FOAN 2023
FIBER OPTICS IN ACCESS NETWORKS
GHENT, BELGIUM, OCTOBER 30 AND 31
HOTEL NH GENT BELFORT

Heterogenous Photonic Integration for Quantum Optical Communication

QUANTERA

uTP4Q

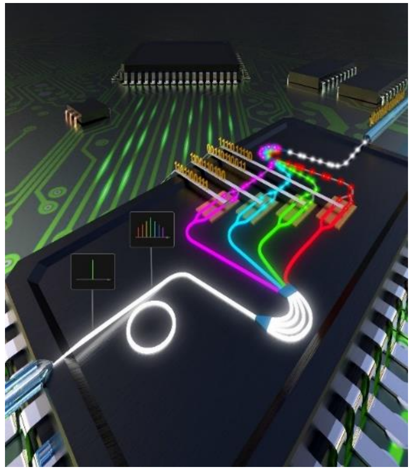
Janez Krc[1], Andraz Debevc[1], Milos Ljubotina[1], Marko Topic[1], Isaac Luntadila Lufungula[2] , Jasper De Witte[2], Leonardo Midolo[3], Claus Pedersen[4], Amir Hossein Ghadimi[5], Hamed Sattari[5], Michel Despont[5], Simone Ferrari[6], Wolfram Pernice[6] and Dries Van Thourhout[2]

[1]University of Ljubljana, Faculty of Electrical Engineering, Ljubljana, Slovenia
[2]Photonics Research Group, Ghent University - IMEC, Belgium
[3]Niels Bohr Institute, University of Copenhagen, Denmark
[4]Sparrow Quantum ApS,, Denmark
[5]Swiss Center for Electronics and Microtechnology (CSEM), Switzerland
[6]Heidelberg University - Kirchhoff-Institute for Physics, Germany

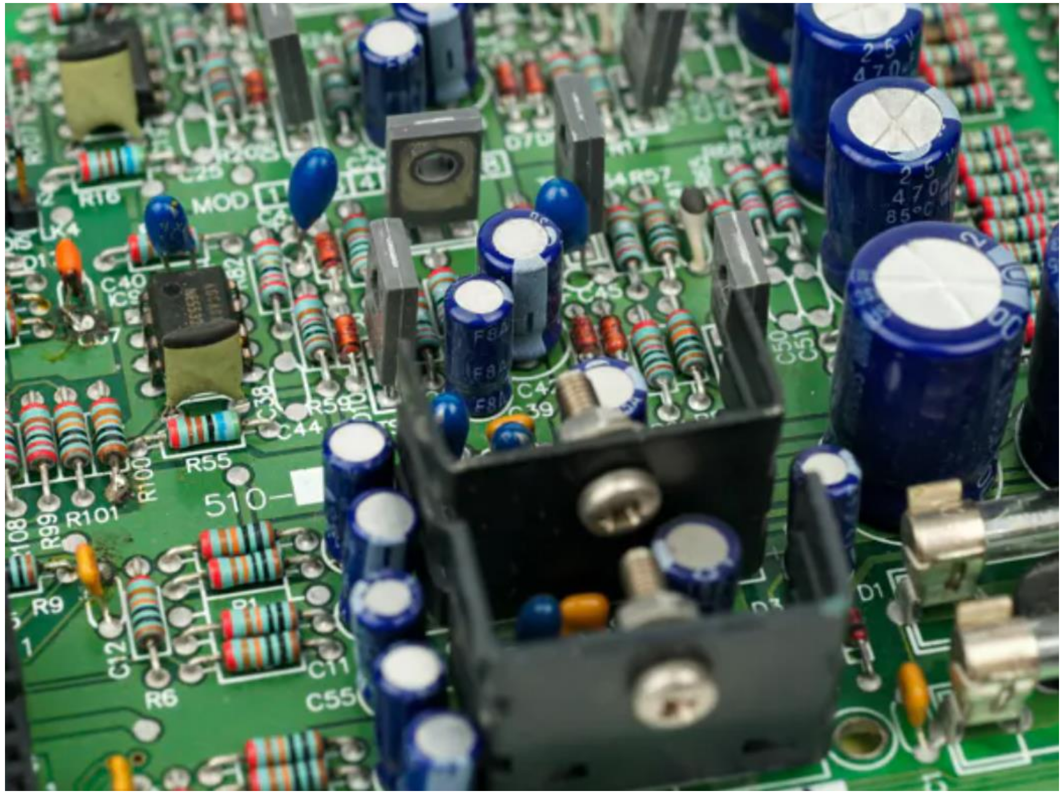
Outline

- **Introduction**
  - – photonic integrated circuits - PICs
  - – quantum PICs - QPICs
- **Quantera project *uTP4Q***
  - – towards quantum PIC (for optical communication)
  - – heterogeneous photonic integration – micro-transfer printing
  - – selected results
- **Conclusion**

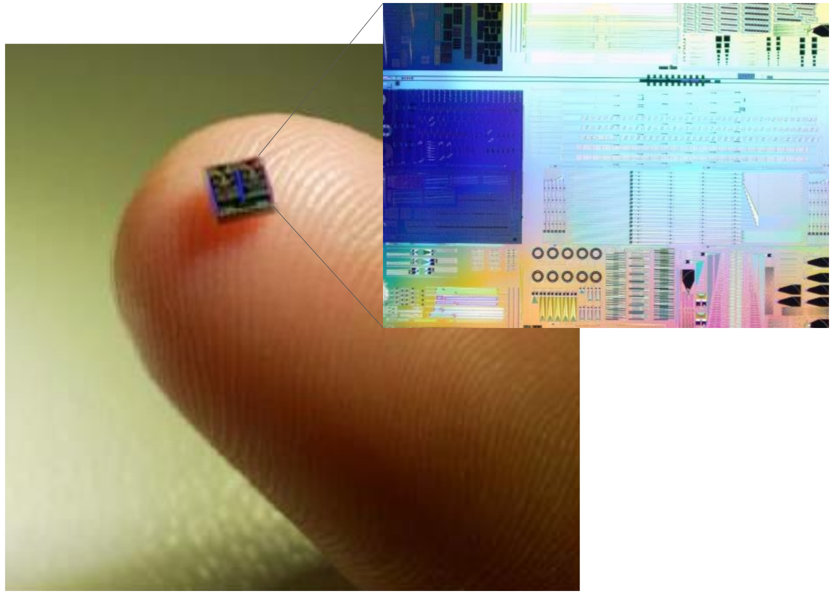
Integration of components



Integrating electronics into **electronic integrated circuits - ICs**



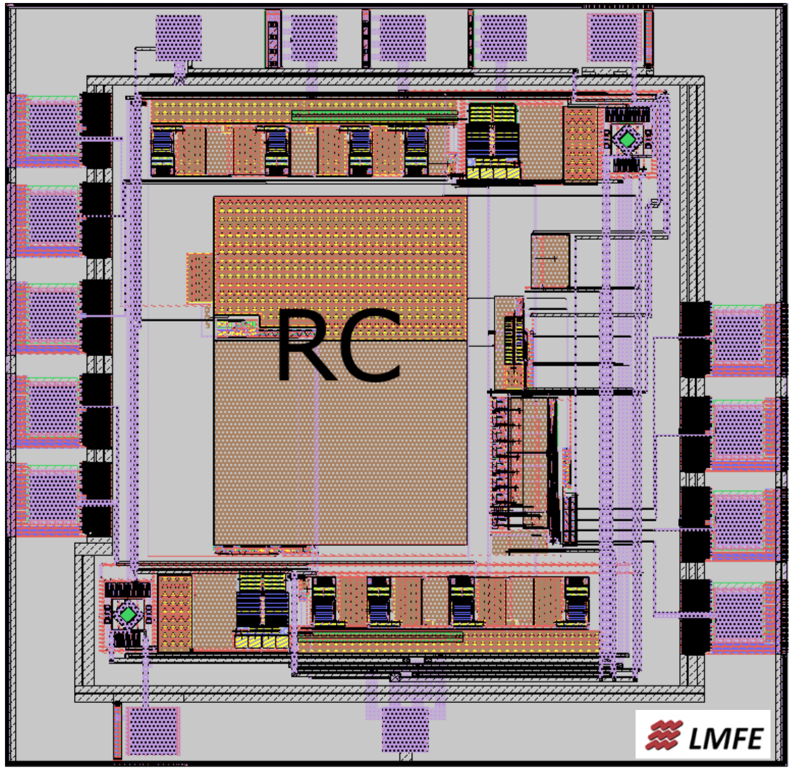
Integrating photonics into **photonic integrated circuits - PICs**



- small, can be co-integrated with IC
- high functionality on small area
- one package required
- uniformity, reliability

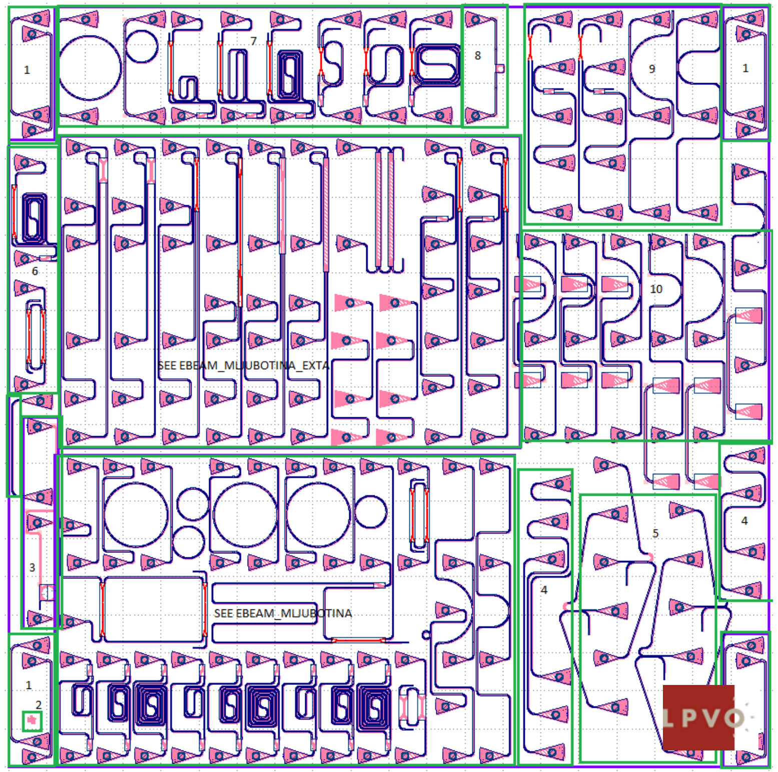
Electronic integrated circuit - IC

- electrons -



Photonic Integrated Circuit - PIC

- photons -

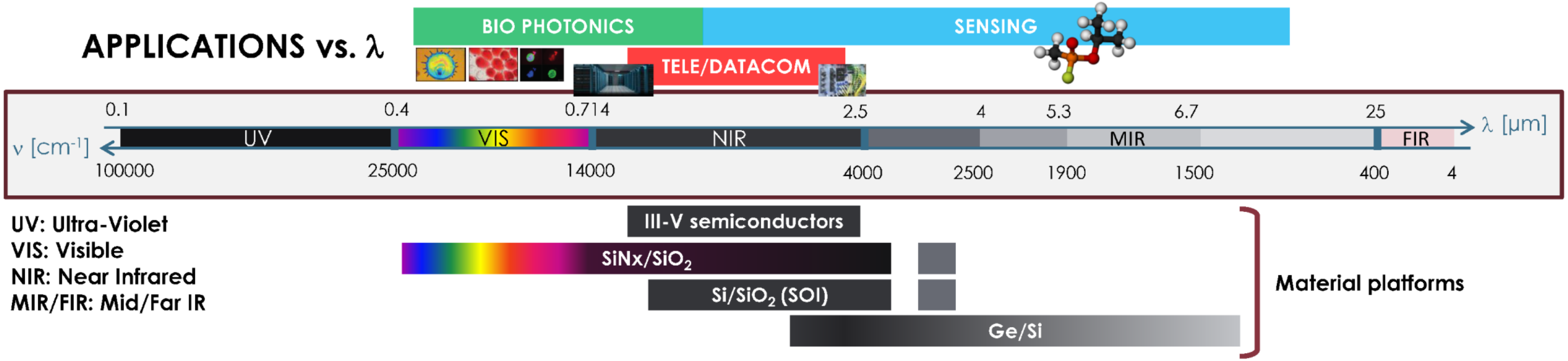


- passive and active components
- different technologies (see further)
- in case of silicon technology **CMOS process**
- low losses at high freq., fast signal processing

PIC material platforms

- **III-V semiconductors: InP, GaAs**
- **Silicon-based: Si, Si_3N_4** , + Ge - use advantages of CMOS processing
- **Lithium Niobate: LiNbO**
- **polymers**
- **others**

Transparency windows for low loss waveguiding for different platforms



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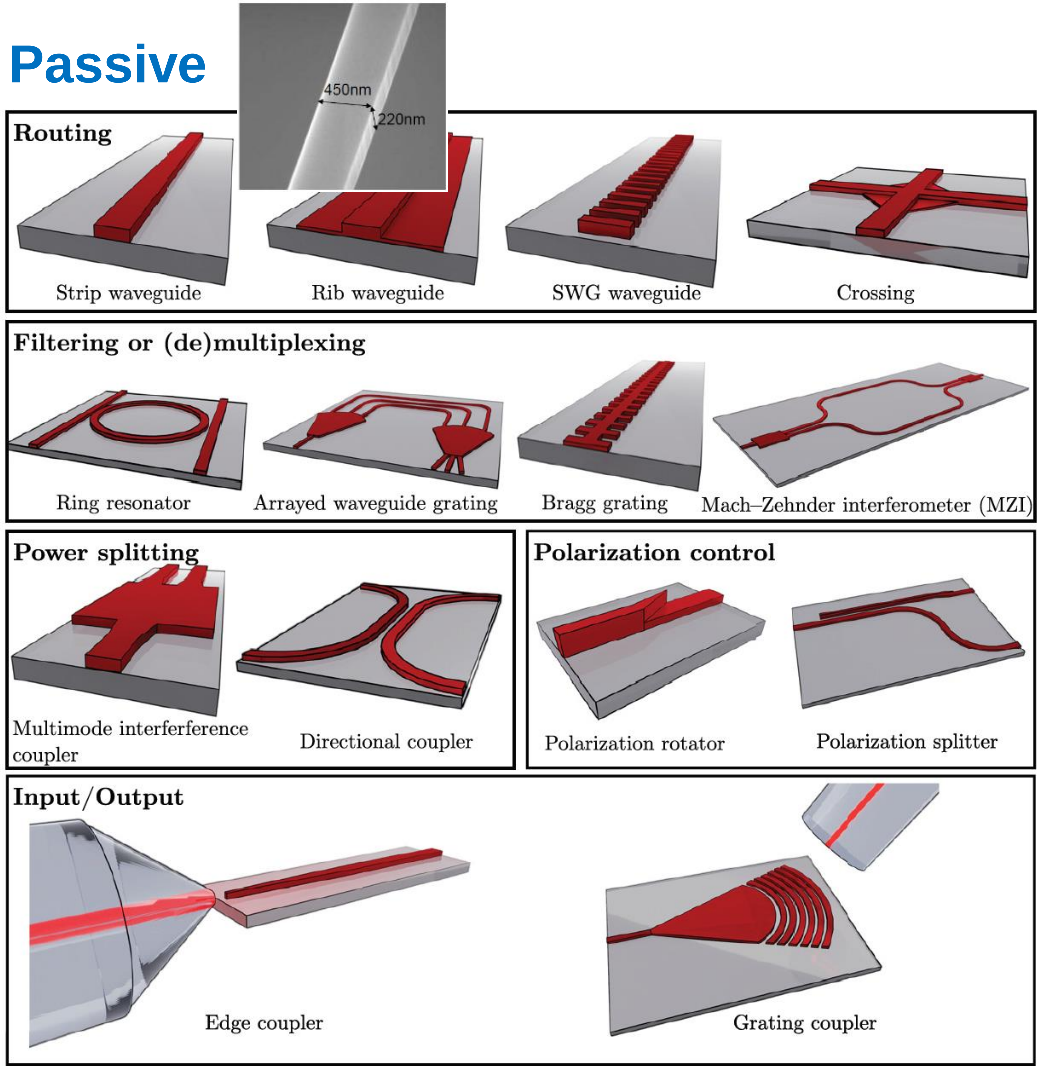
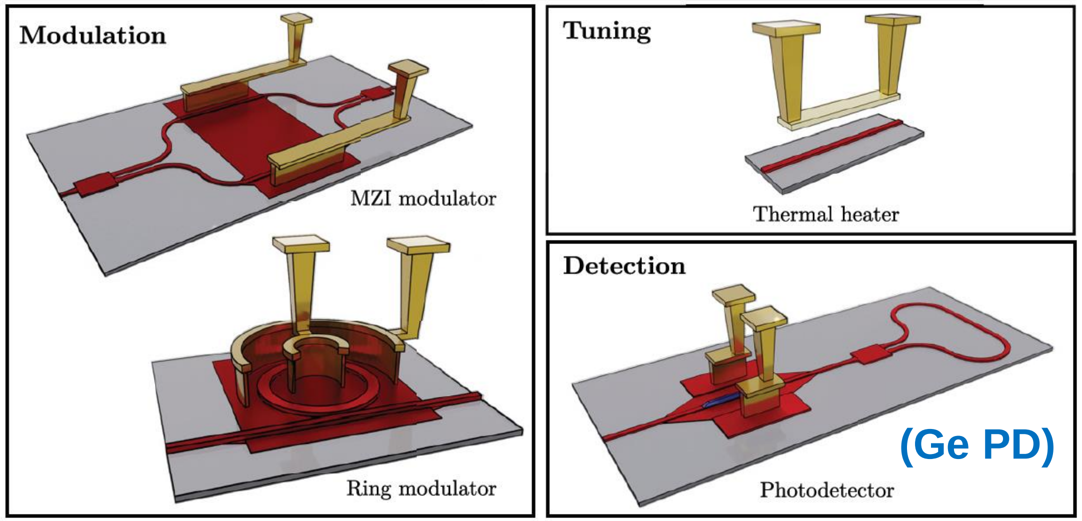
Basic components in Si PICS

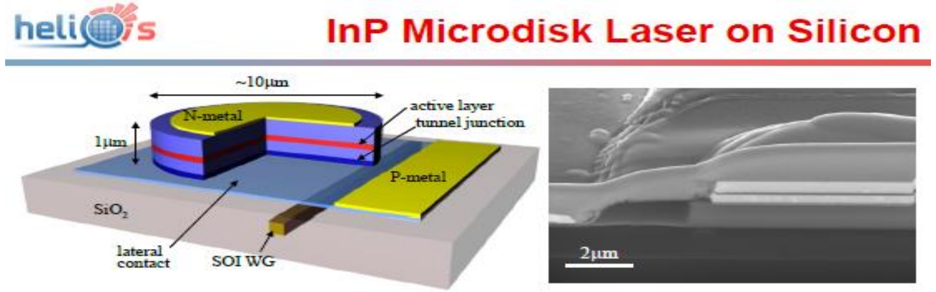
Passive



Active

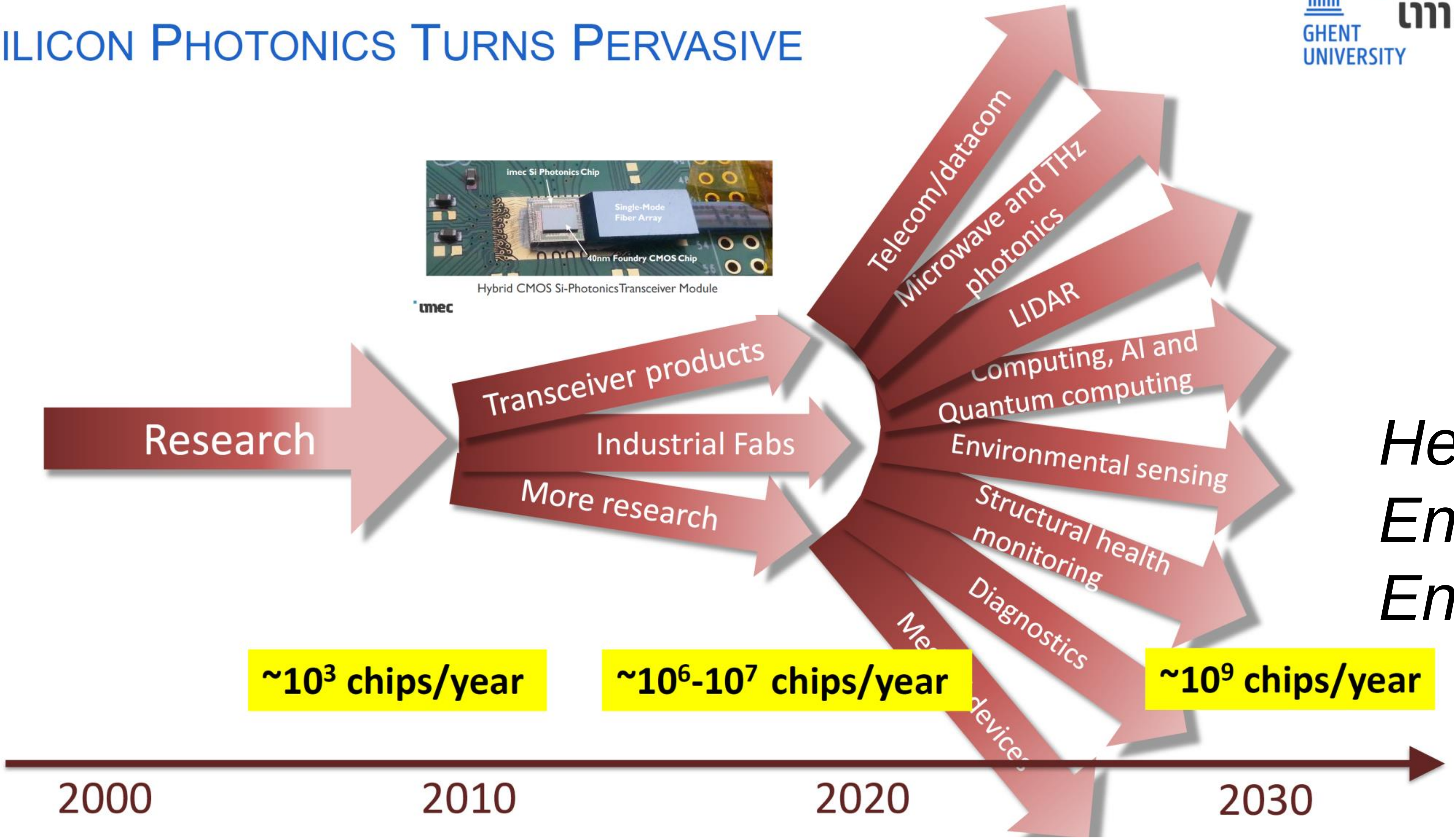


Integrated lasers – heterogeneous integration of III-V



W. Shi et al.: Scaling capacity of fiber-optic transmission systems, **Nanophotonics** 2020; 9(16): 4629–4663

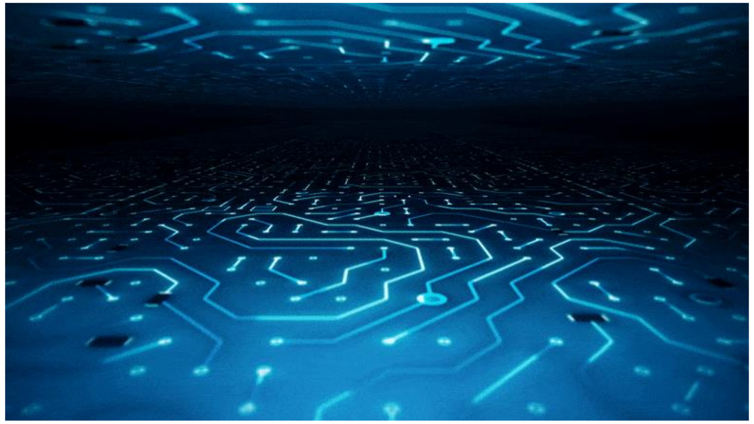
SILICON PHOTONICS TURNS PERVASIVE



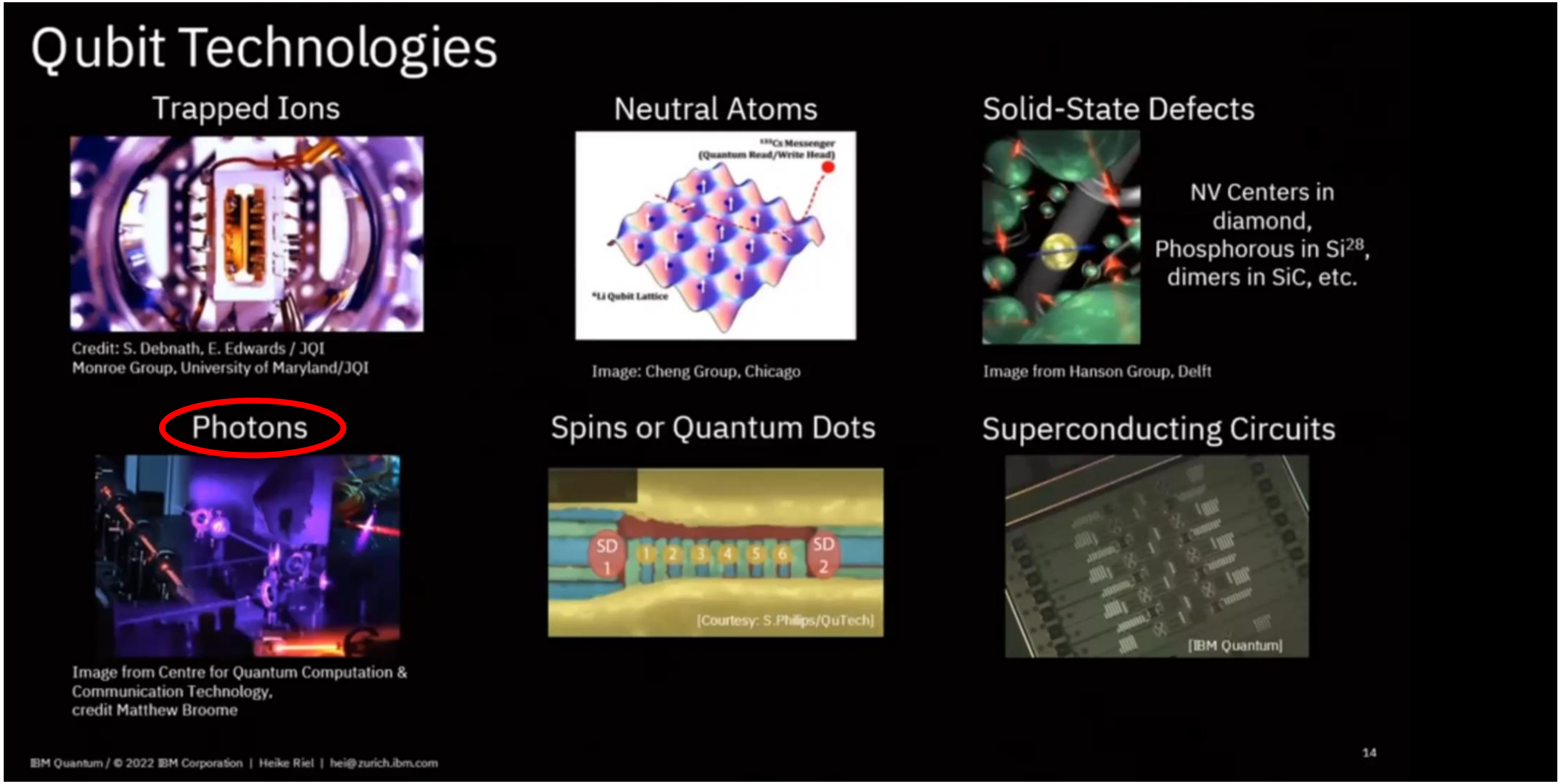
Health
Environment
Energy

Courtesy of Roel Baets and Wim Bogaerts, Ghent University

Quantum technologies & photonic integration



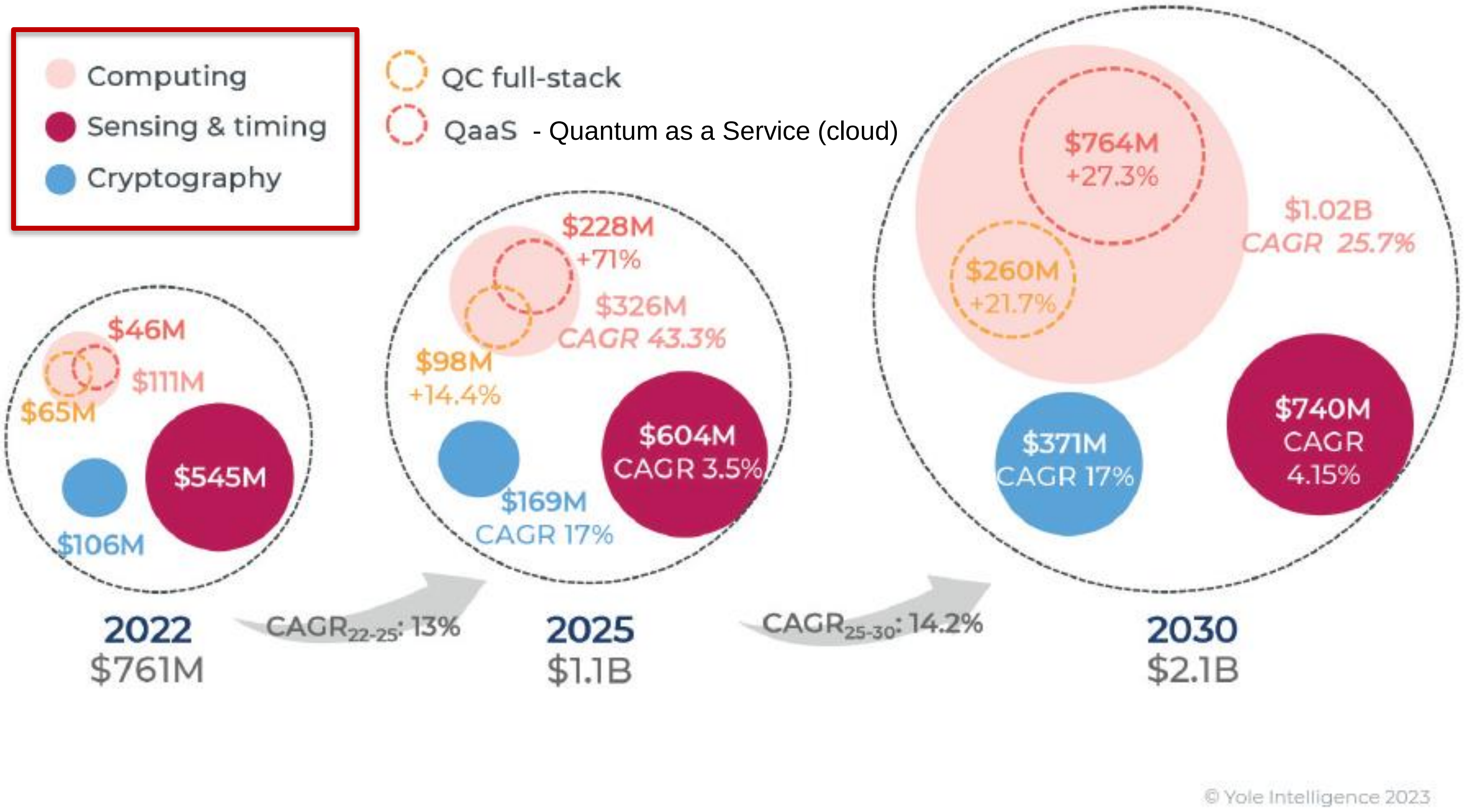
Quantum technologies



Courtesy of Dr. Heike Riel, IBM, SPIE 2022 conference

2022-2030 quantum technologies market forecast

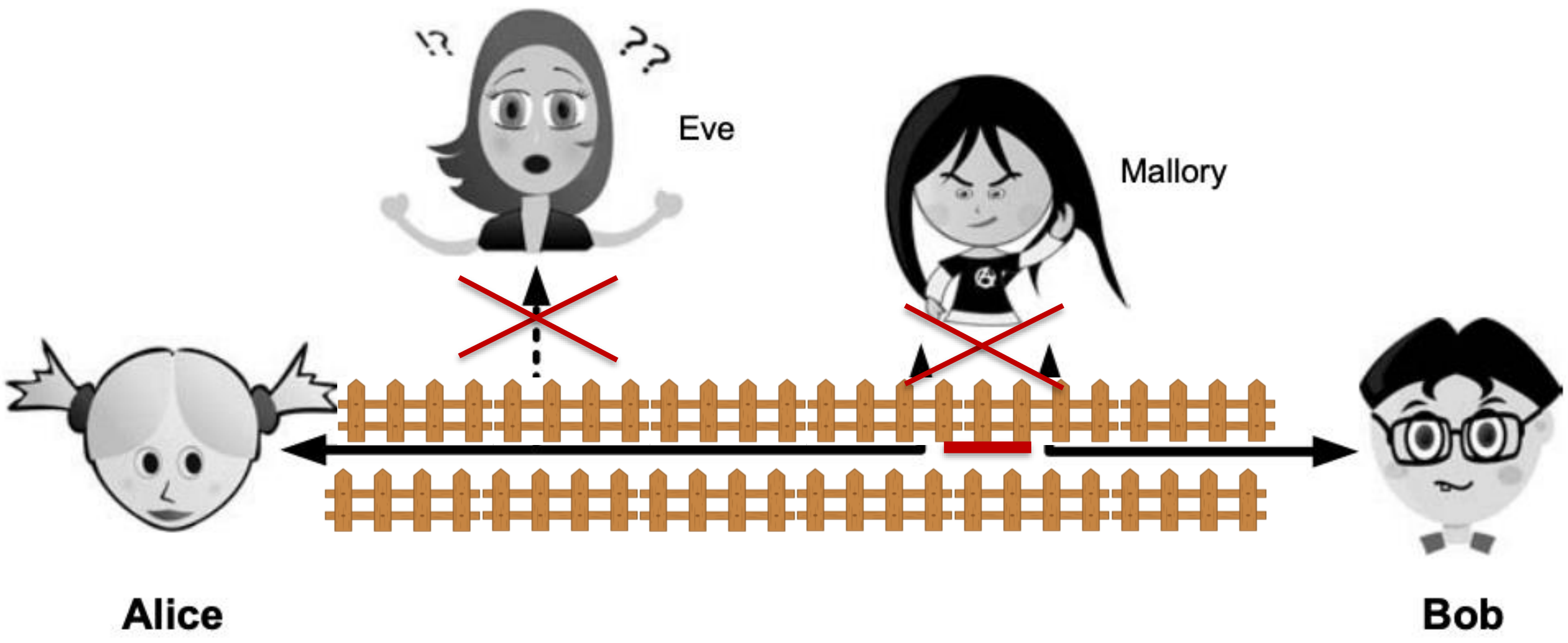
(Source: Quantum Technologies 2023, Yole Intelligence, February 2023)



Quantum optical communication

Secure communication between "Alice and Bob" – **quantum key distribution**

eavesdroppers: passive active



Using single photons for key distribution in optical communication

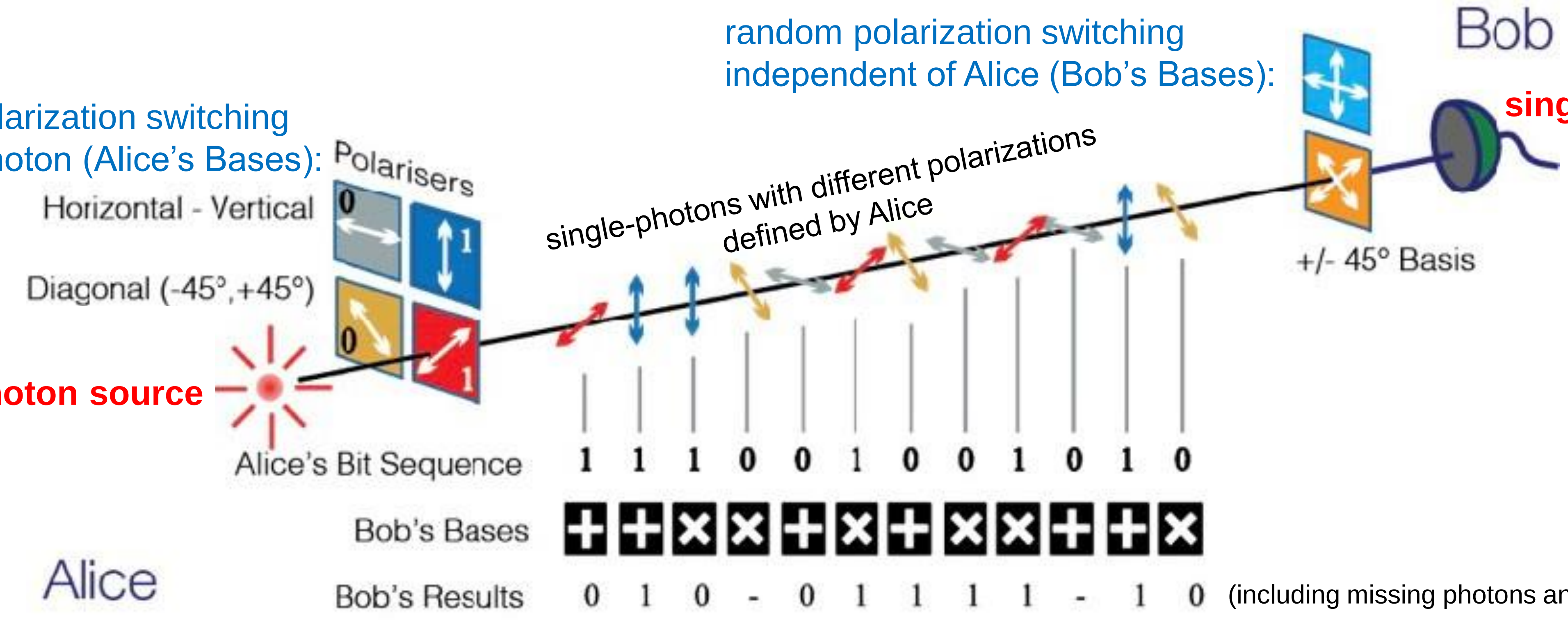
If a photon is detected by an eavesdropper it gets lost or by re-generation it changes its property

random polarization switching
independent of Alice (Bob's Bases):

random polarization switching
for each photon (Alice's Bases):

single-photon detector

single-photon source

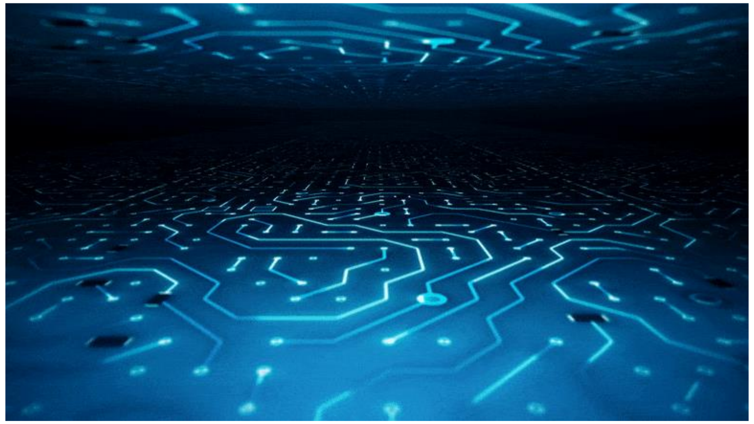


(including missing photons and some uncertainties)

1 0 1 1 1 0

Extracted secret key
at Alice and Bob side
after Bob receives Alice's Bases
and after Alice receives Bob's bits

Quantum photonic integrated circuits - QPICs



QPICs

QPICs for quantum:

- computing
- communications
- simulations
- sensing

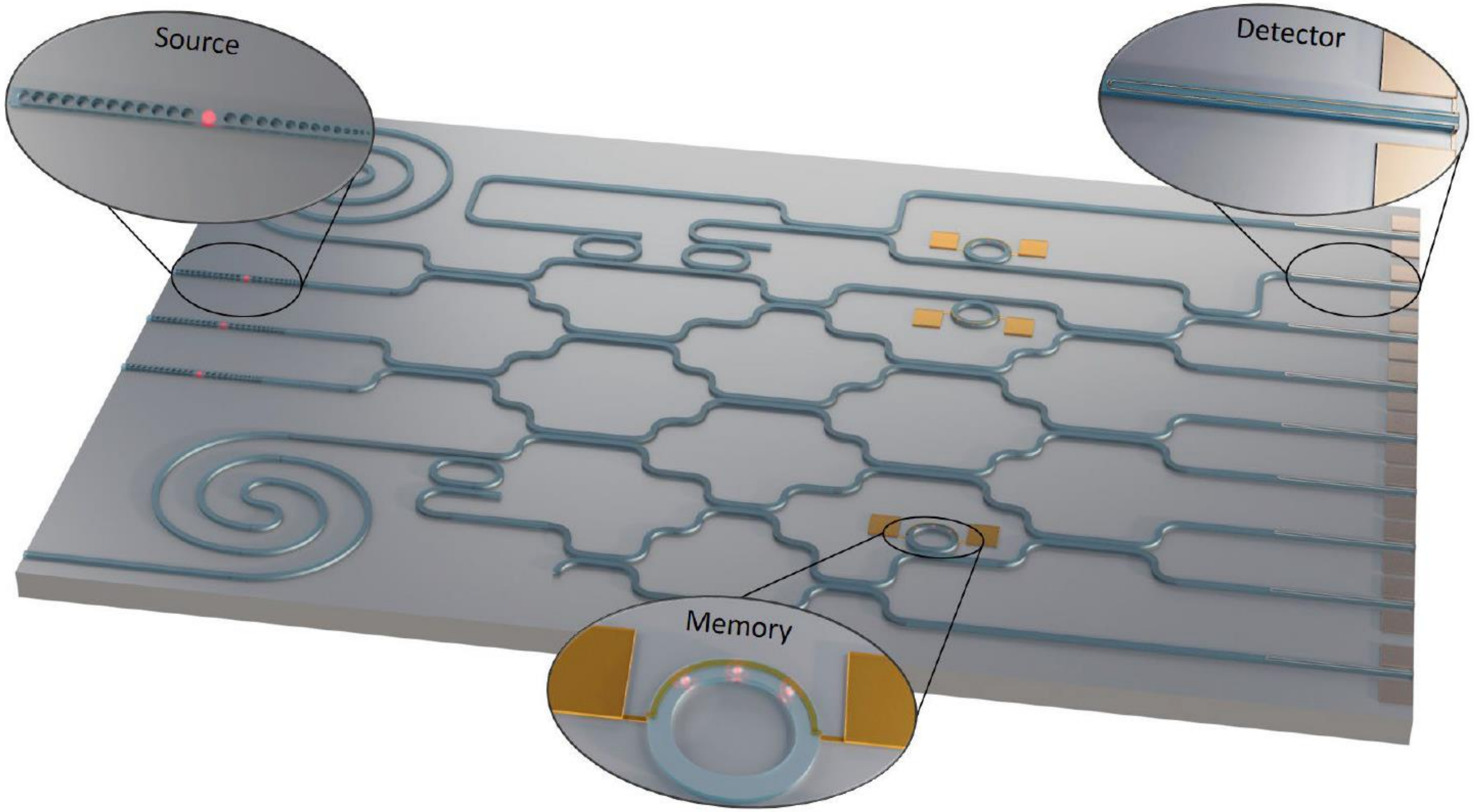


Figure 1: Quantum photonic integrated circuit, including non-linear optics (spirals) and quantum light sources (red dots) in nano-beam cavities, quantum memories (rings including ions), and superconducting detectors (strips), as well as active and passive photonic elements (taken from Nat Rev Phys (2021): https://doi.org/10.1038/s42254-021-00398-z)

Source: QPIC position paper 2022

uTP4Q project

QUANTERA

uTP4Q

A versatile quantum photonic IC platform through micro-transfer printing

QUANTERA

Partner Number	Country	Institution/ Department
1 Coordinator	BE	Ghent University (UG)
2	DK	University of Copenhagen (NBI)
3	DK	Sparrow Quantum (SQ)
4	DE	University of Muenster (MU)
5	CH	Swiss centre for electronics and microtechnology (CSEM)
6	SLO	Univerza v Ljubljani (UL)

Call: QuantERA II JTC 2021

Call topic

Applied Quantum Science

Start date

May 2022

Duration

36 months

Funding support

€ 1 547 570

uTP4Q A versatile quantum photonic IC platform through micro-transfer printing

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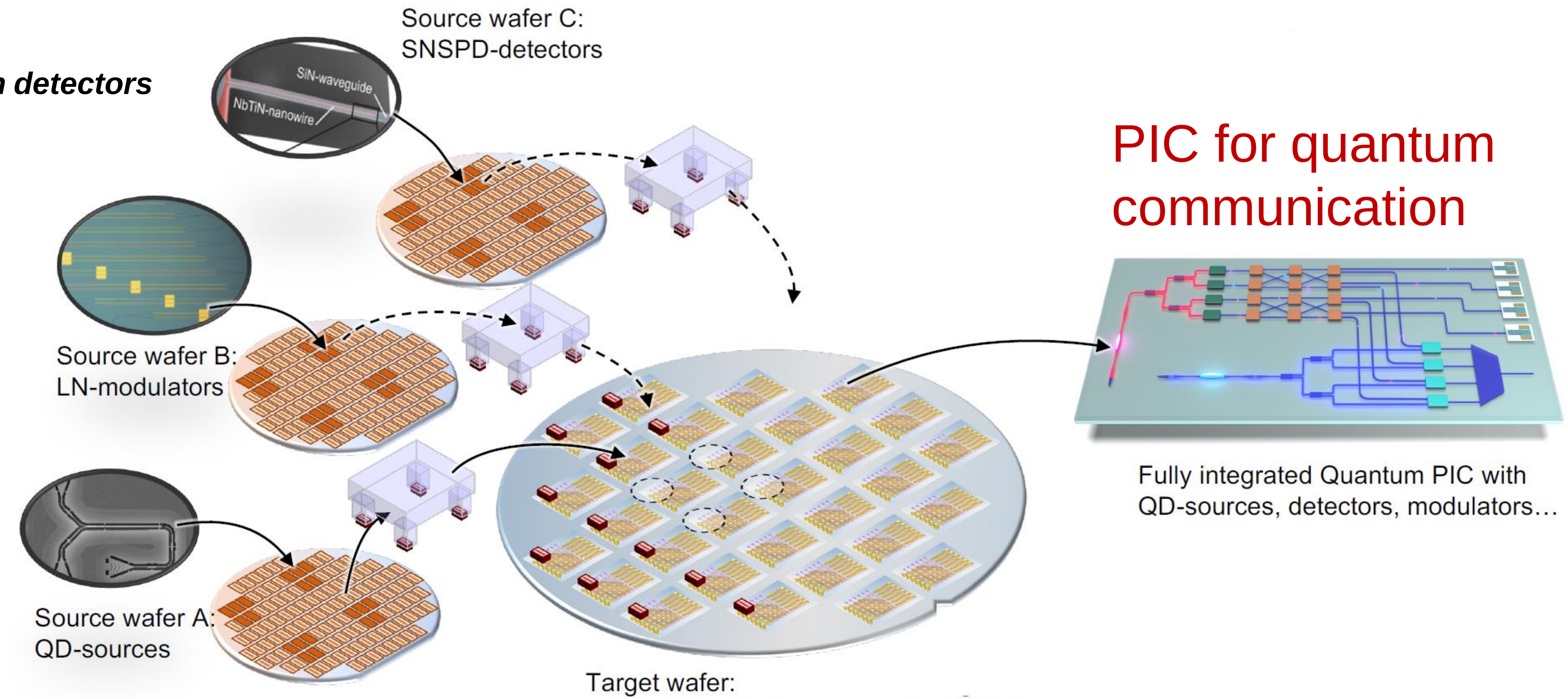
An advantageous way of heterogeneous integration –
combining components from different platforms on wafer scale

Single-photon detectors

Modulators/ Switches

Single-photon sources

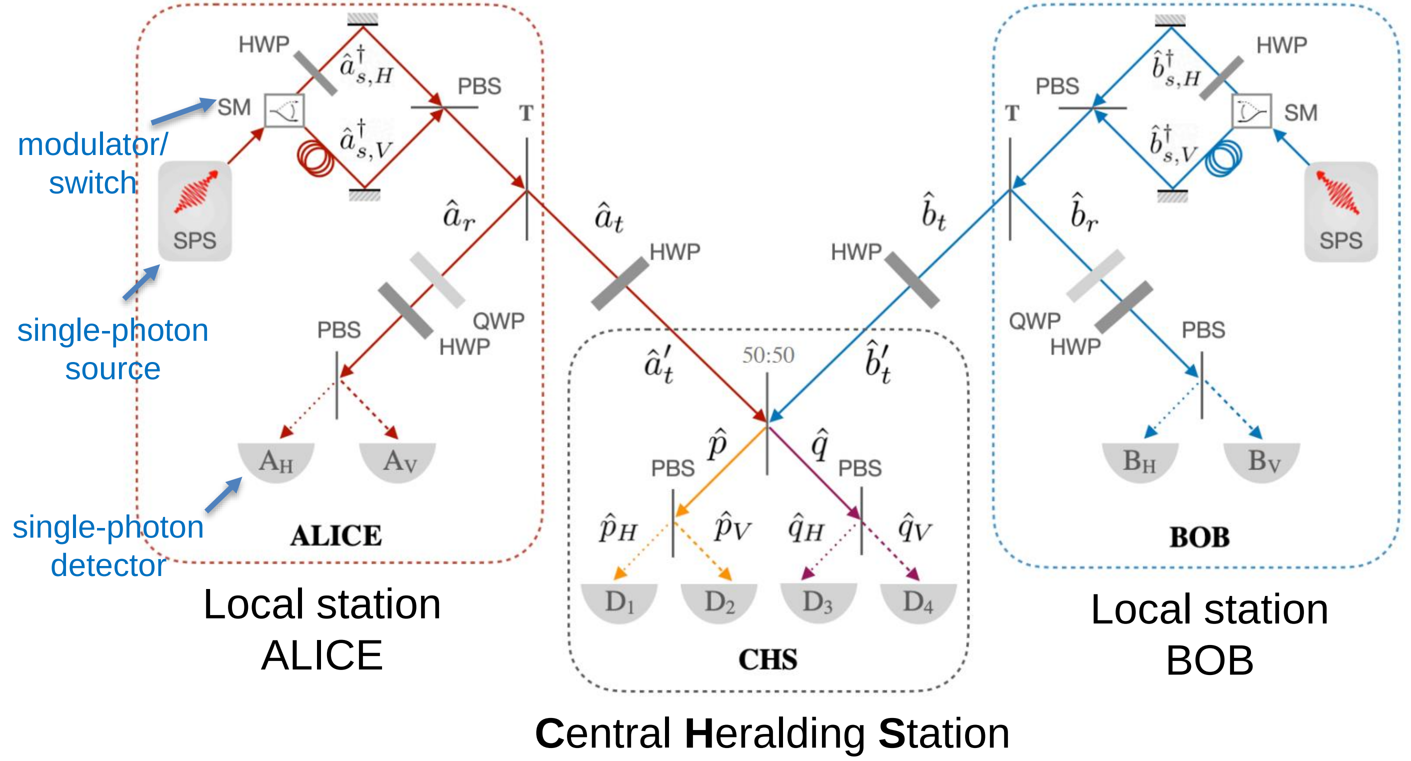


Low-loss SiN connections and passive components

PIC for quantum communication

Device Independent Quantum Key Distribution - DIQKD

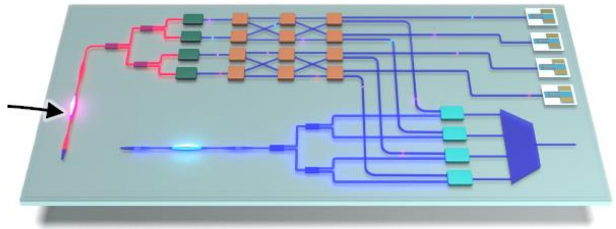
Discrete realization:



photonic integration

uTP4Q

aim

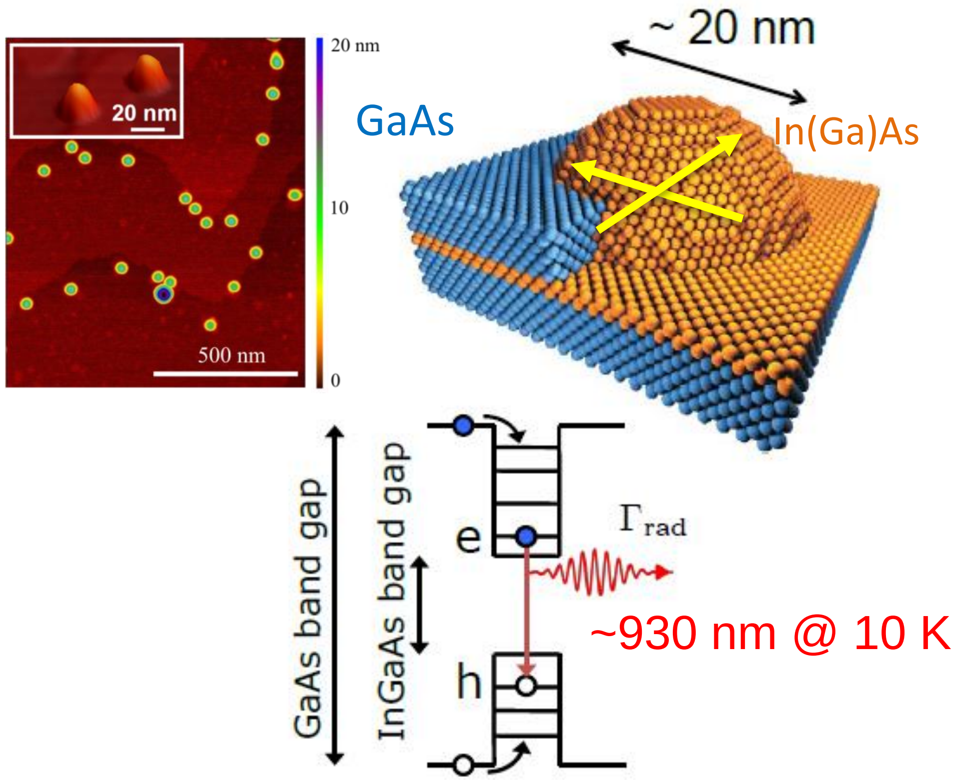


QPICs

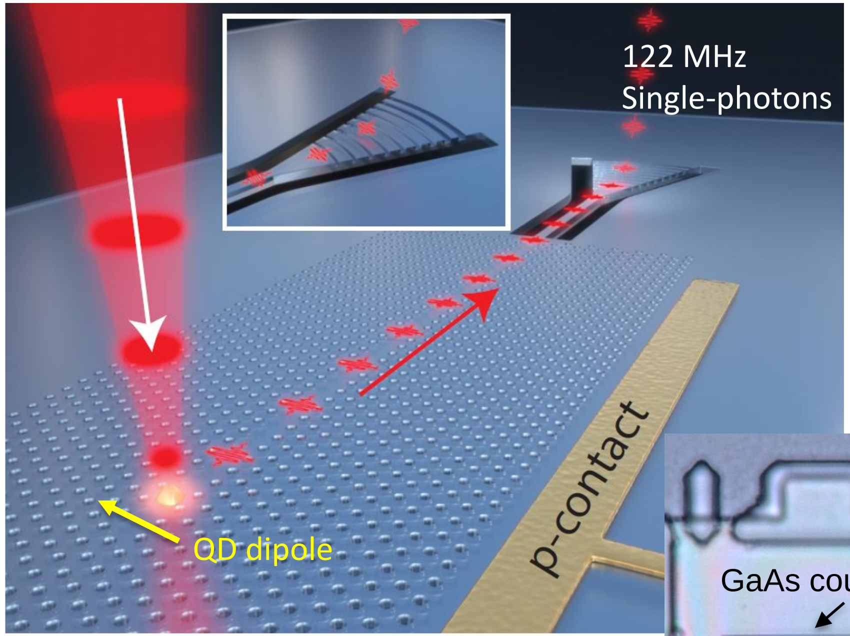
E. Ruiz et al., PRL 106, 012222 (2022)

J. Kolodynski et al., Quantum 4. 260 (2020).

Single photon sources - InAs quantum dots

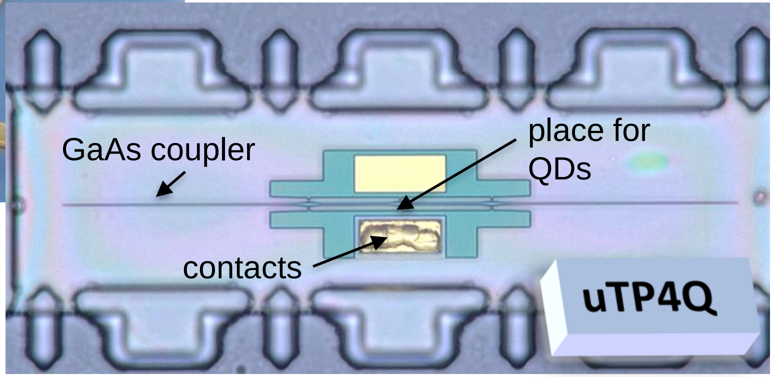


Lodahl et al, Rev. Mod. Phys. 87, 347 (2015).

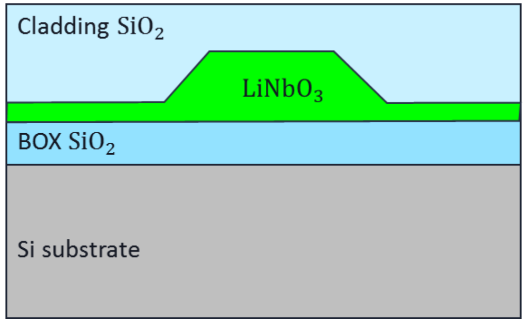


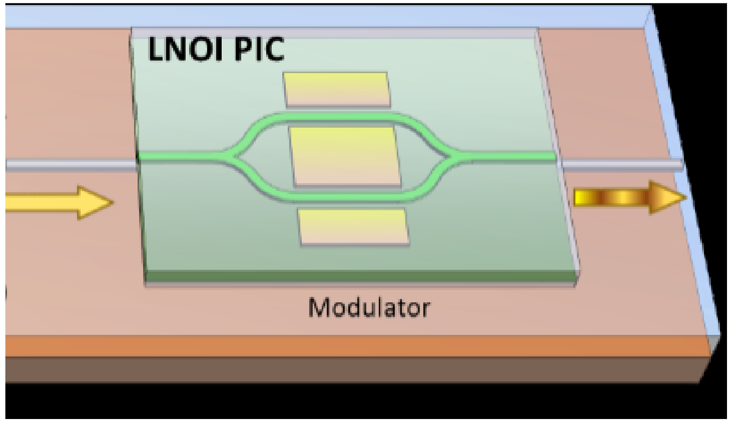
Uppu et al, Science Advances 6, 50 (2020)
Uppu et al, Nat. Comm. 11, 3782 (2020)

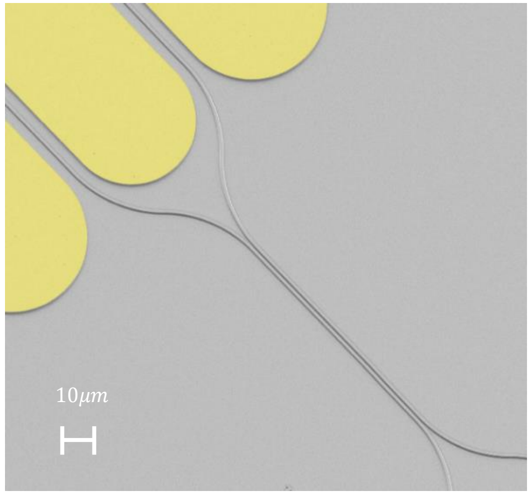
Fabricated GaAs coupon for micro-transfer printing

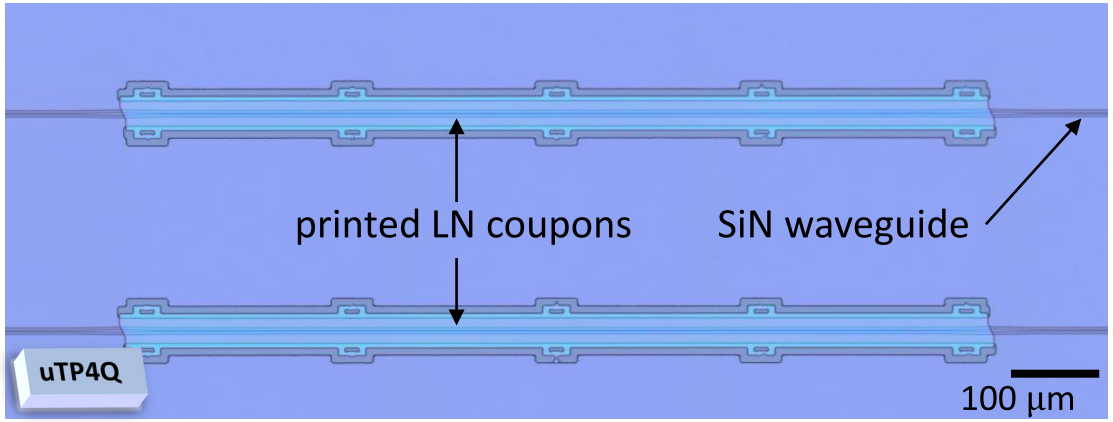


LiNbO modulators, switches

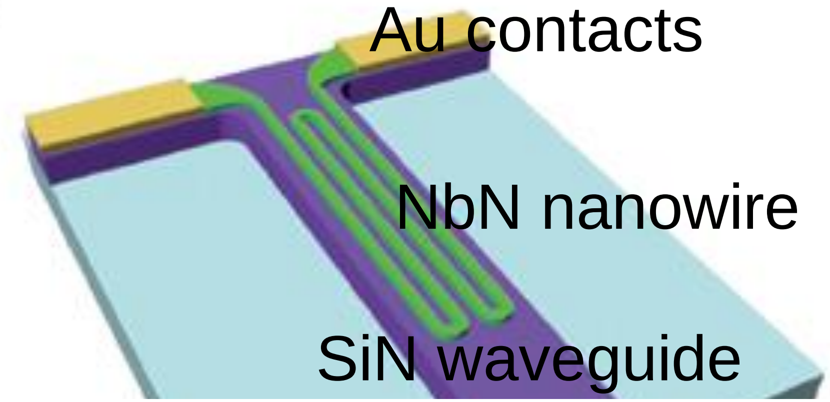


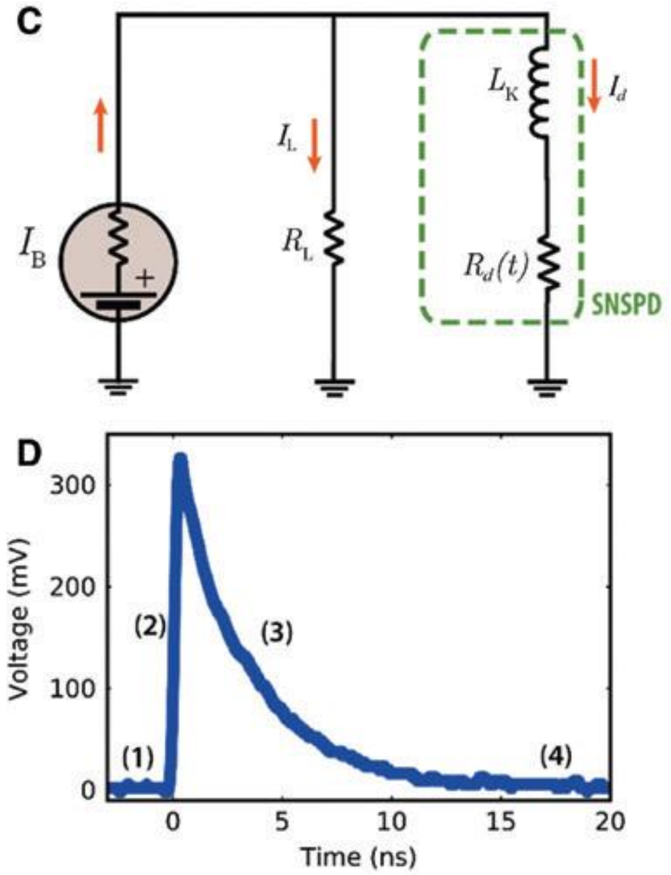


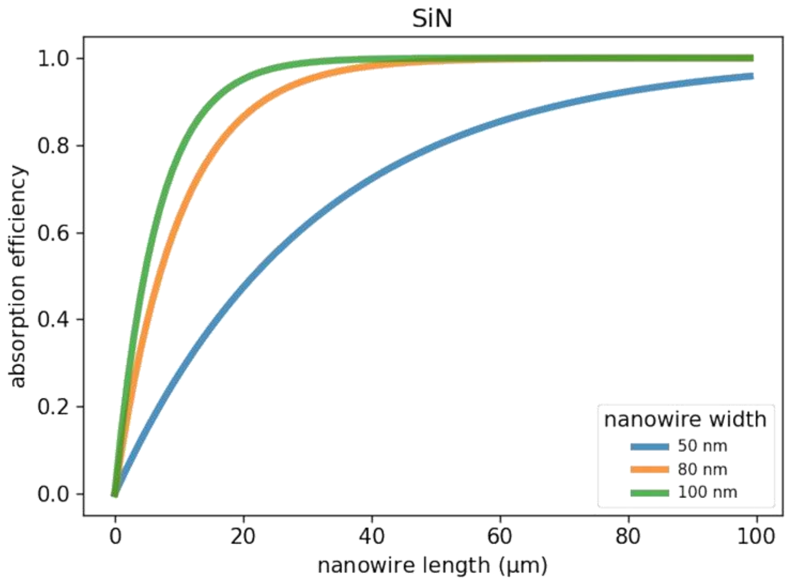




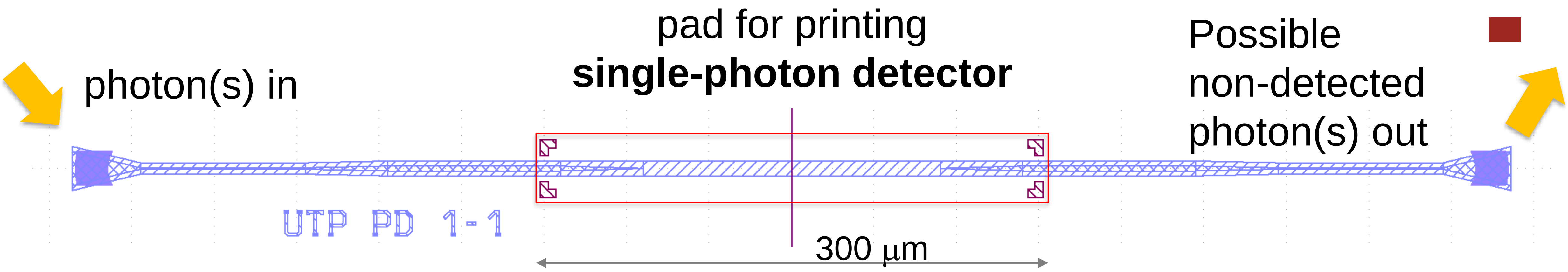
Single photon detectors - NbN superconducting nanowires

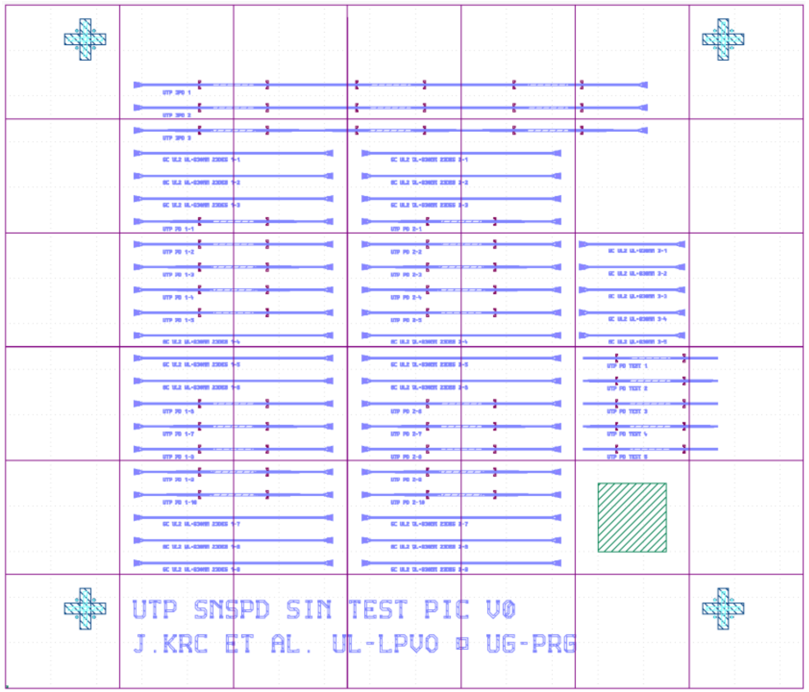






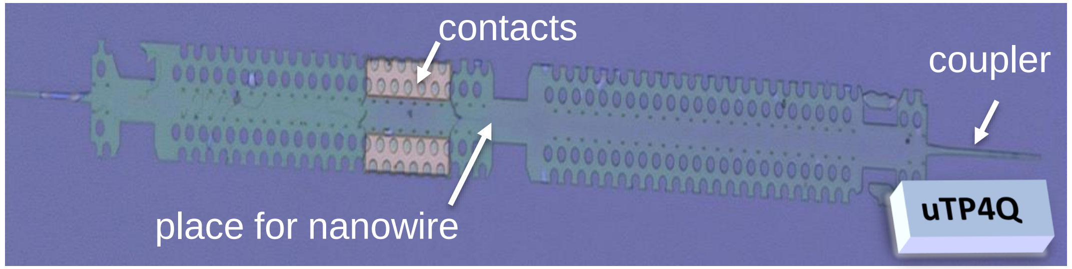
S. Ferrari et al., Nanophotonics 2018; 7(11): 1725–1758





SiN chip for micro-transfer printing of single-photon superconducting nanowire detector

Printed coupon (first tests)



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UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

QUANTERA uTP4Q A versatile quantum photonic IC platform through micro-transfer printing

SiN platform offers low losses

Silicon versus Silicon Nitride

	Wavelength Range (nm)	Refractive Index (at 1550nm)	Waveguide Loss (dB/cm)	Non-linear Process	Thermo-optic Coefficient (K^{-1})	Doping based Modulators (Gb/s)	Integrated Photodetector (GHz)	Layer Stack Flexibility
Silicon	1100 – 4000	3.48	1 – 1.5	Low	1.86×10^{-4}	>40	>60	Limited
Silicon Nitride	400 – 4000	2.0	0.001 – 0.5	High	2.45×10^{-5}	Not available	Not available	Excellent

Abdul Rahim (2017), Expanding the Silicon Photonics Portfolio With Silicon Nitride Photonic Integrated Circuits

Silicon & Silicon Nitride both offers excellent platform for different requirements

EUROPRACTICE has received funding from the European Unions H2020 Framework Programme for research, technological development and demonstration under grant agreement No 825121

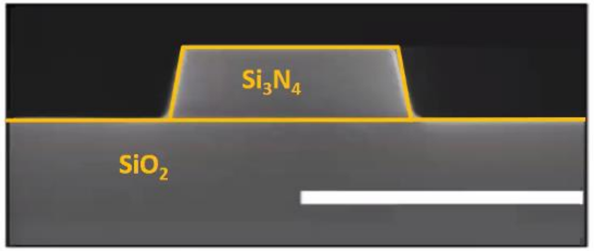
European Commission

EUROPRACTICE Webinar Series on imec's MPW Services
Webinar 1, BioPIX – imec's Silicon Nitride Photonics Platform
26 January 2022 - 18

imec

Europractice & imec webinar on SiN MPW, 2022

Silicon nitride (SiN)

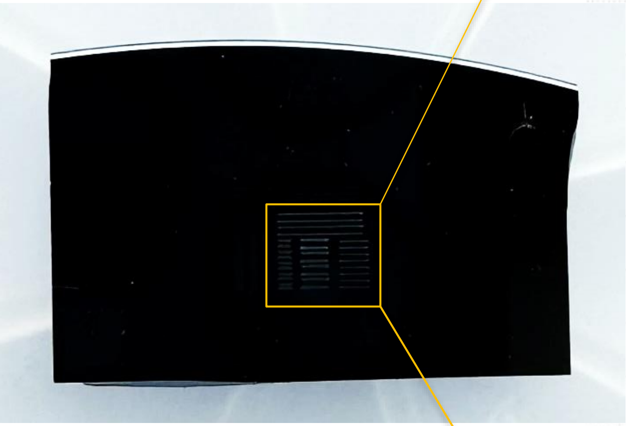


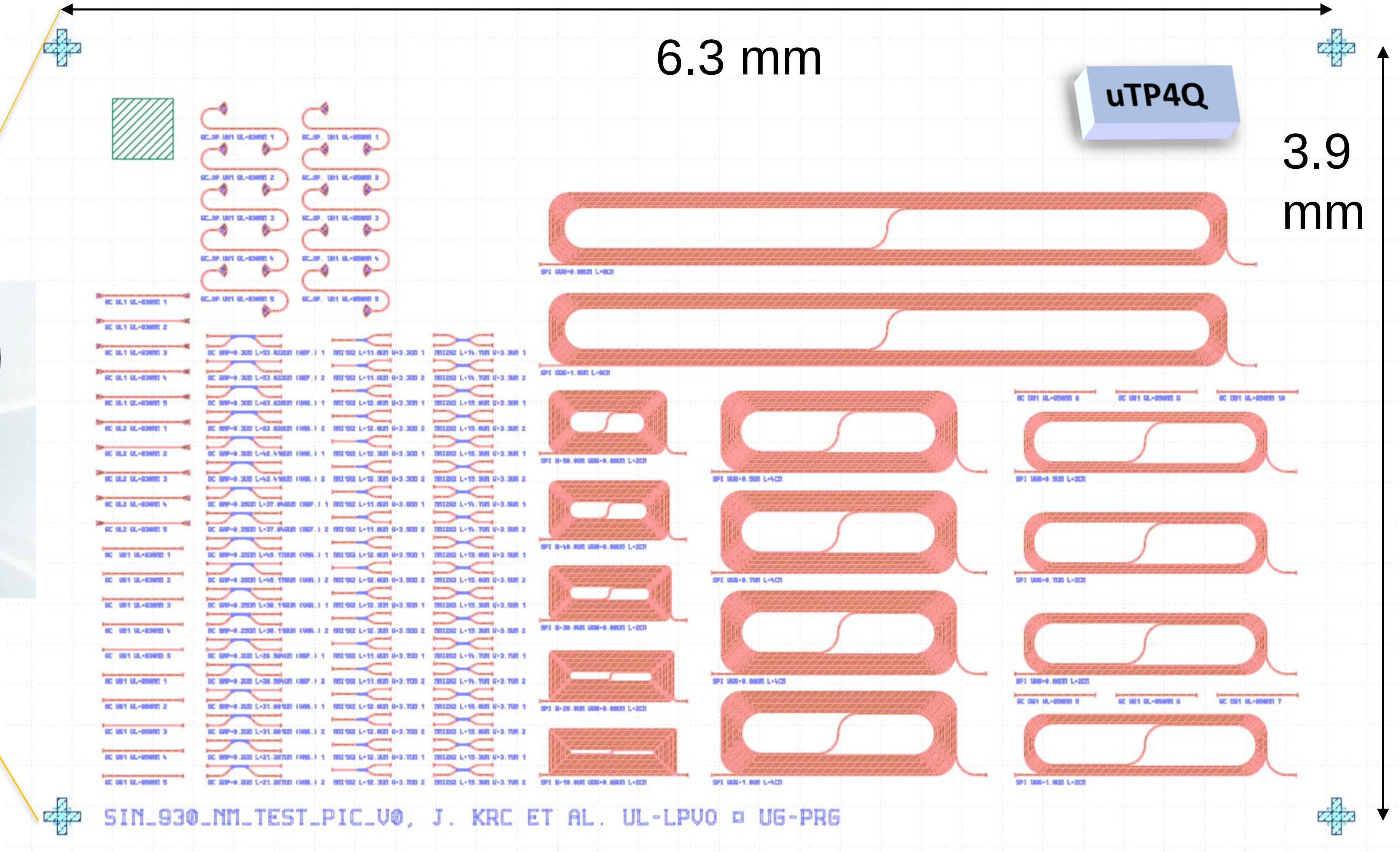
Silicon nitride: n=2
Silicon oxide: n=1.45
Moderately high index contrast

SiN test chip

λ = 930 nm

fabricated at **Ghent Uni.**





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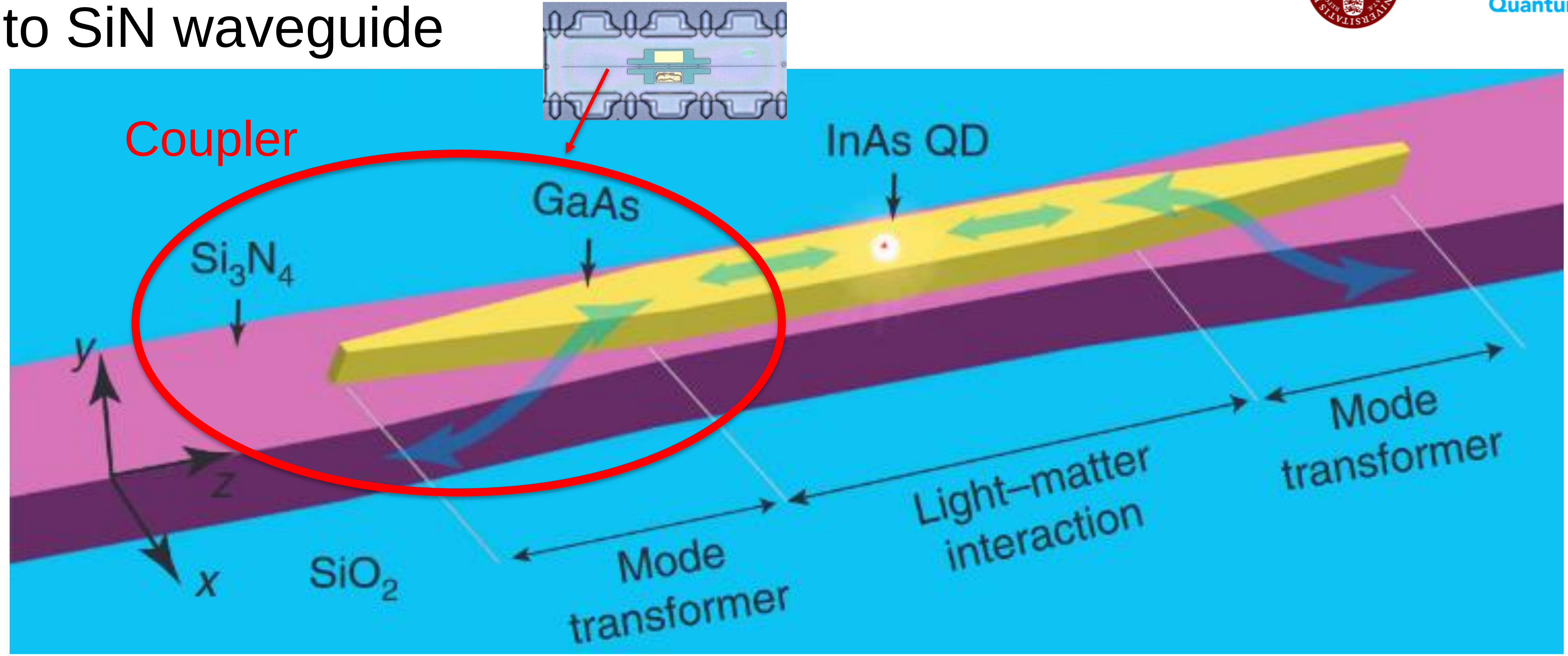
Coupling of light from a **single-photon QD source** to SiN waveguide

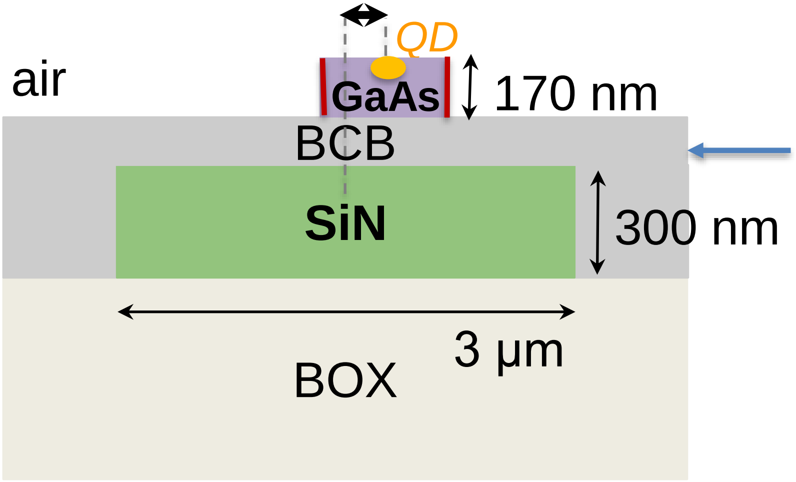


M. Davanco et al., Nat Commun, vol. 8, no. 1, Art. no. 1, Oct. 2017.

Optimization of GaAs coupler considering realistic situation

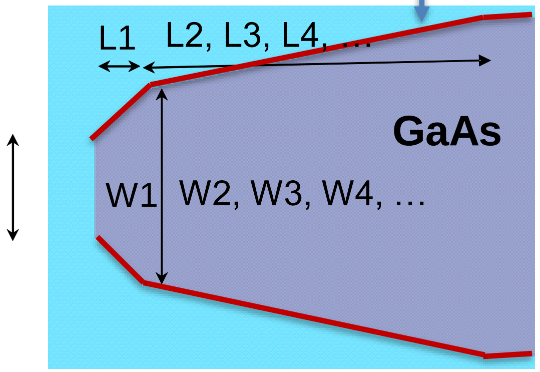
Possible **misalignment** of Ga As waveguide

Different **BCB thicknesses** possible



Cross-section

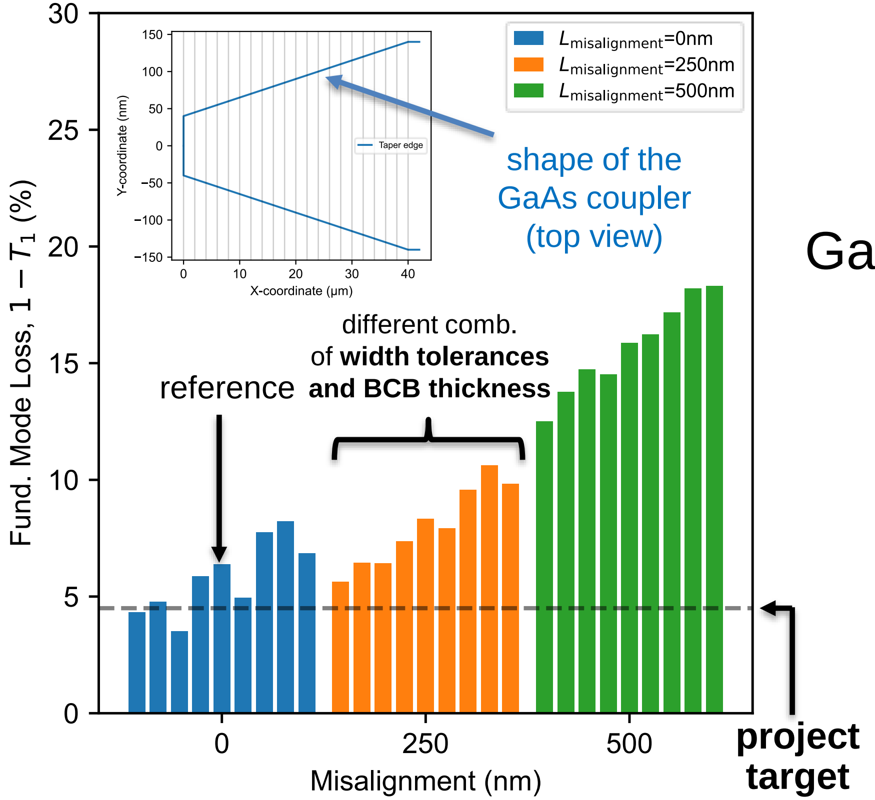
Width (W) fabrication tolerances and possible **sidewall nanoroughness**



Top view of GaAs coupler

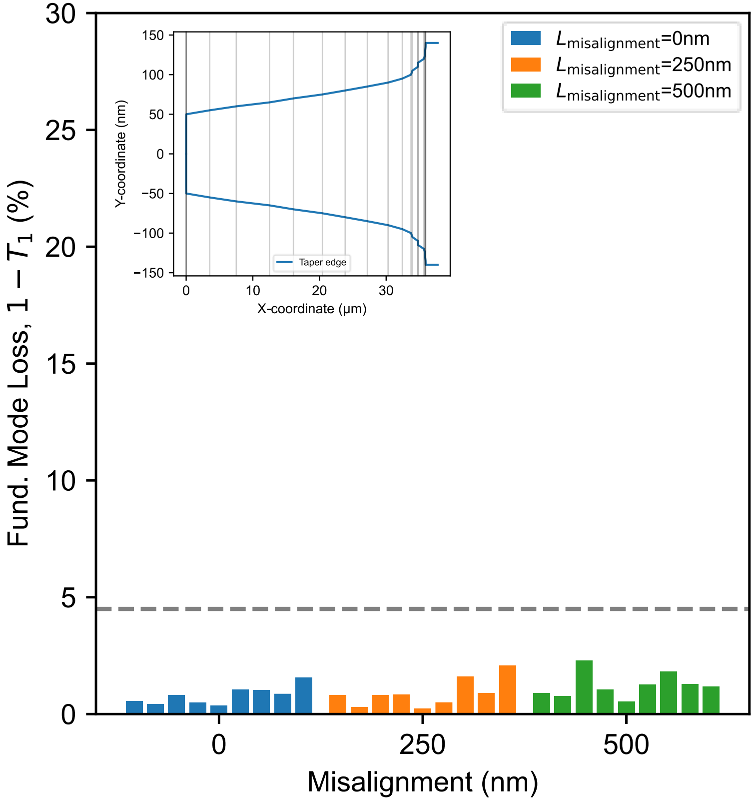
Coupler optimization – simulation results (FDTD, EME)

Before optimisation



optimization of GaAs coupler shape

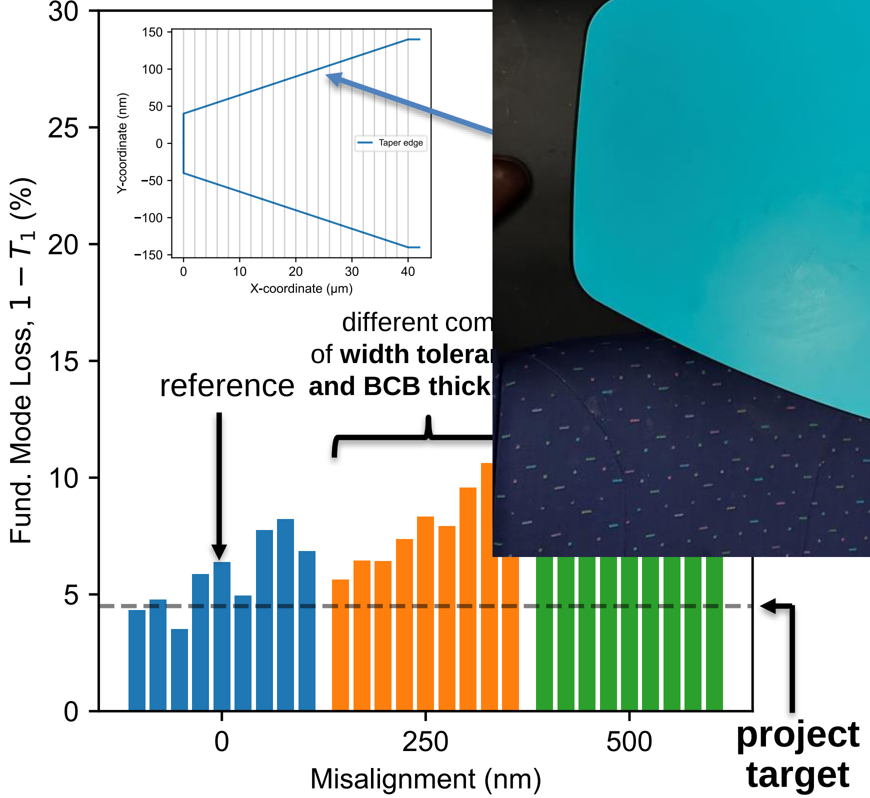
Optimisation for **robust** coupling considering **tolerances in widths and BCB thicknesses**

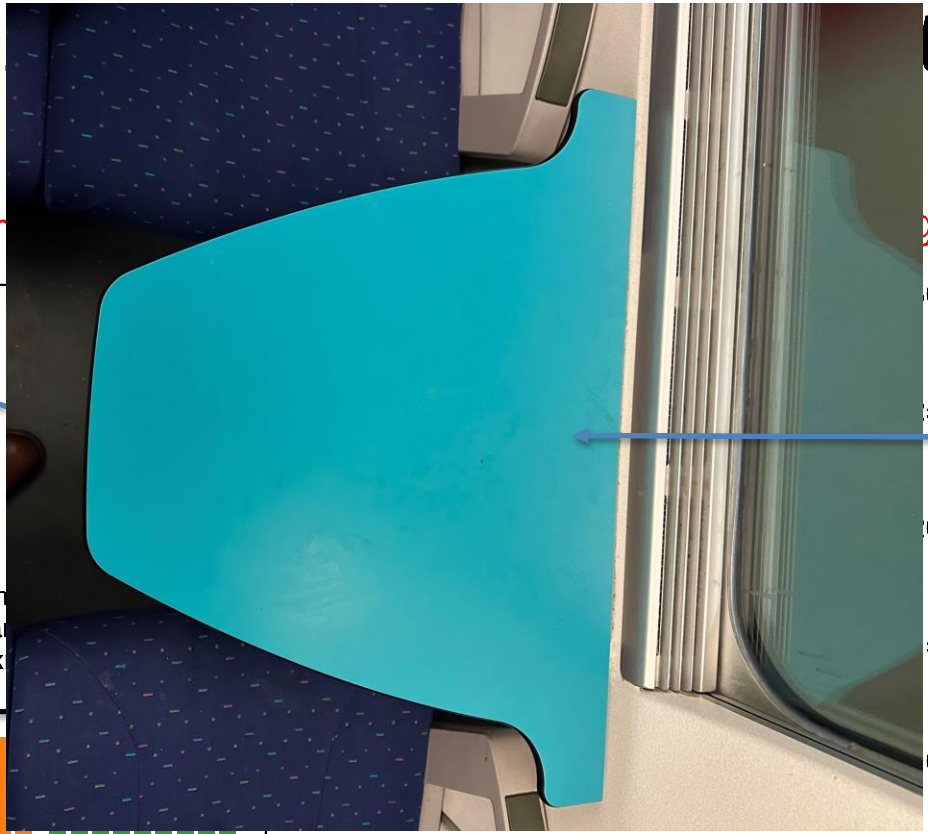


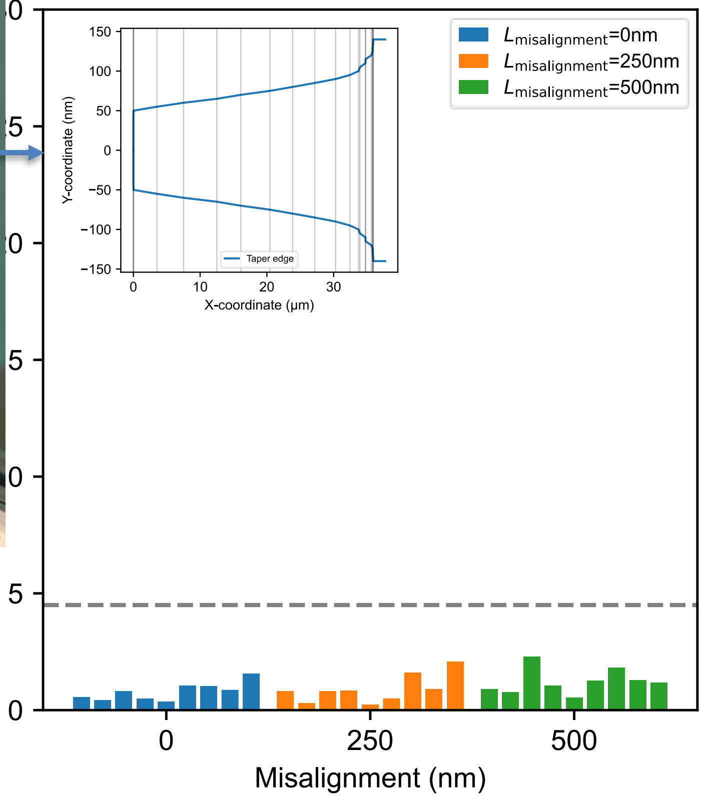
Coupler optimi… ts (FDTD, EME)

Before optir…

Optimisation for **robust** coupling
… **tolerances in widths and BCB thicknesses**







Conclusion

- **Integrated photonic** is important for quantum communication and other quantum applications

- **Micro-transfer printing** enables heterogeneous integration of high-performance quantum components on wafer scale

- Both is combined in the project uTP4Q aiming to establish a **versatile platform for quantum photonic ICs**, such as integrated DIQKD solutions

- Successful **demonstration of printed devices** (single-photon sources, modulators, single-photon detectors) on low-loss SiN platform was presented and also some results of **optimization of GaAs couplers**.

Acknowledgement

Funded by the
European Union

QUANTERA

QuantERA II programme (GA No: Grant Agreement No 101017733)

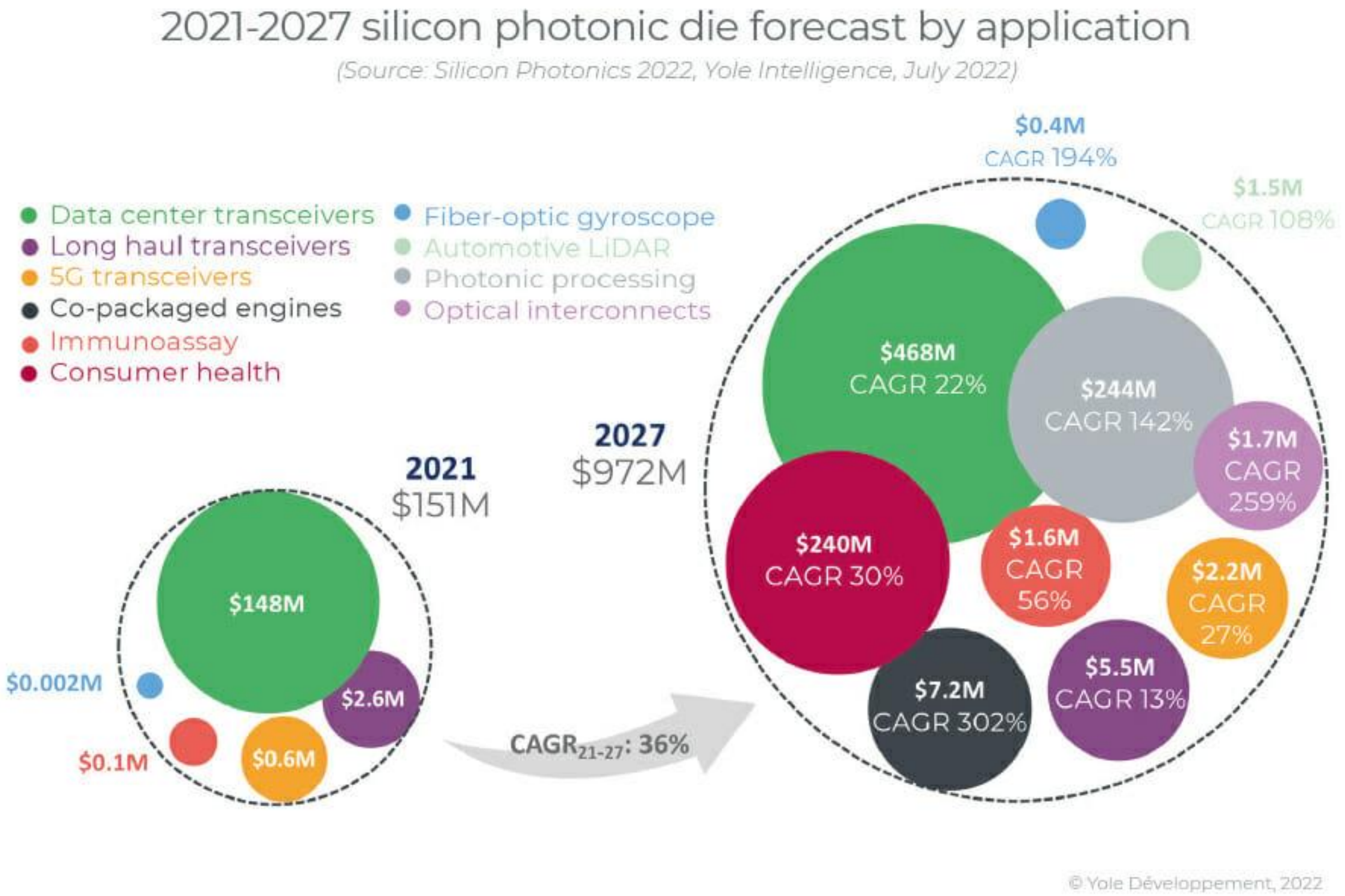
uTP4Q

REPUBLIC OF SLOVENIA
GOV.SI
Ministry of Higher Education, Science and Innovation

Slovene contract No: C3330-22-252001

aris Slovenian Research and Innovation Agency

Research Programme Photovoltaics and Electronics (P2-0415)


2021-2027 silicon photonic die forecast by application
(Source: Silicon Photonics 2022, Yole Intelligence, July 2022)
Data center transceivers
Long haul transceivers
5G transceivers
Co-packaged engines
Immunoassay
Consumer health
Fiber-optic gyroscope
Automotive LiDAR
Photonic processing
Optical interconnects
2021
$151M
$148M
$0.002M
$2.6M
$0.1M
$0.6M
CAGR21-27: 36%
2027
$972M
$0.4M
CAGR 194%
$1.5M
CAGR 108%
$468M
CAGR 22%
$244M
CAGR 142%
$1.7M
CAGR
259%
$240M
CAGR 30%
$1.6M
CAGR
56%
$2.2M
CAGR
27%
$7.2M
CAGR 302%
$5.5M
CAGR 13%
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NATURE PHOTONICS | VOL 4 | AUGUST 2010 | www.nature.com/naturephotonics

Integrating silicon photonics

Mario Paniccia, Intel fellow and director of Intel's Photonics Technology Lab, talks to *Nature Photonics* about the company's progress in commercializing high-speed silicon photonics.

The latest breakthrough from Intel: an integrated link consisting of a fully integrated silicon photonic transmitter chip with hybrid silicon lasers (left) and a fully integrated receiver chip based on germanium photodetectors (right).

QPIC

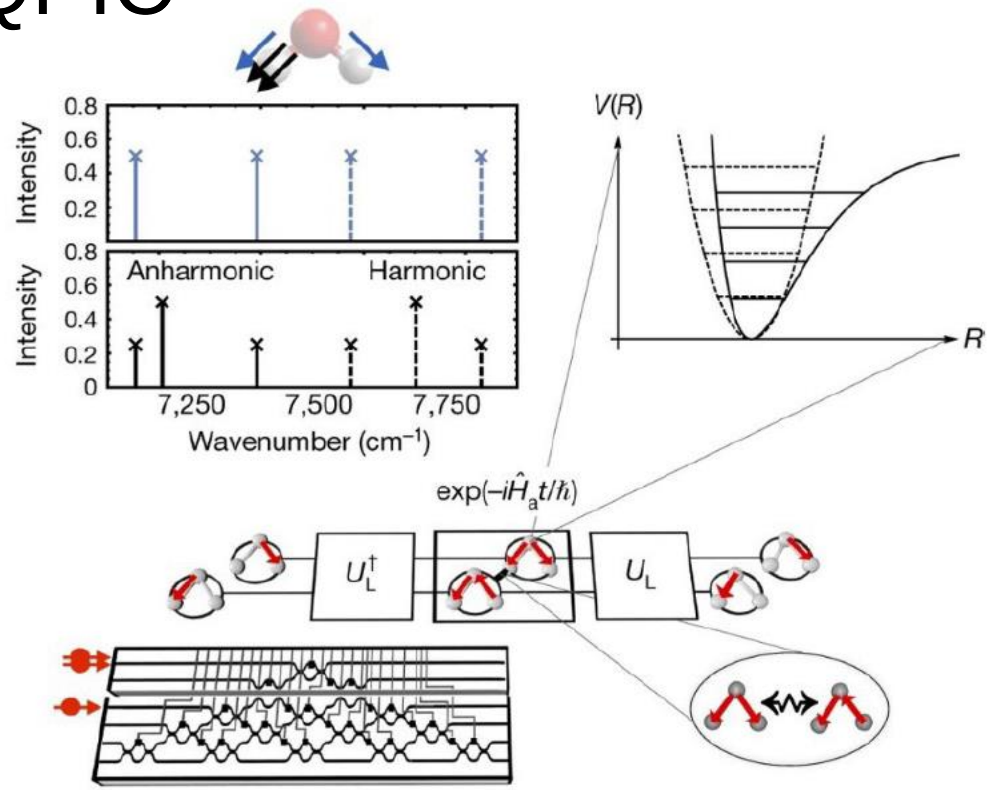


Figure 5: Quantum photonic integrated circuit with thermo-optic phase shifters (bottom) allows for simulating the vibrational quantum dynamics of molecules (taken from Nature (2018): https://doi.org/10.1038/s41586-018-0152-9)

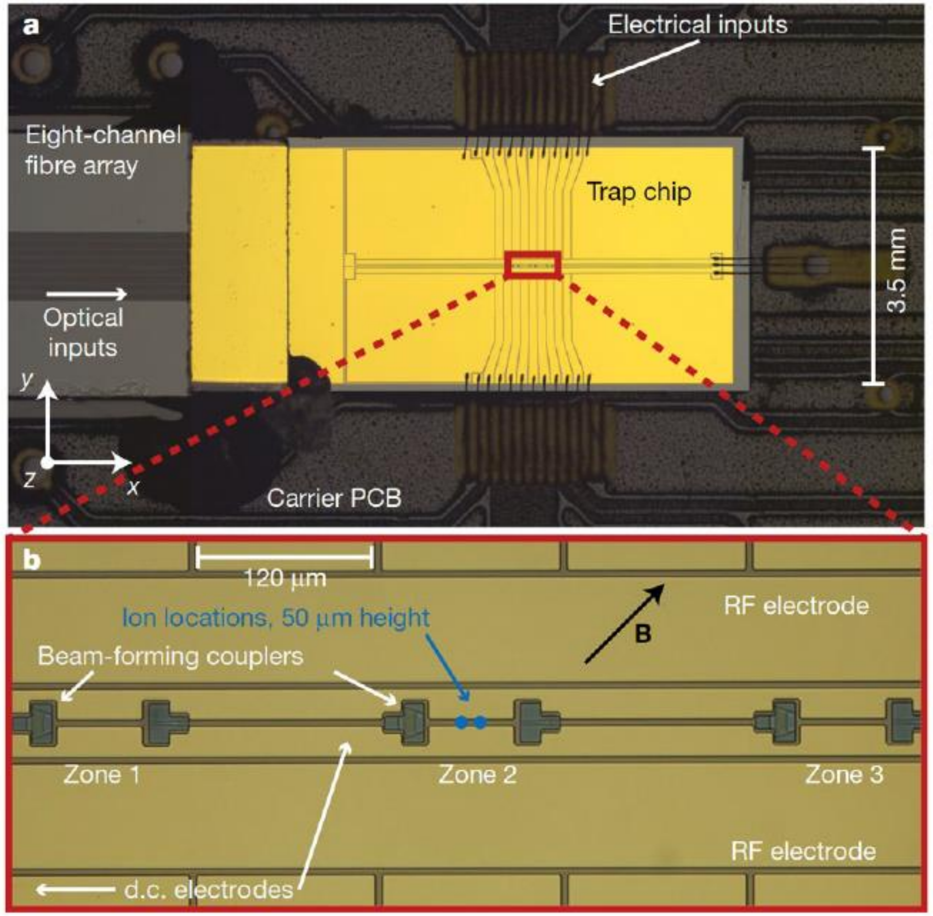
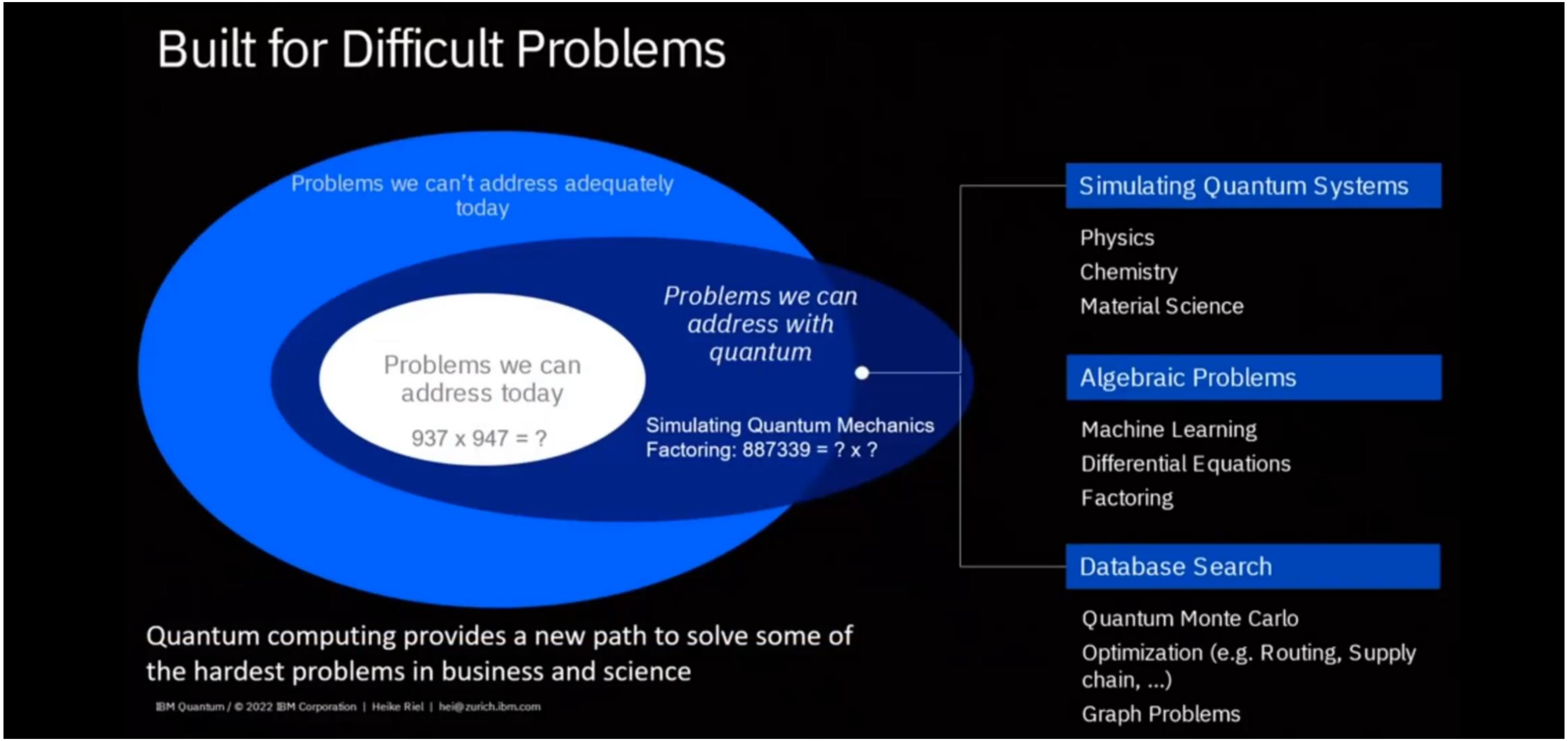


Fig. 4: Optical micrograph of an assembled ion trap device with an eight-channel fibre array attached. b, Higher-magnification view near the trap zones (taken from Nature (2020) https://doi.org/10.1038/s41586-020-2823-6)

Source: QPIC position paper 2022

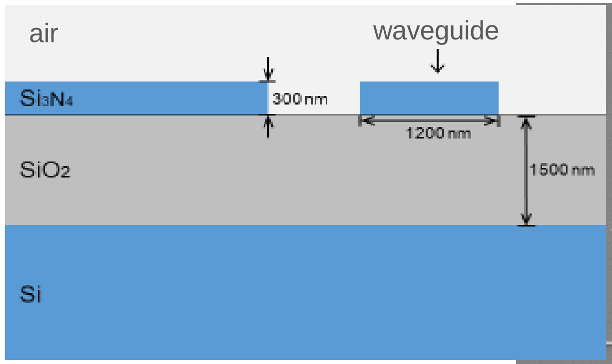
Quantum computing

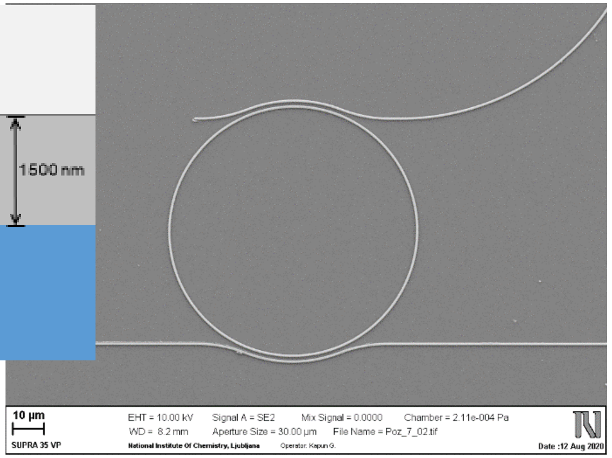


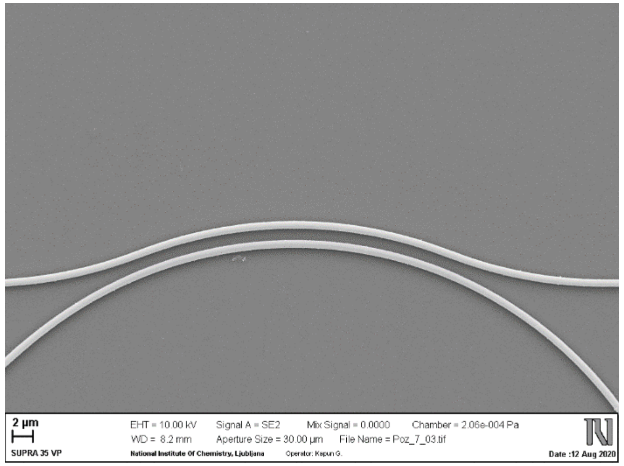
Courtesy of Dr. Heike Riel, IBM, SPIE 2022 conference

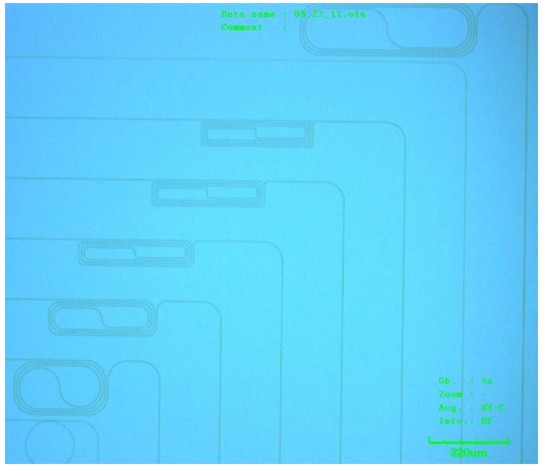
SiN integrated structures – University of Ljubljana (PECVD, litho, plasma etching)

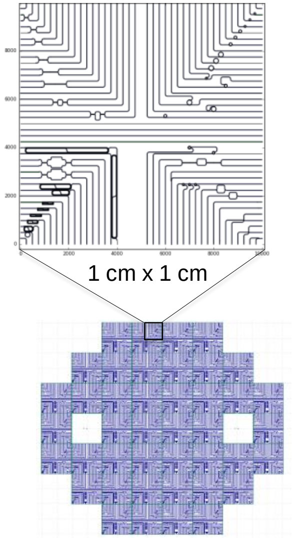
cross-section



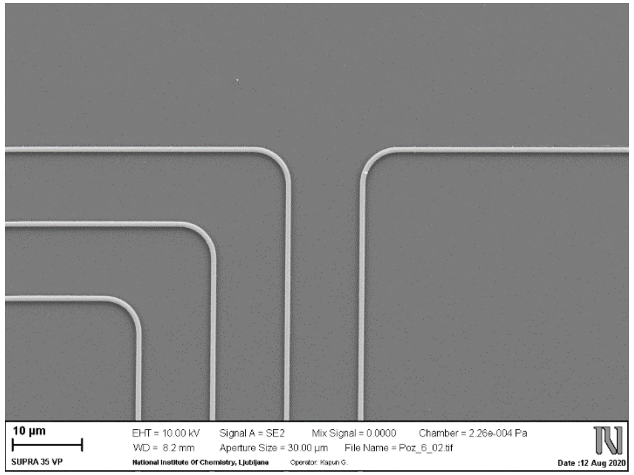


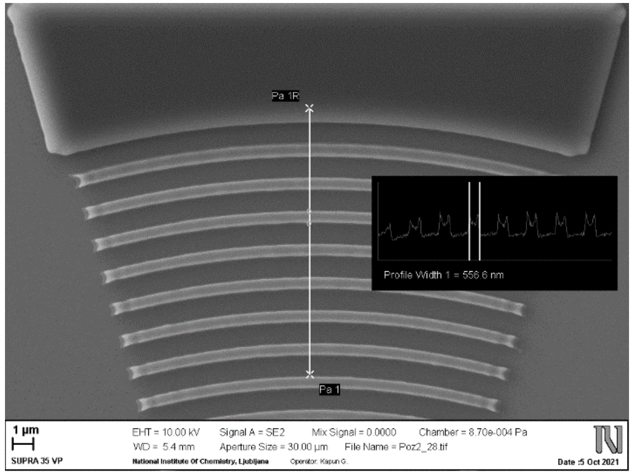


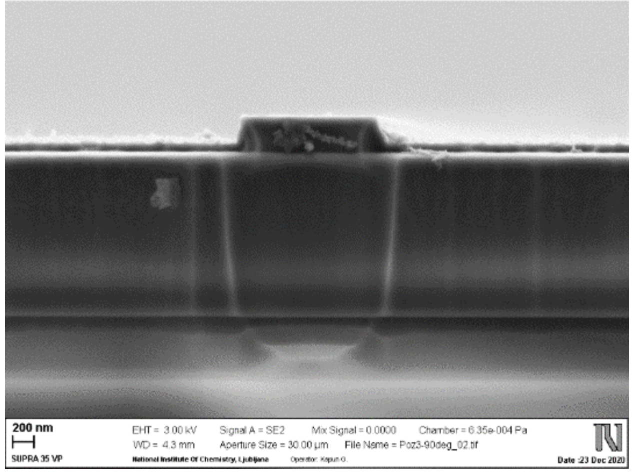




4” wafer



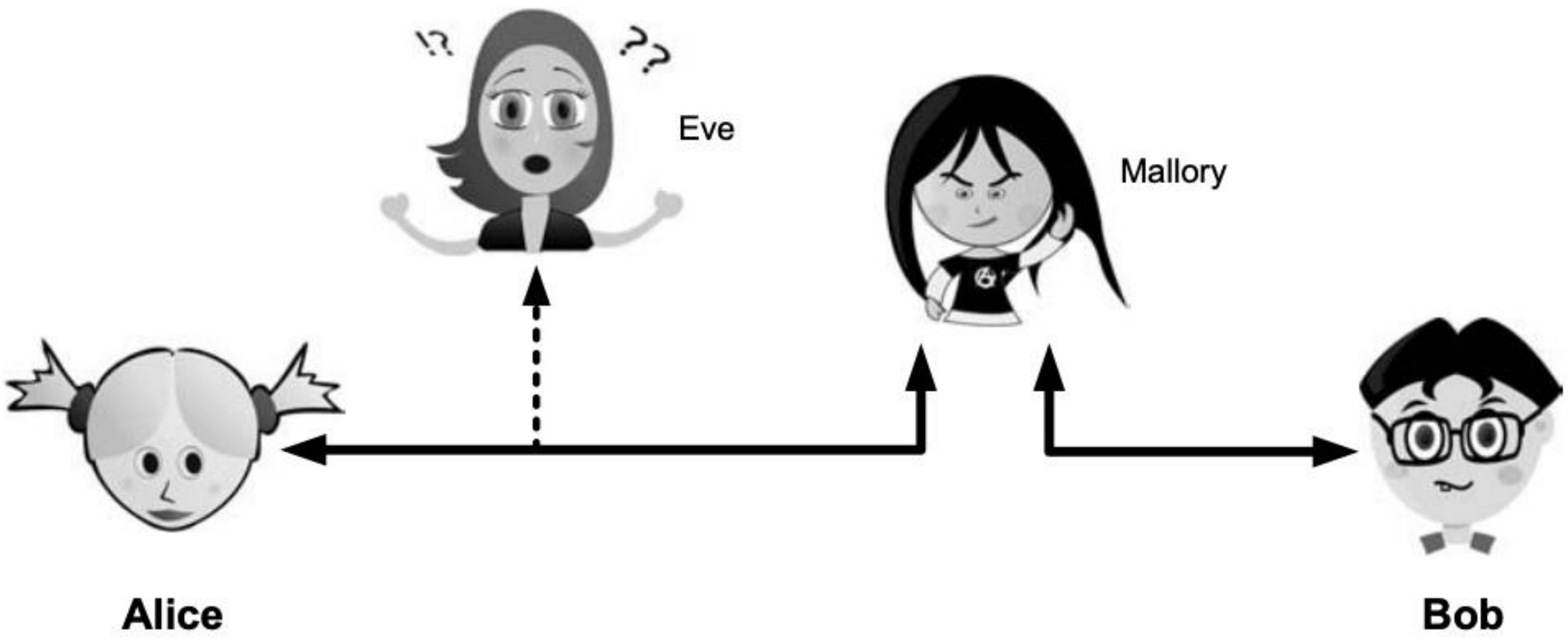




Quantum communication

Communication between “Alice and Bob”

eavesdroppers: passive active



Micro-transfer printing basics

Device processing, release, pick-up & print