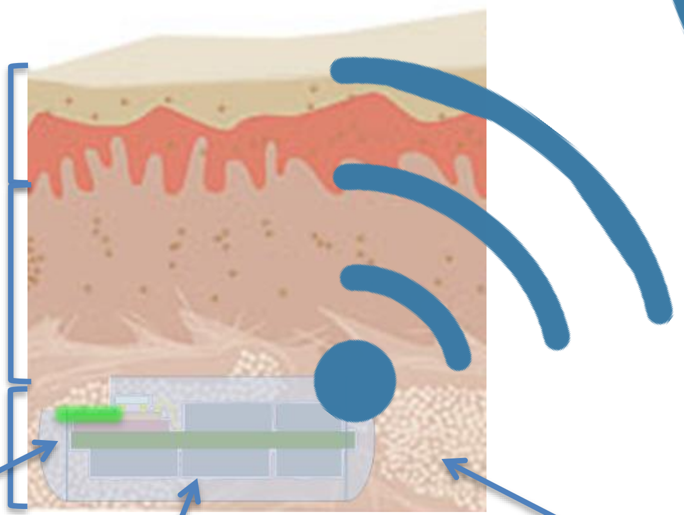


Demonstrated sensitivity of 1mM

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

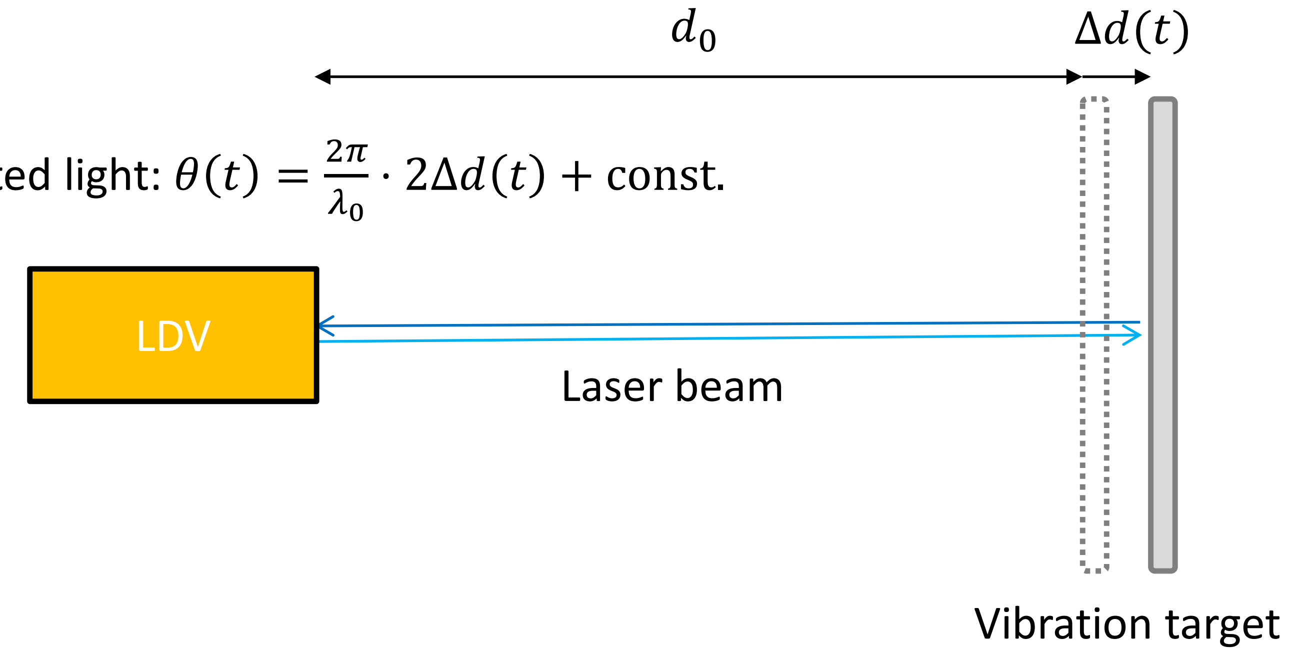
Continuous Glucose Monitoring enabled by silicon photonics

Subcutaneously implanted IR spectral analyser connected wirelessly to external transceiver (>6 months implantation time)



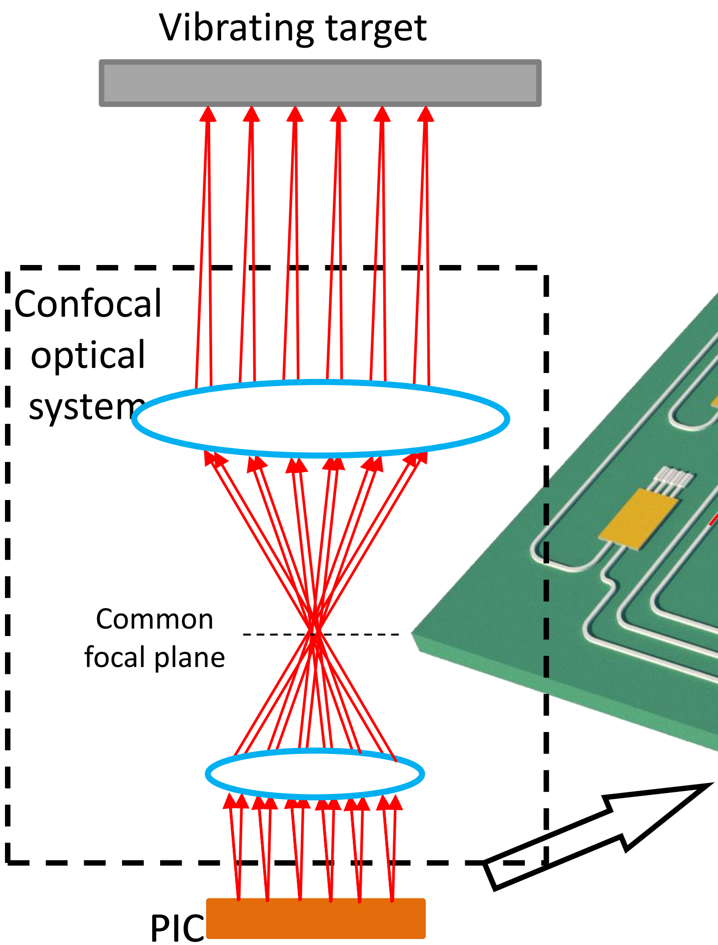
Laser Doppler Vibrometry (LDV): Displacement measurement

Phase shift of reflected light: $\theta(t) = \frac{2\pi}{\lambda_0} \cdot 2\Delta d(t) + \text{const.}$

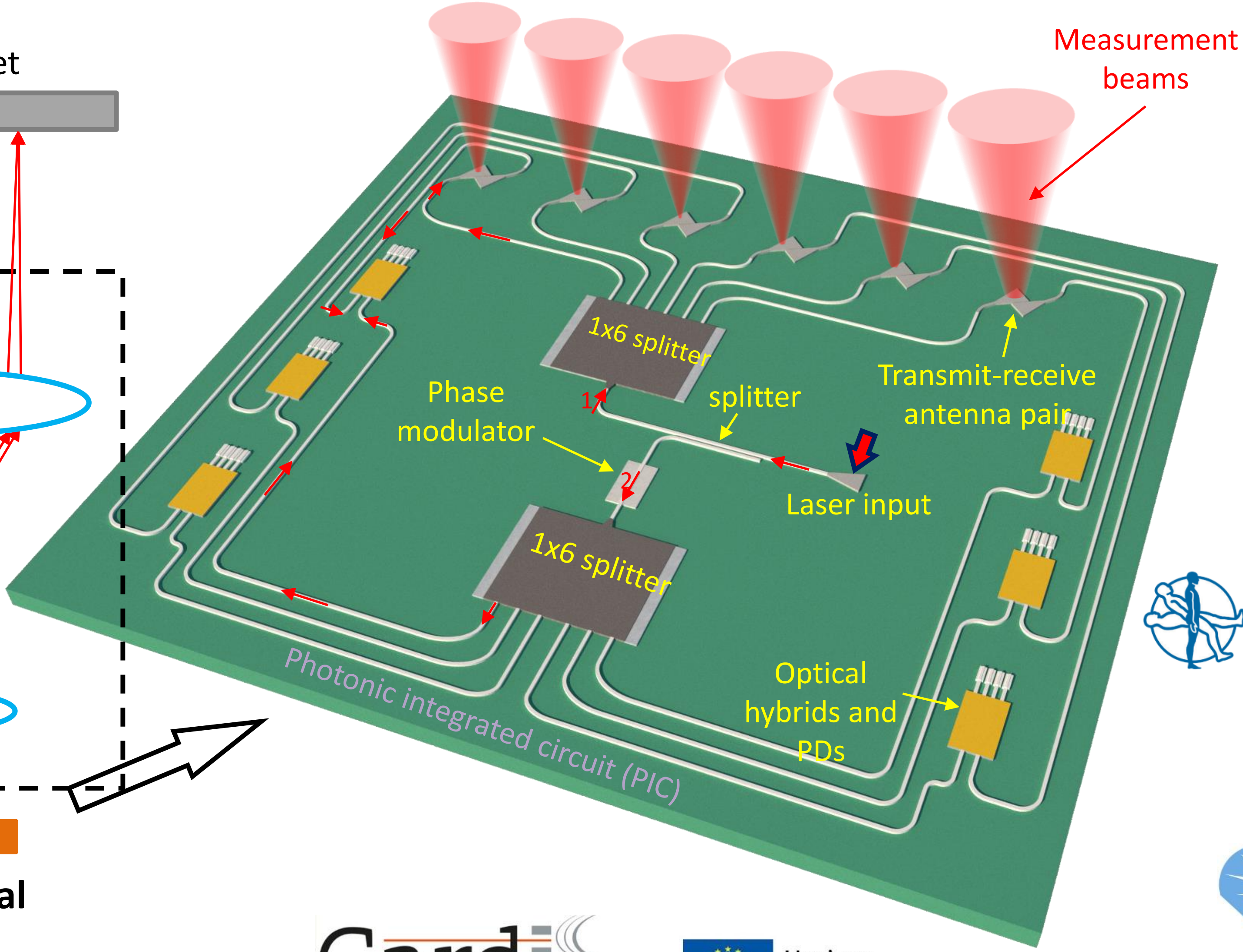


The displacement $\Delta d(t)$ can be retrieved by measuring $\theta(t)$.

Six-beam LDV



PIC and external optics



Medtronic

SIOS Meßtechnik GmbH

Tyndall National Institute Institiúid Náisiúnta

CardiS

Horizon 2020

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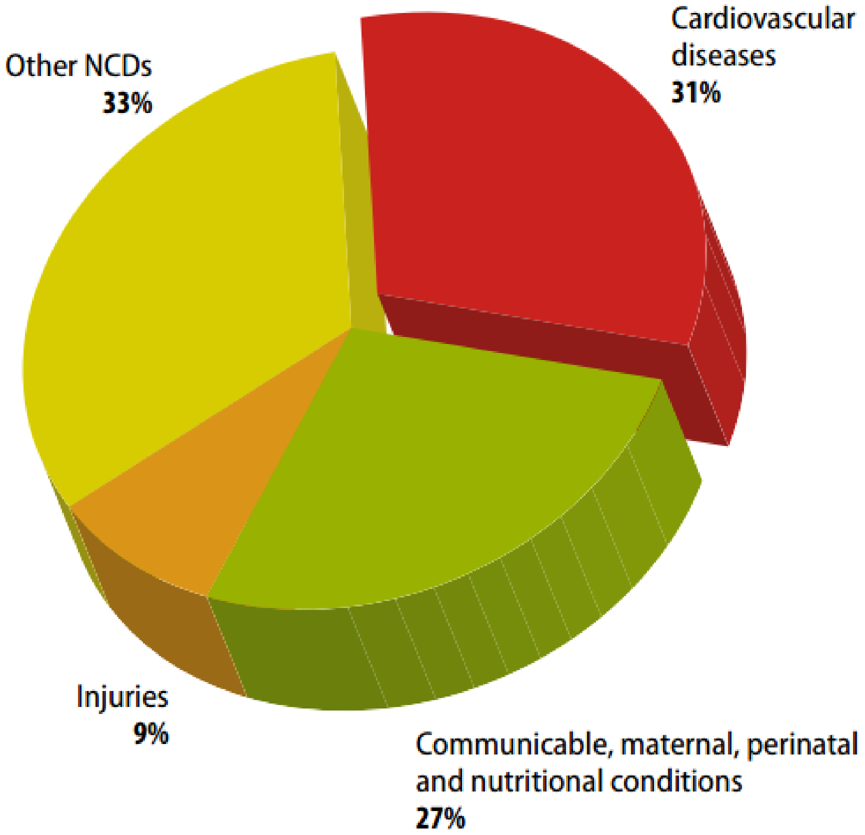
CARDIOVASCULAR DISEASES



Distribution of major causes of death including CVDs

Cardiovascular disease: The biggest killer in the world, responsible for **30%** of deaths (WHO, 2011)

Arteriosclerosis, Atherosclerosis and Stenosis

Arteriosclerosis: stiffening of arterial walls

Atherosclerosis: deposition of plaque on the inner arterial walls (which can lead to stiffening)

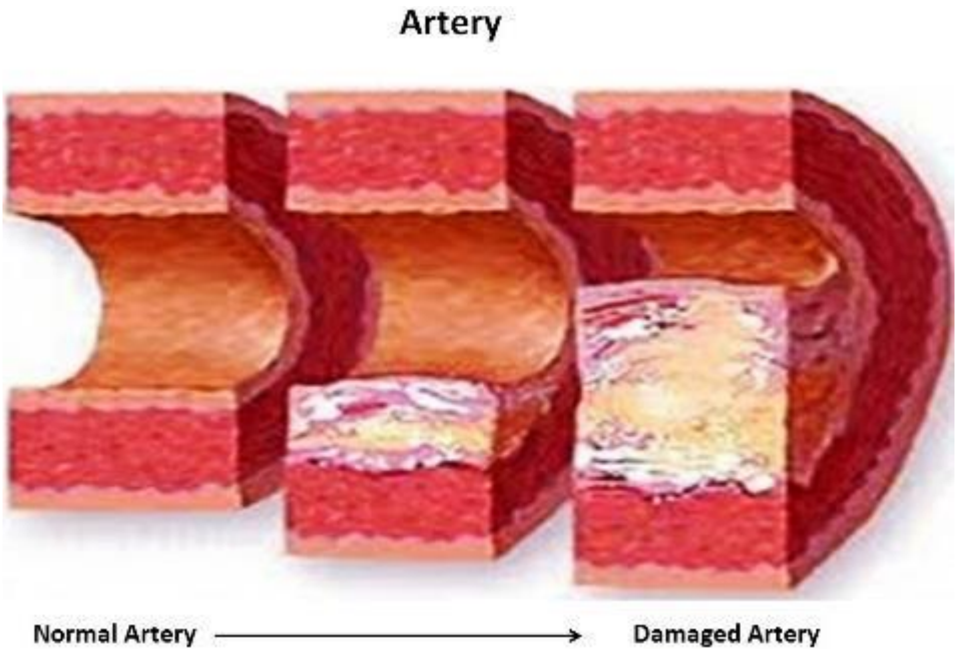
Stenosis: abnormal narrowing in a blood vessel

A **map of the skin displacement** above arteries can help for early diagnosis of these pathologies.

Method: laser Doppler vibrometry

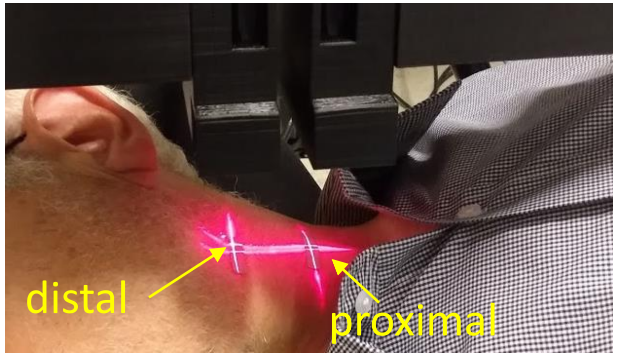
Technology: silicon photonics

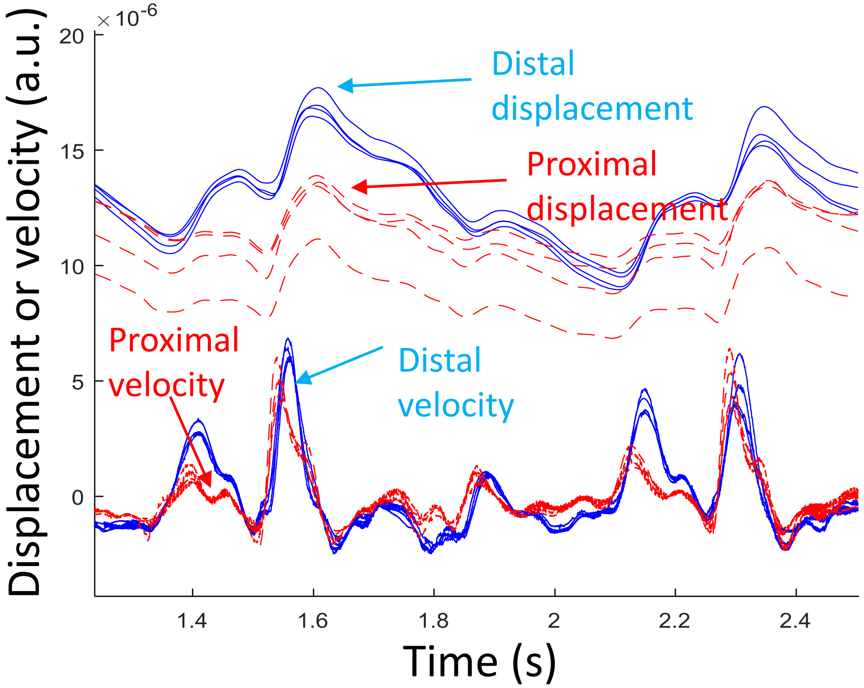
Use: by general practitioner

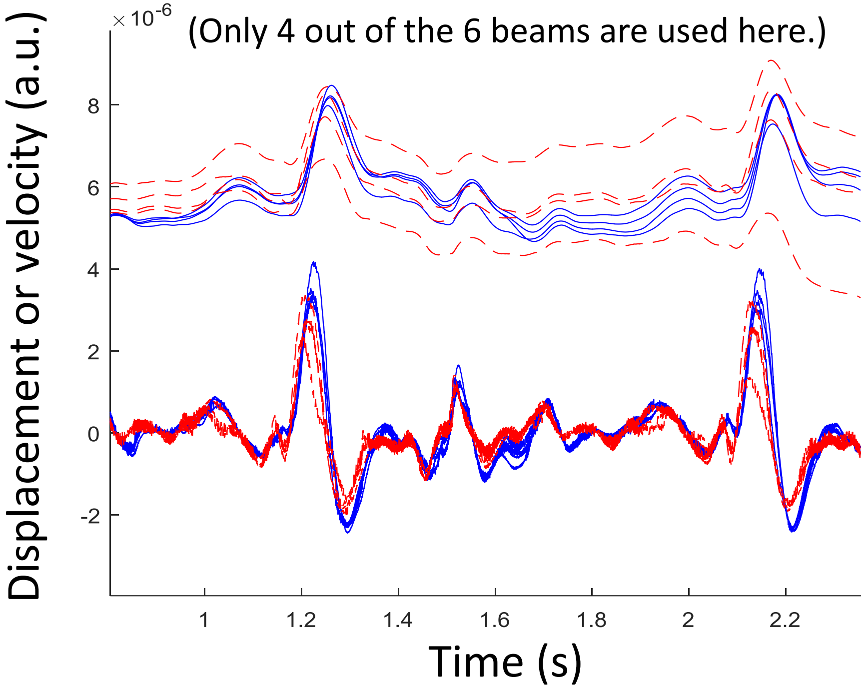


In-vivo measurement results

We measure the pulse wave velocity in the carotid artery, which indicates cardiovascular disease risks.







Cardis Horizon 2020

Queen Mary University of London

It turned out that the shapes of the vibrations also changes at different locations. More study should be done to retrieve the time delay between the two lines.

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OUTLINE

Silicon photonics for high speed optical transceivers

Silicon photonics for sensing and life science

➡ Integrated light sources

INTEGRATED LIGHT SOURCES: THE HOLY GRAIL

Silicon is an indirect semiconductor ⇒ no light emission

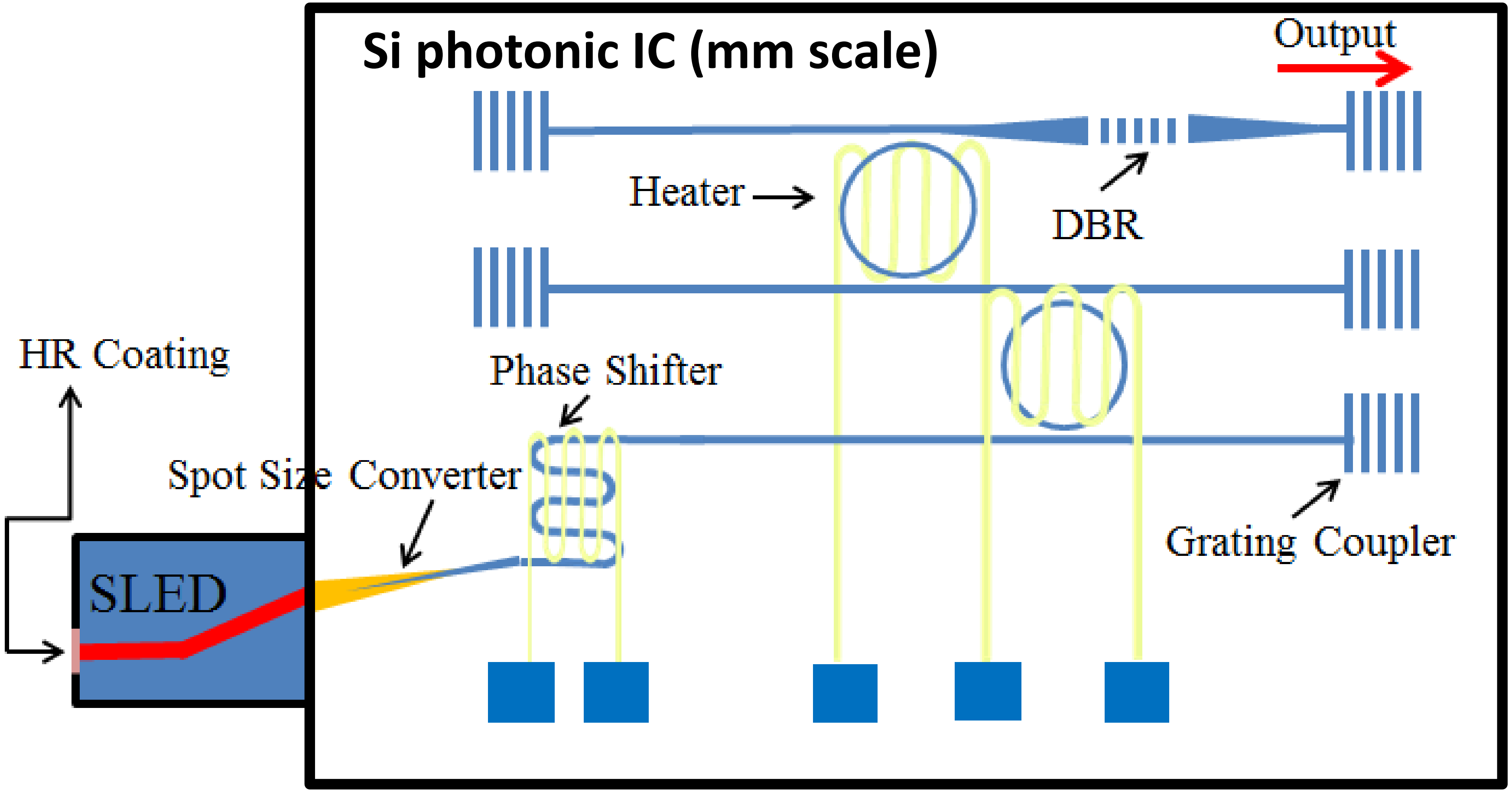
↓

Hybrid approaches: combine III-V semiconductors with silicon

HOW?

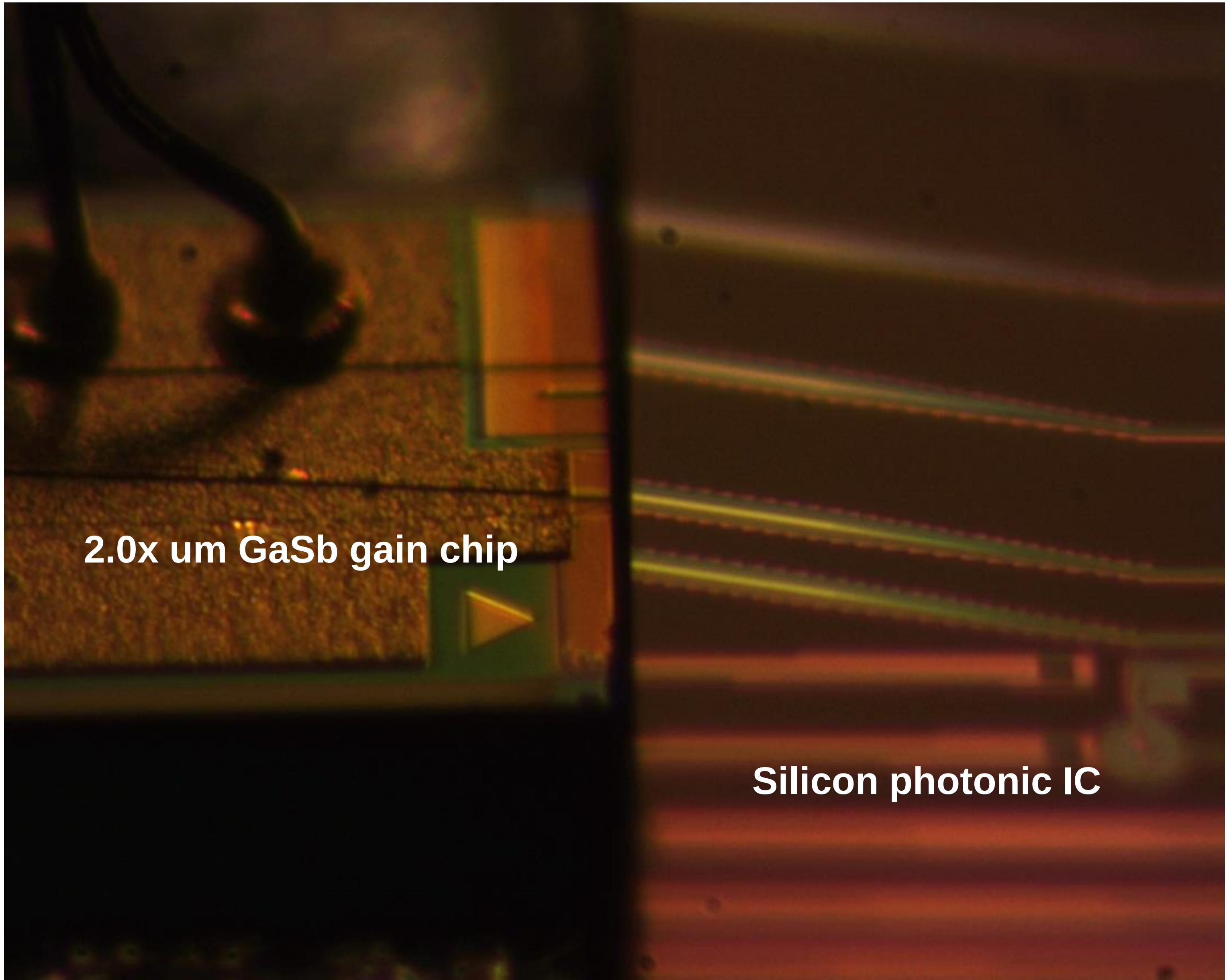
1. III-V chip + silicon chip co-packaging (or flip-chip)
2. Wafer-level approaches

HYBRIDLY INTEGRATED TUNABLE LASERS



GaSb gain chip + silicon photonics widely tunable filter

HYBRIDLY INTEGRATED TUNABLE LASERS



R. Wang et al,
Optics Express 2016

BROLIS SEMICONDUCTORS

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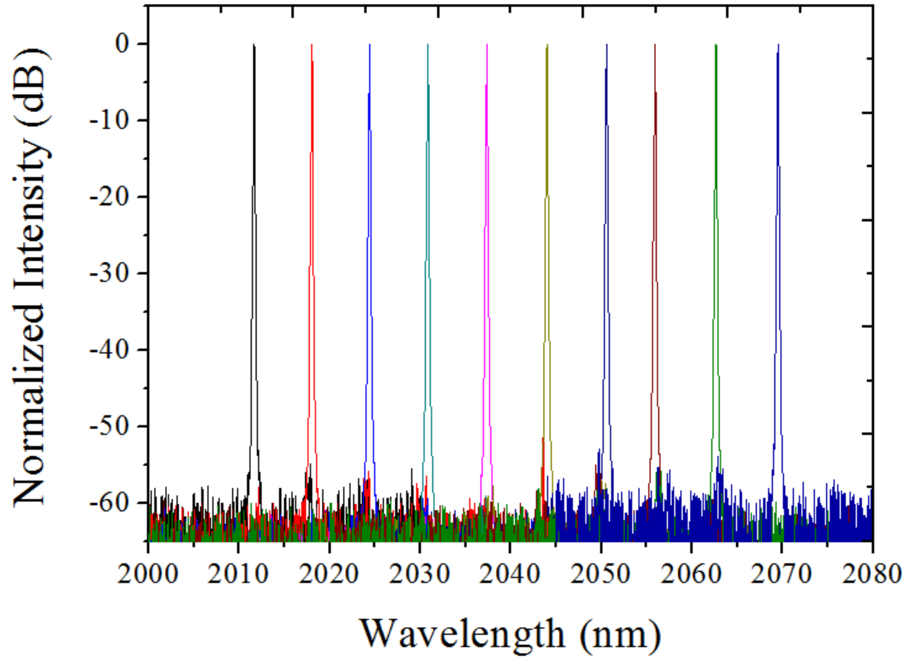
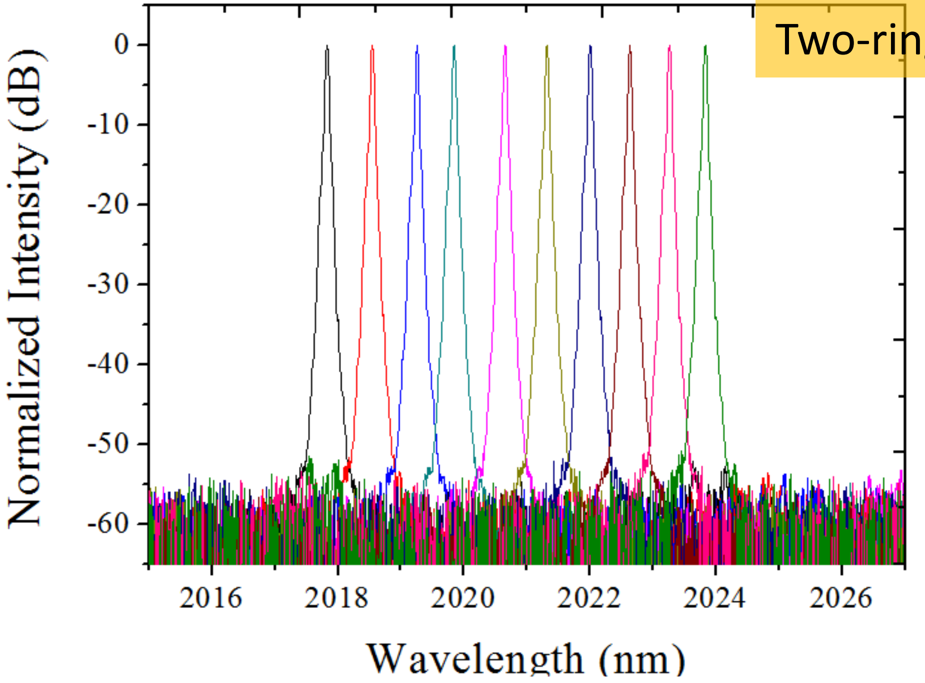
HYBRIDLY INTEGRATED TUNABLE LASERS

Vernier tuning

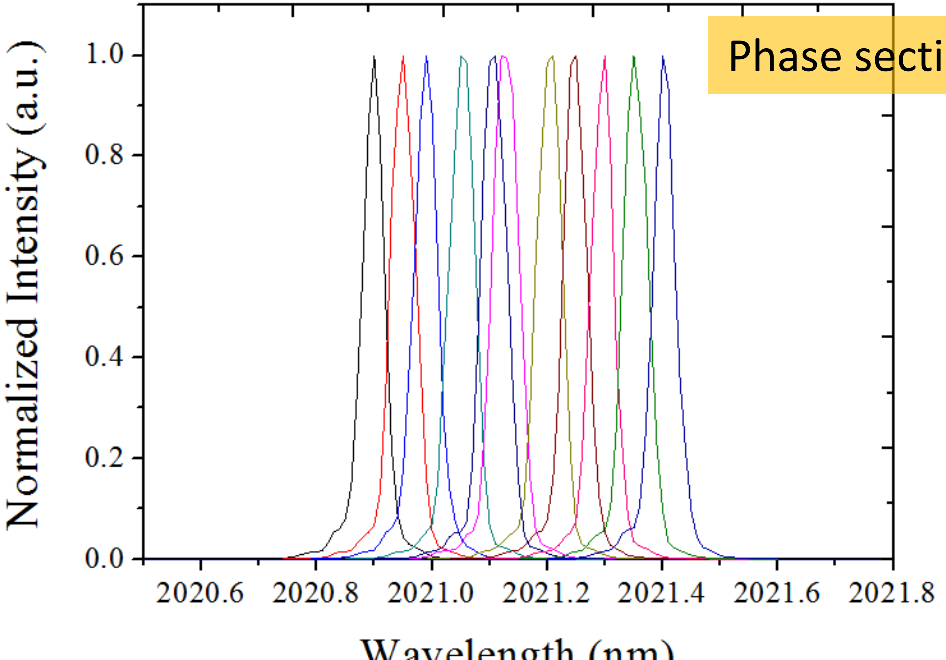
Single ring tuning



Two-ring tuning



Phase section tuning



BROLIS SEMICONDUCTORS

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Optics Express 2016

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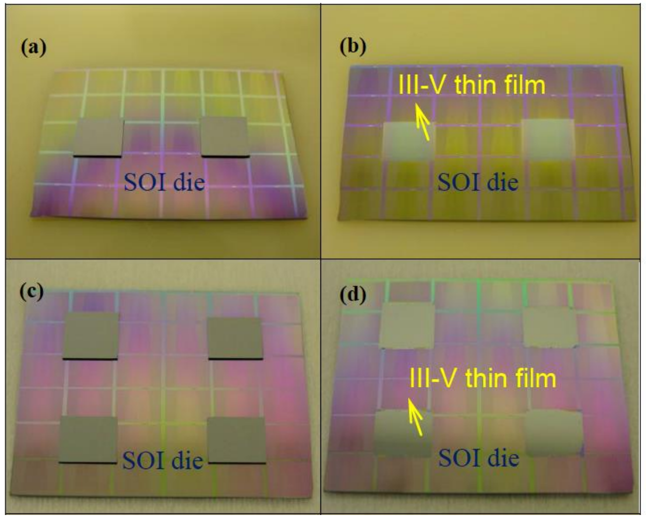
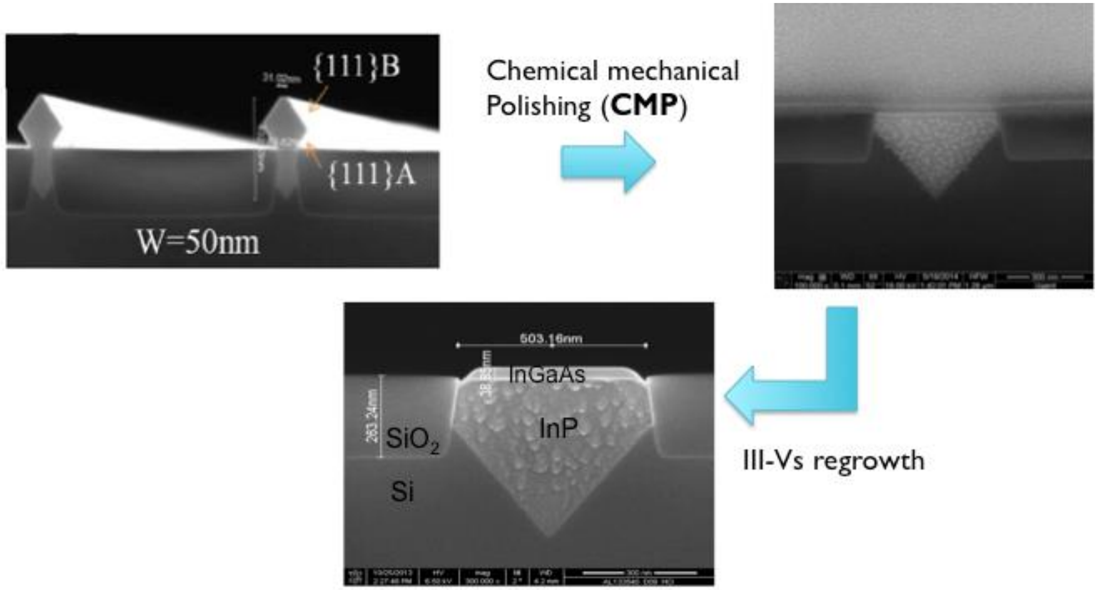
Wafer-level approaches for III-V integration on Si PICs

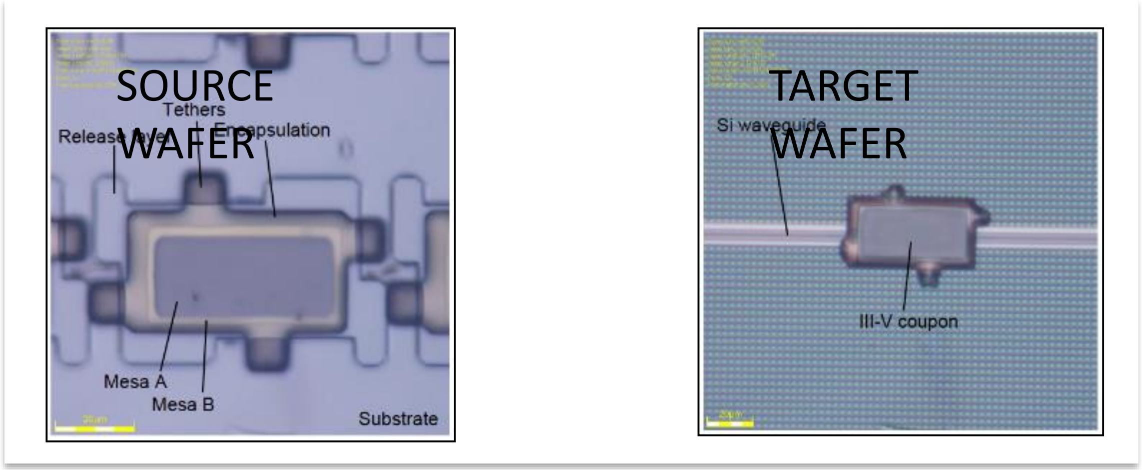
adhesive die-to-wafer bonding



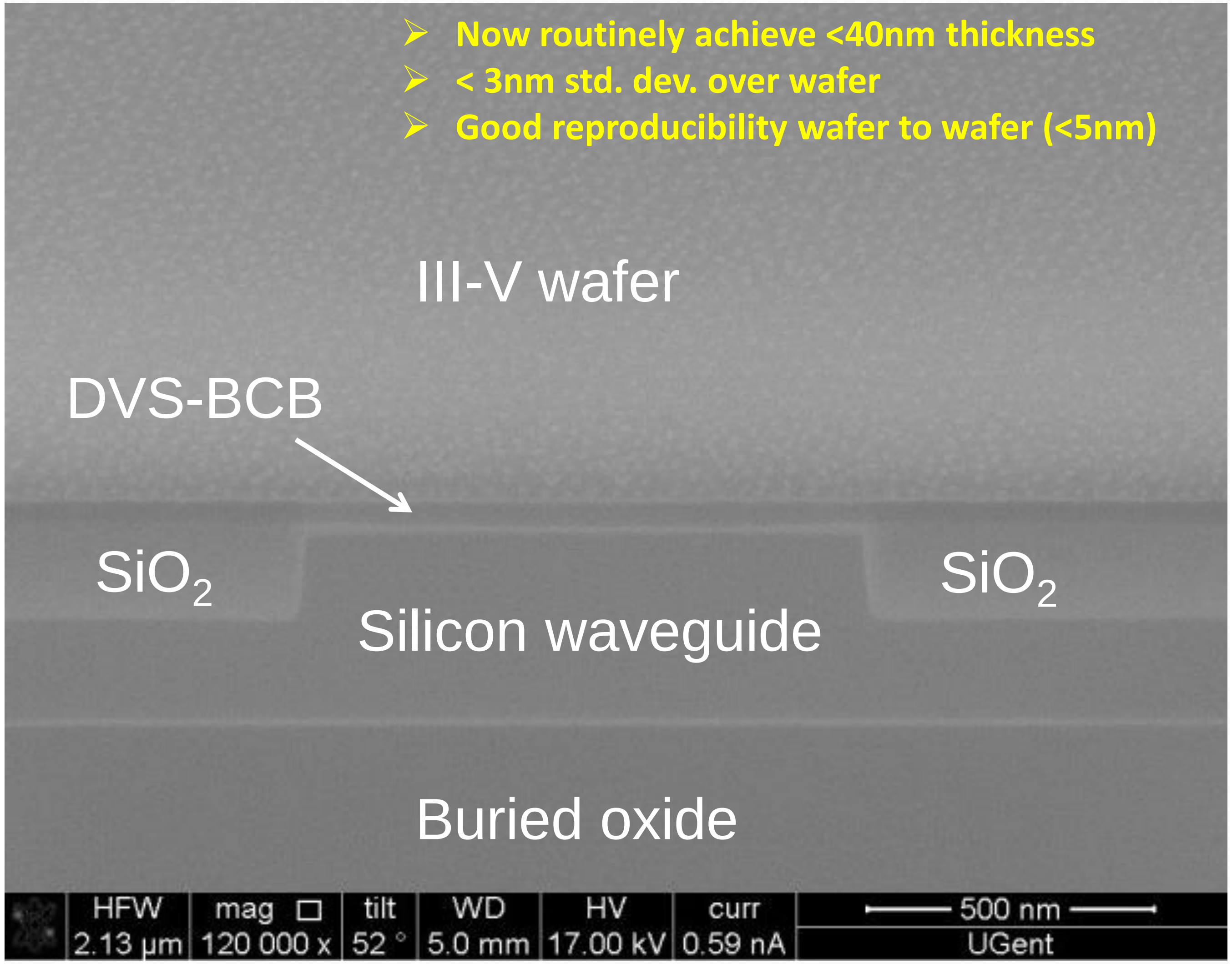
III-V epitaxy on silicon



transfer printing



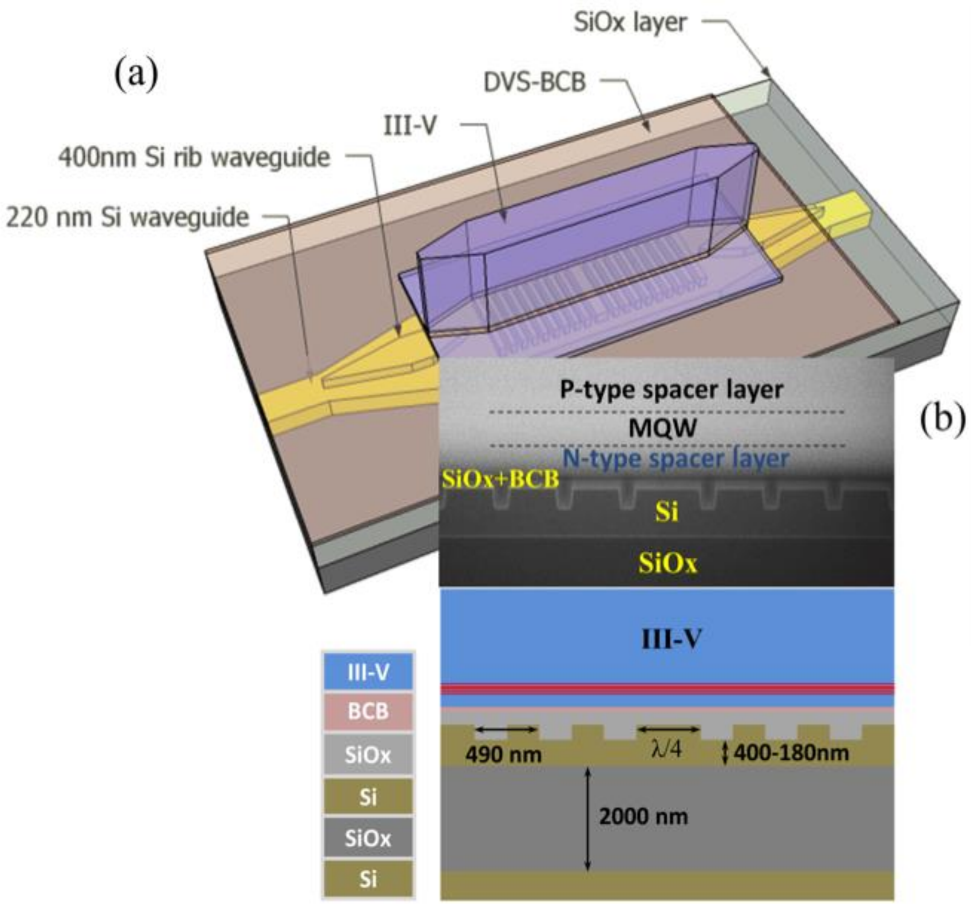
III-V ON SILICON BONDING

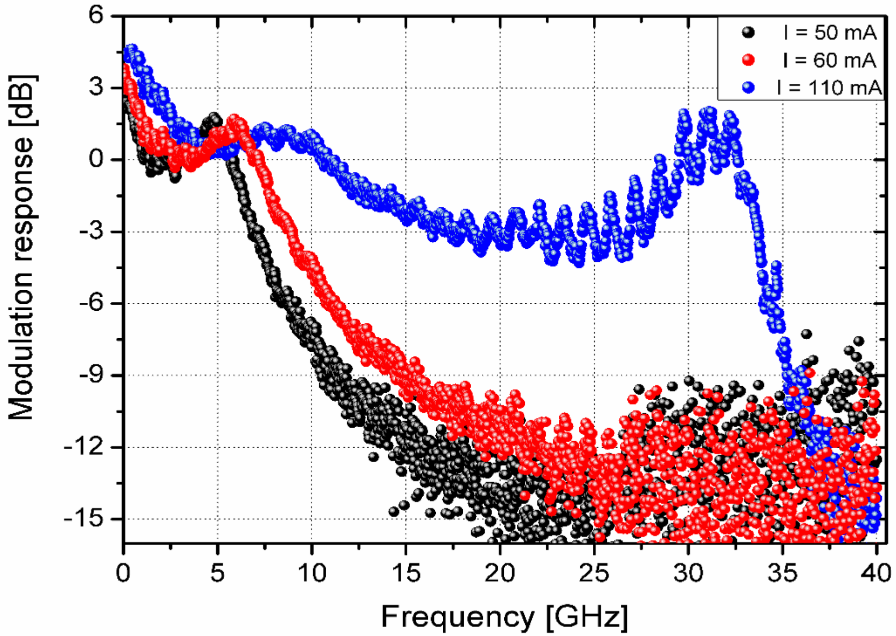


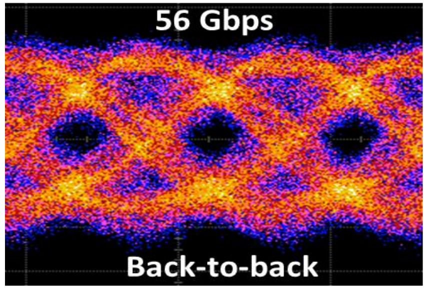
DIRECTLY MODULATED DFB LASERS

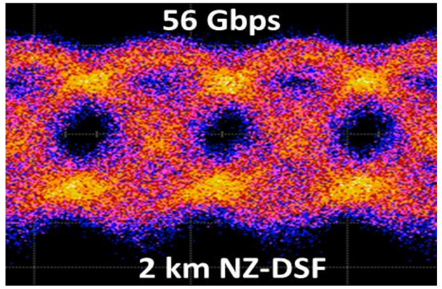
[A. Abassi et al., OFC 2017]

- 34GHz bandwidth through external feedback (photon-photon resonance)
- 56Gbit/s directly modulated lasers

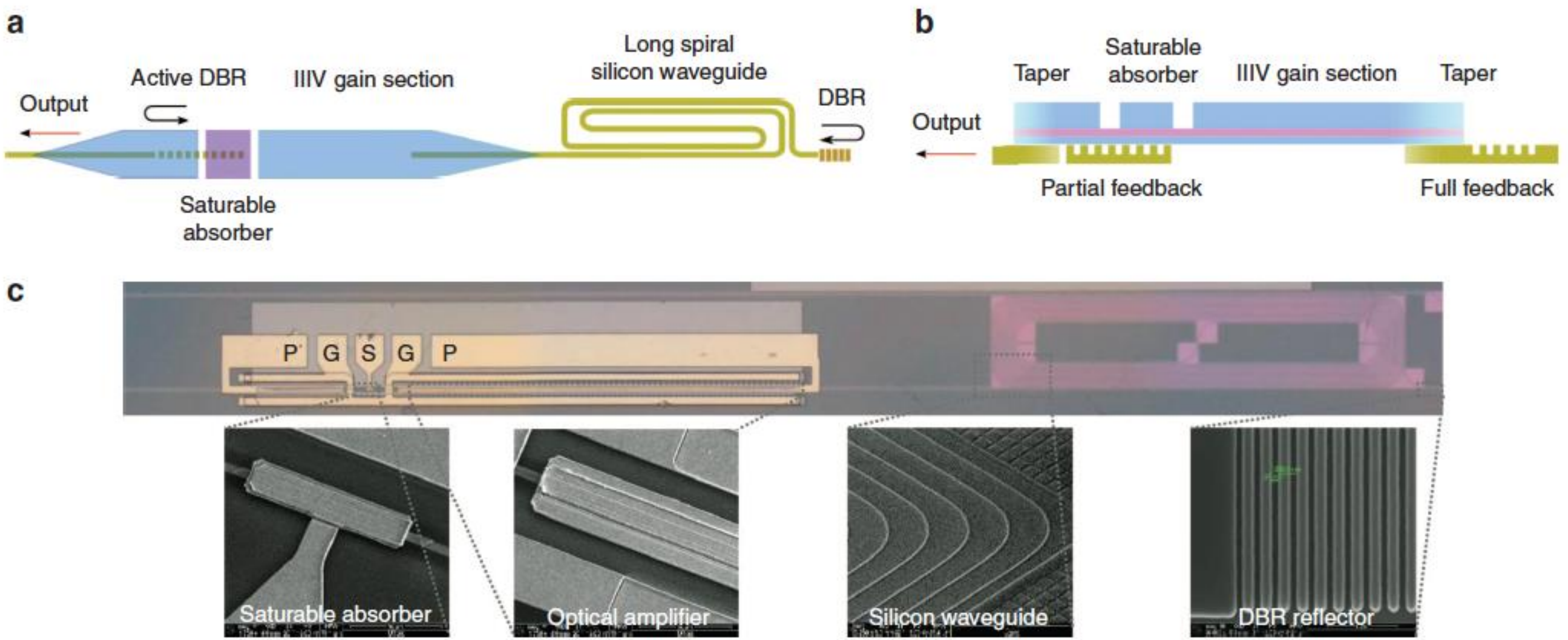








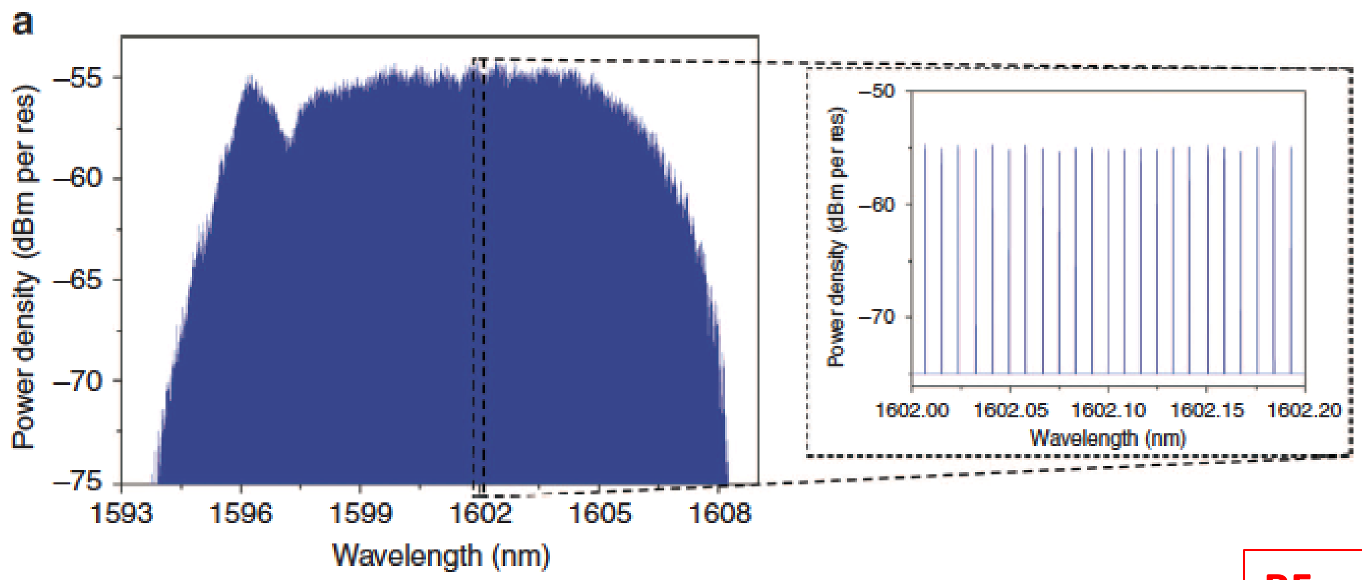
MODELOCKED LASER



- 1GHz repetition rate modelocked laser
- III-V gain section, III-V saturable absorber & long Si waveguide (0.7dB/cm loss) to form the laser cavity

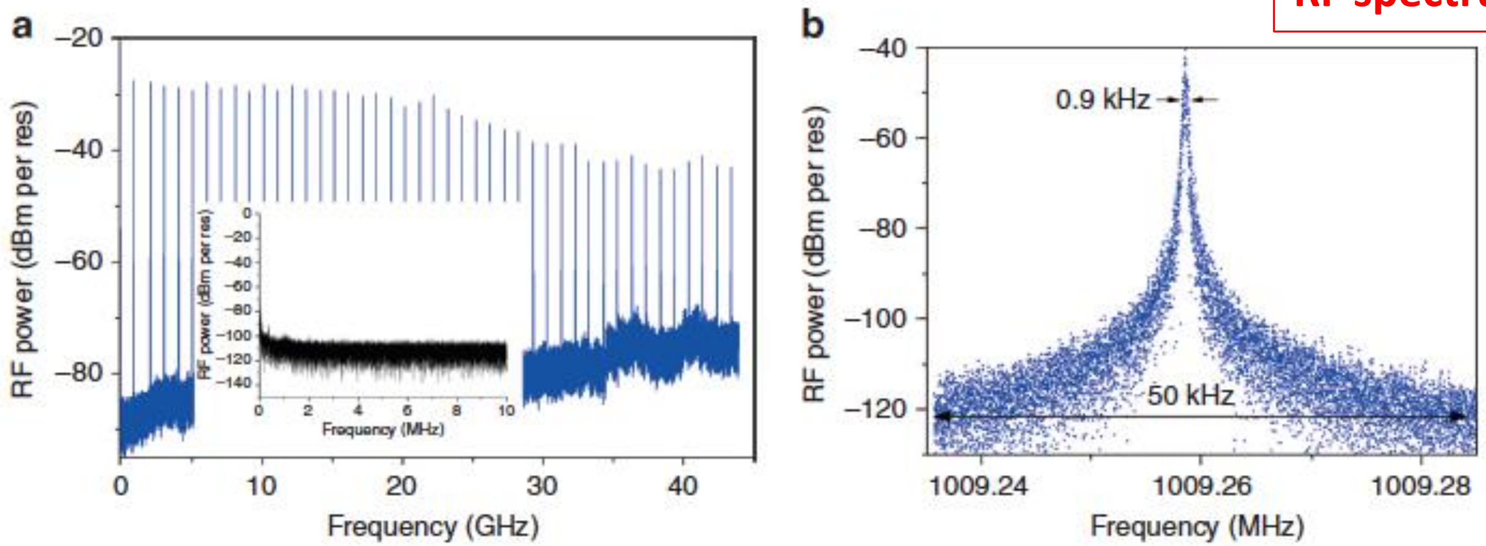
[Z. Wang et al., Light: Science and Applications, 2017]

MODELOCKED LASER – PASSIVE MODELOCKING



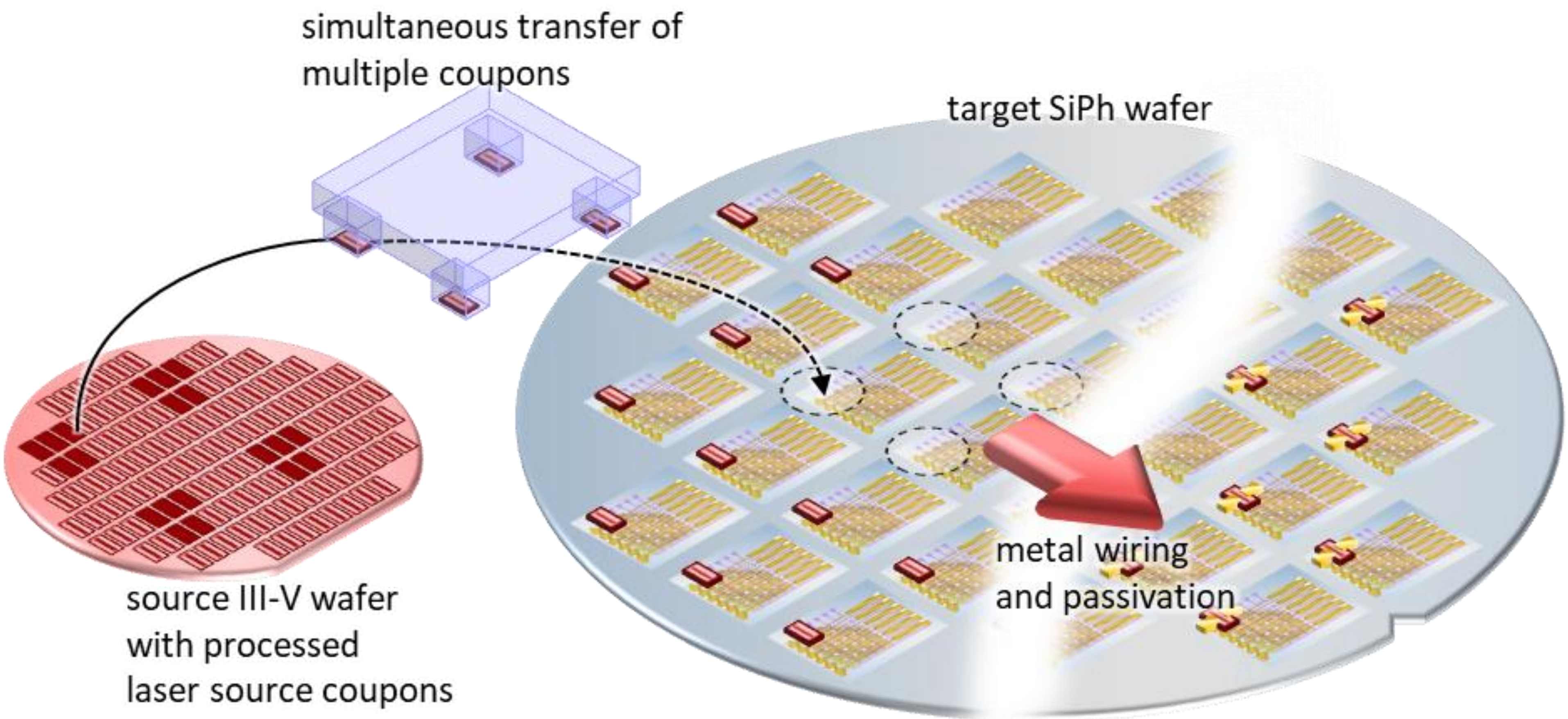
Optical spectrum: comb source

RF spectrum

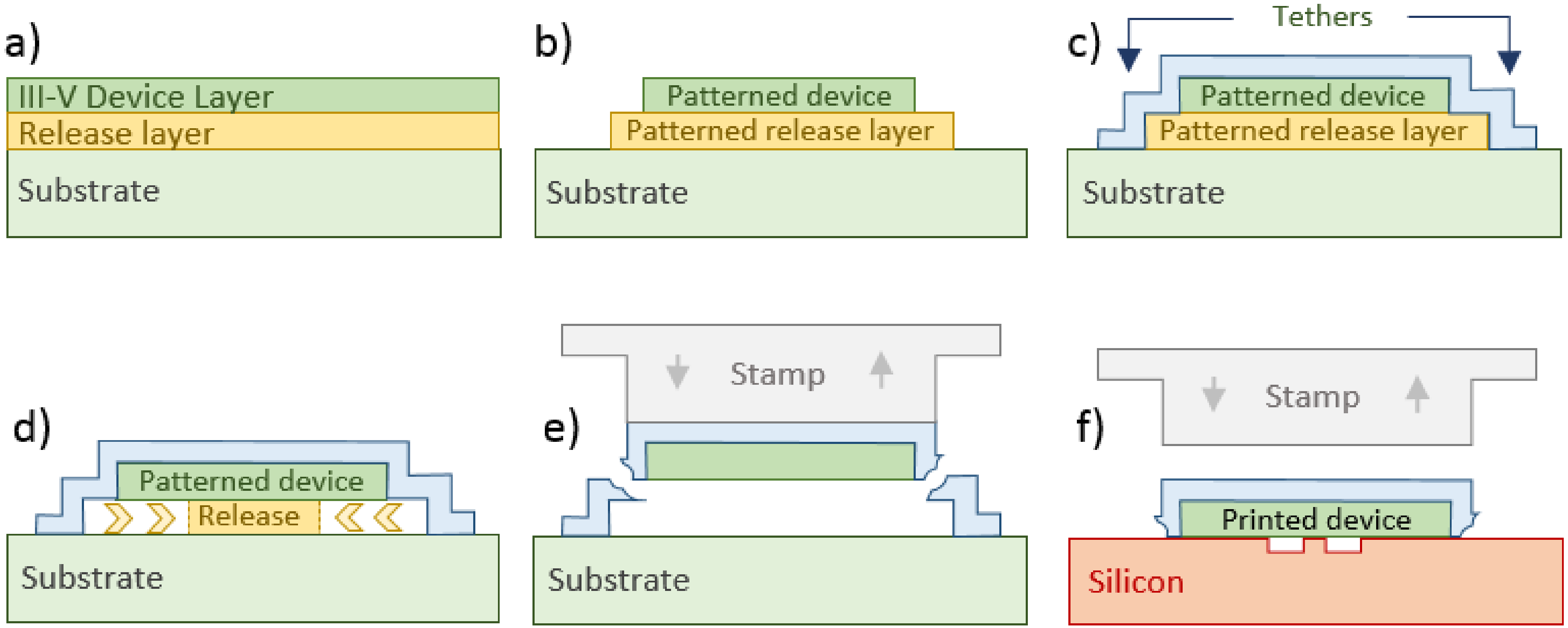


GHENT UNIVERSITY imec

Transfer printing



THE NEW WAY: TRANSFER PRINTING

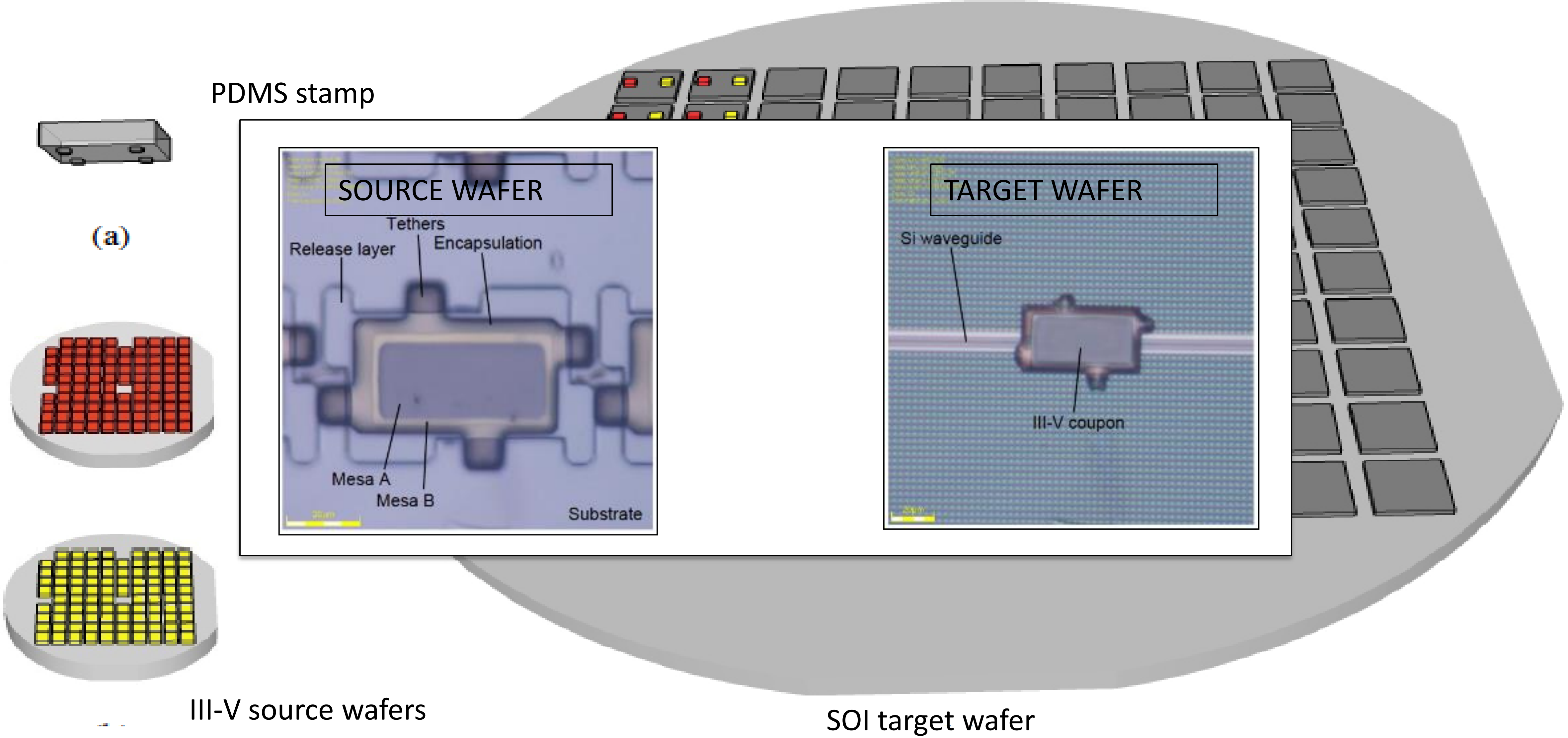


Transfer of <u>micro-scale </u>III-V coupons/devices to a Si target wafer

InP, GaAs, SOI, 2D materials, 0D materials

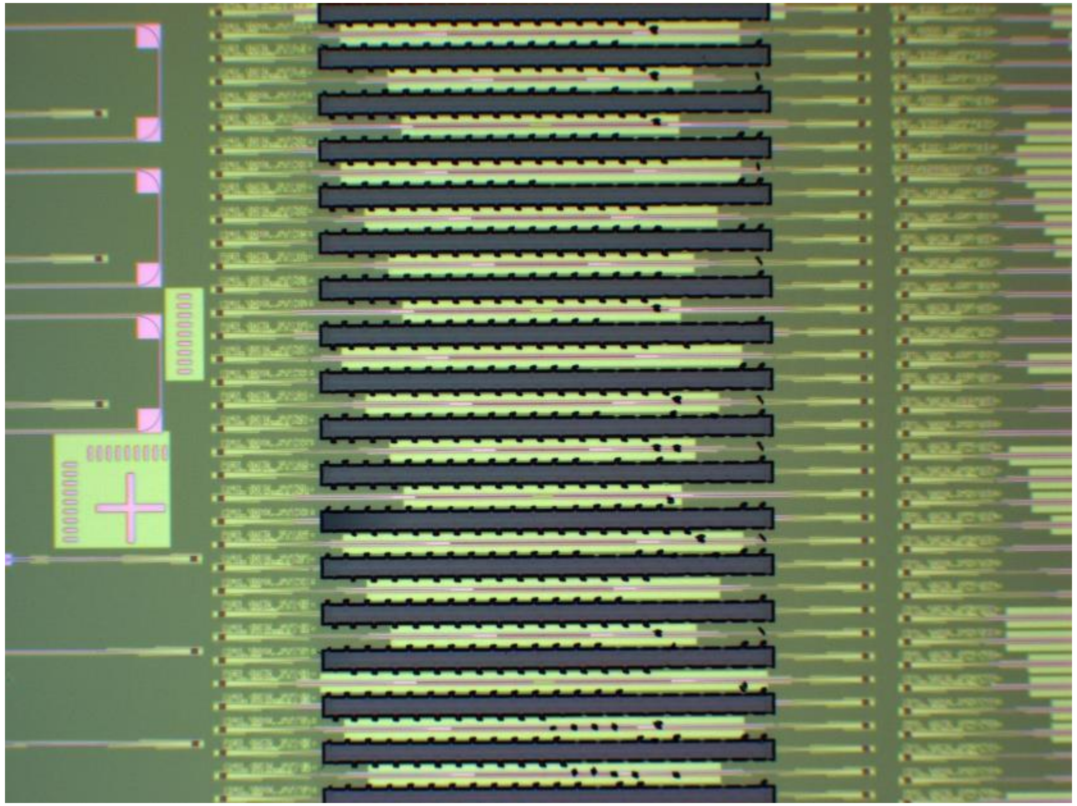
GHENT UNIVERSITY imec X-Celeprint

TRANSFER PRINTING OF III-V SEMICONDUCTORS

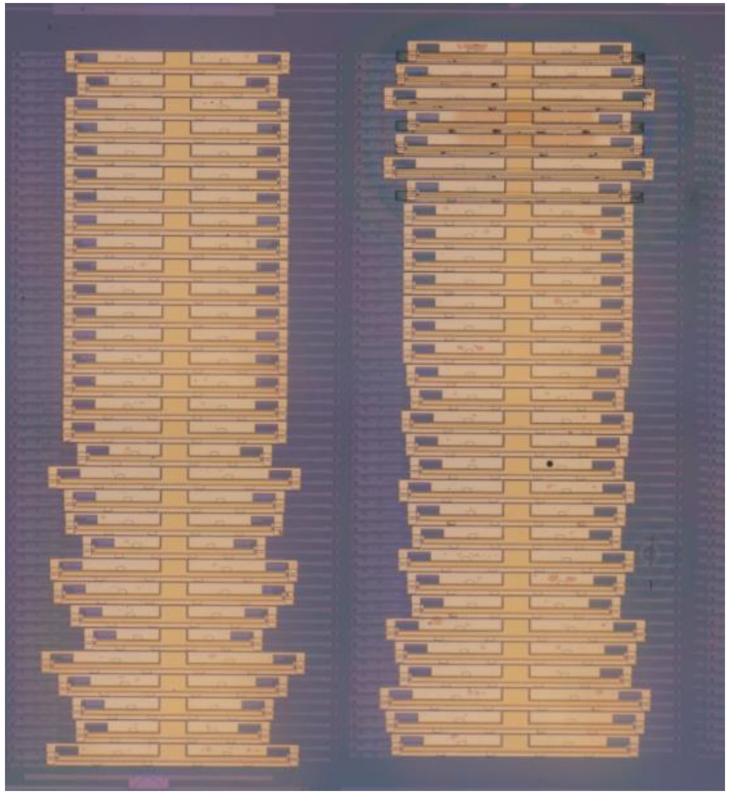


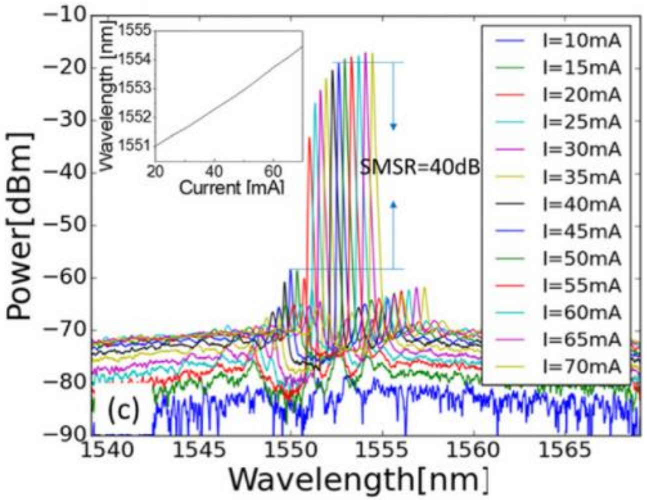
First III-V-on-Silicon TP DFB Lasers

After transfer printing of coupons



Lasers after post-processing





[J. Zhang et al, Optics Express 2018]

CONCLUSION

Silicon photonics:

- Mature technology in CMOS-fab, low cost (even in moderate volume)
- Strong industrial traction for telecom/datacom/interconnect applications
- From visible to mid-IR
- Very large potential for sensing, especially in life science
- Light source integration is gaining maturity

ACKNOWLEDGEMENTS

Photonics Research Group

professors P. Bienstman, W. Bogaerts, B. Kuyken, G. Morthier,

G. Roelkens, N. Le Thomas, D. Van Thourhout

many postdocs and PhD's

IMEC CMOS process line

and ePIXfab www.epixfab.eu

Funding and collaborations through national and EU research projects

Pranešėjai / Speakers

Gediminas Juška
Tyndall National Institute, Cork, Ireland

Gediminas Juska is a Researcher at Tyndall National Institute, Cork, Ireland. His main research interests are in engineering and spectroscopic characterisation of site-controlled quantum dots (QDs), QD-based devices for potential quantum information processing applications. He received his PhD in Physics in 2013 from University College Cork with the thesis titled 'Pyramidal quantum dots: single and entangled photon sources and correlation studies'. He has been continuing the successful project as a Postdoctoral Researcher at Tyndall. Dr. Juska is the author of 24 papers in peer-reviewed journals (including two Nature Photonics publications as the first author), co-author of 63 communications.

Dag Syrrist
USA

Twenty-eight years in the venture capital industry. Extensive Trans-Atlantic and US investing in early and venture-stage companies. Raised and co-managed $175 million in three funds across multiple industry and technology cycles as General Partner with Vision Capital. Extensive environmental venture equity and debt investing, regulatory, environmental and public policy experience as Vice President with Technology Funding, a $325 million venture group with 4 equity and 3 venture debt funds. Co-founded Global BSN, corporate sustainability network of 15 Fortune 200 companies.
Served on local, regional, and national policy, technology and environmental boards. extensive corporate, Federal, State and public advisory groups and boards. Member of US National Technology Policy initiative under Clinton / Gore administration (1993-1997). Testified before US Senate Committee on Environment and Public Works.

Alvydas Žabolis
Zabolis Partners, Lithuania

Coordinates all business activity and is responsible for core services at Zabolis Partners where he supervises business development and provides guidance to all teams.
Alvydas holds a physics degree from Vilnius University, and started his career at Eksma, a producer of laser equipment, where he continues to serve as a board member for the company. Alvydas has 25 years of experience in investment banking, private equity, executive management, corporate advisory, and M&A. He has led a large number of major privatizations, M&A deals, buyout transactions, and financing initiatives since the early 1990s. In 2002 he co-founded Zabolis Partners.

Konferenciją globoja:

LIETUVOS RESPUBLIKOS PREZIDENTĖ
DALIA GRYBAUSKAITĖ

VILNIUS

Konferenciją organizuoja:

BROLIS SEMICONDUCTORS

LIETUVOS LAZERIŲ ASOCIACIJA / LITHUANIAN LASER ASSOCIATION

CENTER FOR PHYSICAL SCIENCES AND TECHNOLOGY

Lazeriai: mokslas ir technologijos

Lasers: Science and Technology

14-oji nacionalinė konferencija skirta Lietuvos valstybės atkūrimo šimtmečiui

14th National Conference Dedicated to the centenary of Lithuania

2018 m. rugpjūčio 24 d., penktadienis
Nacionalinis fizinių ir technologijos mokslų centras,
Saulėtekio al. 3, Vilnius

August 24, 2018, Friday
National Center for Physical Sciences and Technology,
Saulėtekio av. 3, Vilnius

Konferencijos programa

8:30 – 9:00	**Dalyvių registracija**
9:00 – 9:30	**Konferencijos atidarymas** Lietuvos Respublikos Prezidentė Dalia Grybauskaitė (laukiamas patvirtinimas) Remigijus Šimašius, Vilniaus miesto meras Algis Petras Piskarskas, Lietuvos lazerių asociacijos prezidentas Gintaras Valušis, Nacionalinio fizinių ir technologijos mokslų centro direktorius Augustinas Vizbaras, UAB Brolis semiconductors įkūrėjas, mokslininkas; Konferencijos moderatorius
09:30 – 10:00	**Lietuvos aukštųjų technologijų rinkos ir investicijų apžvalga** Alvydas Žabolis, Žabolis ir partneriai, Lietuva
10:00 – 10:30	**40 metų puslaidininkiniams lazeriams** Markus-Christian Amann, Walter Schottky institutas, Miuncheno technikos universitetas, Vokietija
10:30 – 11:00	**Silicio fotonika: fotoniniai integriniai grandynai** Roeland Baets, Gento universitetas, UGent-IMEC, Belgija
11:00 – 11:20	**Kavos pertraukėlė**
11:20 – 11:50	**Atominiai laikrodžiai ir sinchronizuotų modų lazeriai** Steve Lecomte, CSEM, Šveicarija
11:50 – 12:20	**Lazerinių šaltinių technologija nuo 1 µm iki 100 µm** Ralf Meyer, Walter Schottky institutas, Miuncheno technikos universitetas, Vokietija
12:20 – 13:30	**Pietūs ir stendinė paroda I aukšto fojė**
13:30 – 14:00	**Vienfotoniai šaltiniai** Gediminas Juška, Tyndallo nacionalinis institutas, Airija
14:00 – 14:30	**Silicio slėnio verslo ir investicijų patirtis** Dag Syrrist, rizikos kapitalo investuotojas, Jungtinės Amerikos Valstijos
14:30 – 14:50	**Kavos pertraukėlė**
14:50 – 16:00	**Diskusija** Iššūkiai ir galimybės mažųjų šalių aukštųjų technologijų įmonėms konkuruoti pasauliniu mastu. Valstybės, švietimo ir verslo ekosistemos vaidmuo Moderatorius - Vaidotas Beniušis, Baltic News Service (BNS) vyriausiasis redaktorius
15:00 – 01:00	**Vakaro programa ir vakarienė** Vilnius Grand Resort viešbučio teritorija ir lauko kupolas www.vilniusgrandresort.lt

*Registracija į konferenciją būtina.
Programa gali nežymiai keistis. Konferencija vyks anglų kalba.

Conference Programme

8:30 – 9:00	**Registration**
9:00 – 9:30	**Opening ceremony** HE the President of the Republic of Lithuania Dalia Grybauskaitė Remigijus Šimašius, Vilnius City Mayor Algis Petras Piskarskas, President of Lithuanian laser association Gintaras Valušis, Director of national center for Physical sciences and technologies Augustinas Vizbaras, UAB Brolis semiconductors co-founder, Conference moderator
09:30 – 10:00	**Overview of Lithuanian high-tech market and investments** Alvydas Žabolis, Žabolis and partners, Lithuania
10:00 – 10:30	**40 years of semiconductor lasers** Markus-Christian Amann, Walter Schottky institute, Technical University Munich, Germany
10:30 – 11:00	**Silicon Photonics: Integrated photonic circuits** Roeland Baets, Ghent University, UGent-IMEC, Belgium
11:00 – 11:20	**Coffee break**
11:20 – 11:50	**Atomic clocks and mode locked lasers** Steve Lecomte, CSEM, Switzerland
11:50 – 12:20	**Laser source technology: from 1 µm to 100 µm** Ralf Meyer, Walter Schottky institute, Technical University Munich, Germany
12:20 – 13:30	**Lunch and poster session (ground floor foyer)**
13:30 – 14:00	**Single-photon sources** Gediminas Juška, Tyndall national institute, Ireland
14:00 – 14:30	**Silicon Valley experience: business and investments** Dag Syrrist, Investor, United States of America
14:30 – 14:50	**Coffee break**
14:50 – 16:00	**Discussion:** Challenges and opportunities for high-tech companies from small countries to compete globally. The role of government, education and business ecosystem. Moderator - Vaidotas Beniušis, Baltic News Service (BNS) chief editor
15:00 – 01:00	**Evening program and dinner** Vilnius Grand Resort territory and outside premises www.vilniusgrandresort.lt

Pranešėjai / Speakers

Roel Baets,
Ghent Univeristy-Imec, Belgium.

Roel Baets is a professor in the Photonics Research Group at Ghent University. He is also associated with IMEC. Roel Baets is director of the multidisciplinary Center for Nano- and Biophotonics (NB Photonics) at UGent, founded in 2010. He is a Fellow of the IEEE, the EOS and the OSA. Roel Baets has published over 600 publications with an h-index over 60. He has guided over 30 PhD students over his career. Roel Baets has mainly worked in the field of integrated photonic components. He has made contributions to research on photonic integrated circuits, both in III-V semiconductors and in silicon, as well as their applications in telecom, datacom, sensing, biosensing and medical devices.

Markus-Christian Amann,
Walter Schottky Institut
Technische Universität München, Germany.

Prof. Amann (b. 1950) has held the Chair of Semiconductor Technology at the Walter Schottky Institute since 1998. His research field is optoelectronic components and III-V compound semiconductor technology. In this field, he focuses on innovative semiconductor lasers for sensor technology and broadband communication applications in the near and mid-infrared range as well as terahertz radiation sources. After completing his studies in electrical engineering at TUM, Prof. Amann received his doctorate in 1981. From that year until 1994, he played a key research role at Siemens AG, becoming a member of the senior management team for the development of laser diodes. Prior to becoming a full professor at TUM, he headed up the Chair of Technical Electronics at the University of Kassel until 1998.

Ralf Meyer,
Walter Schottky Institut,
Technische Universität München, Germany.

Ralf Meyer was born in Oldenburg, Germany, in 1963. He studied physics at the RWTH Aachen, Germany, where he received his diploma degree with in 1990 and PhD in 1994. His research expertize is II-V semiconductor technology with a particular focus on MOVPE technology for advanced optoelectronic devices. Since 1998, Ralf Meyer is the head of the III-V technology group at the Walter Schottky Institut (Technische Universität München, Germany) which is dedicated to the development and realization of a variety of different types of light emitters in the wavelength range from 1 to 250 µm based on III-V semiconductors. Two companies were founded by PhD students of this chair and both are actively cooperating with the chair since years.

Steve Lecomte,
CSEM, Switzerland.

Steve Lecomte is Section Head of the Time and Frequency Section of the Centre Suisse d'Electronique et de Microtechnique (CSEM) in Neuchâtel. He occupies this position since 2007. Prior to this he was research engineer for two years at the Observatory of Neuchâtel, contributing to the development of an optically-pumped cesium thermal beam clock. He received the PhD degree in 2005 from ETH for his work on multi-GHz repetition rate optical parametric oscillators and passively mode-locked solid-state lasers performed in the group of Prof. Ursula Keller. The PhD thesis followed two years as scientific assistant in the group of Prof. Günter, also at ETH, and Physics studies at the University of Neuchâtel from which he graduated on 1999.