FONDAZIONE BRUNO KESSLER

ISSW 2024

THE INTERNATIONAL SPAD SENSOR WORKSHOP & THE SPAD SENSOR SCHOOL

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Silicon SPAD monolithically integrated with SiON-based photonic circuit

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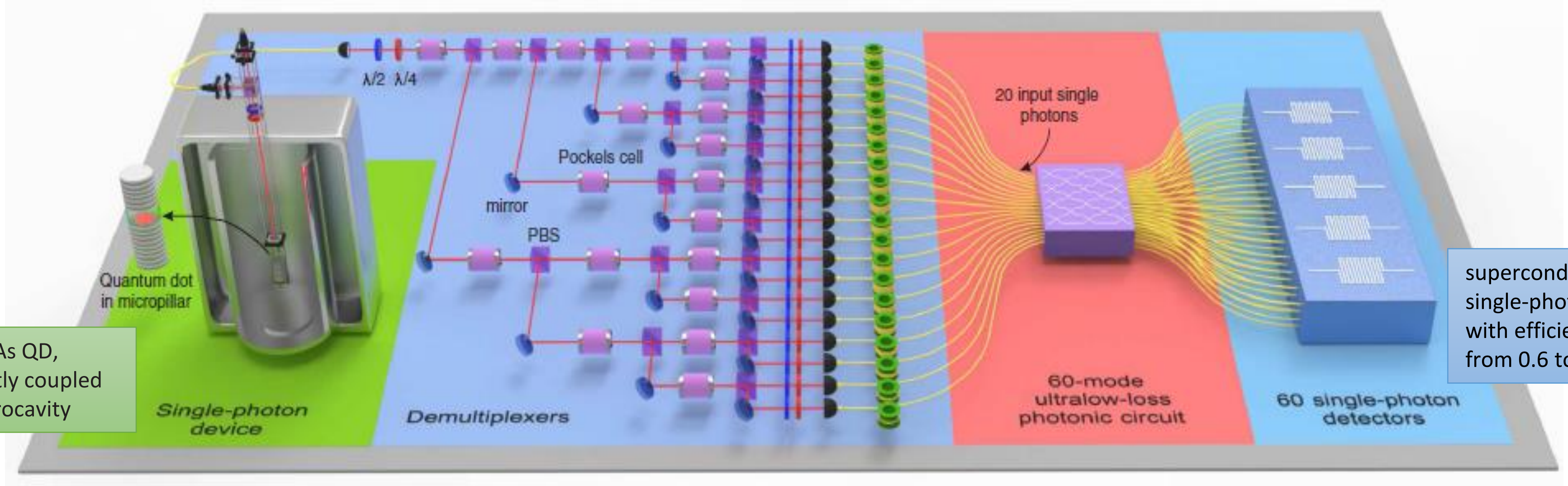
Introduction: Integrated quantum photonic circuits



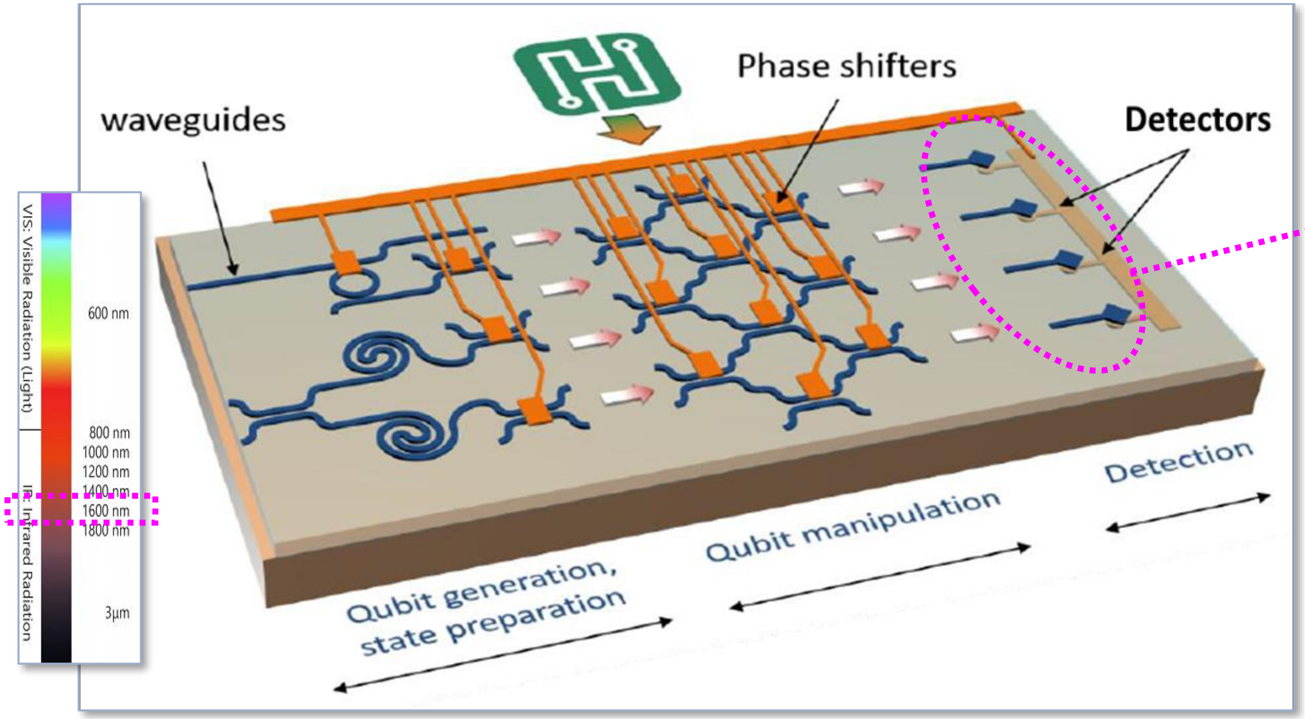
InAs/GaAs QD, resonantly coupled to a microcavity

superconducting nanowire single-photon detectors with efficiencies ranging from 0.6 to 0.82.

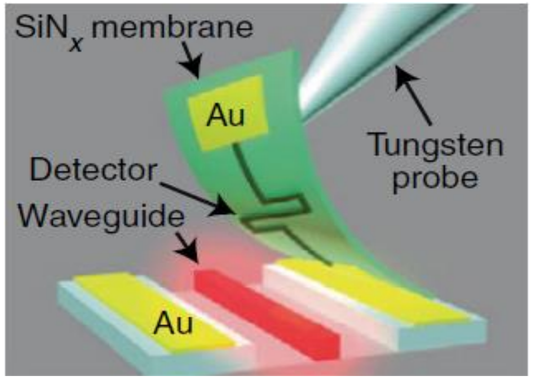
PHYSICAL REVIEW LETTERS 123, 250503 (2019)

- A **breakthrough in quantum photonics** → monolithic **integration** of ph. sources and detectors within quantum PICs.
- Significant interest in this scenario shown by the scientific community for multiple reasons:
  1. Fully exploit all the advantages of the integration, like the unrivaled *miniaturization and scalability*.
  2. *Avoid coupling* with external optical fibers and, thus, to guarantee *minimal photon losses*,
  3. *Prompt sensing* of a given photonic quantum state thanks to on-chip single photon detection

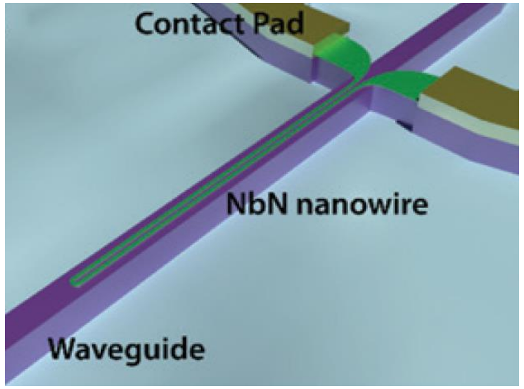
Introduction: Integrated quantum photonic circuits



Detector integration in quantum PIC



DOI: 10.1038/ncomms6873



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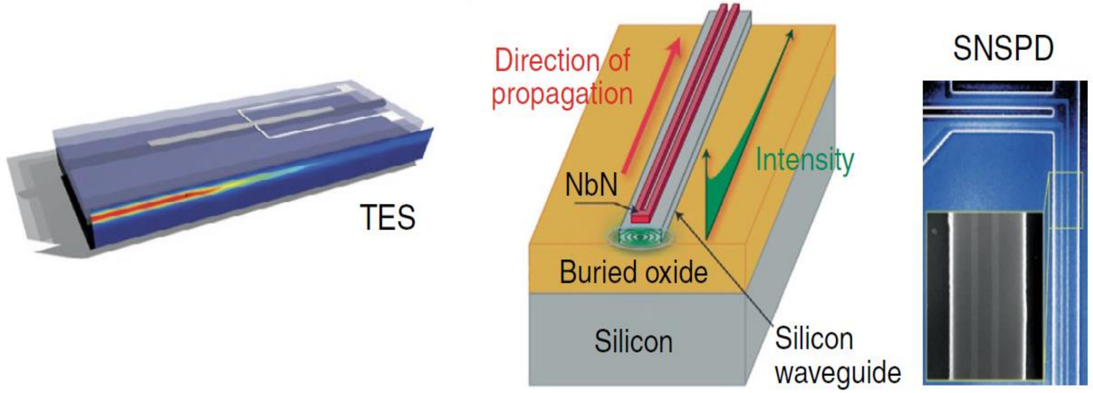
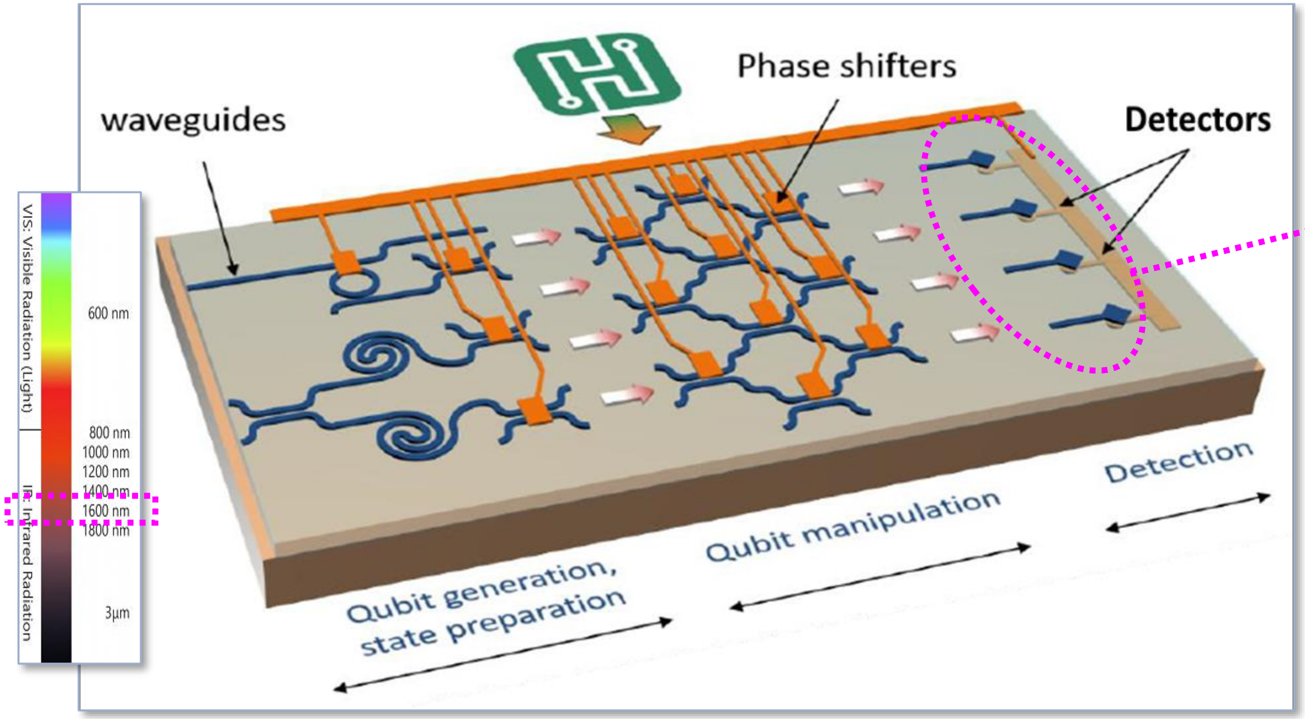
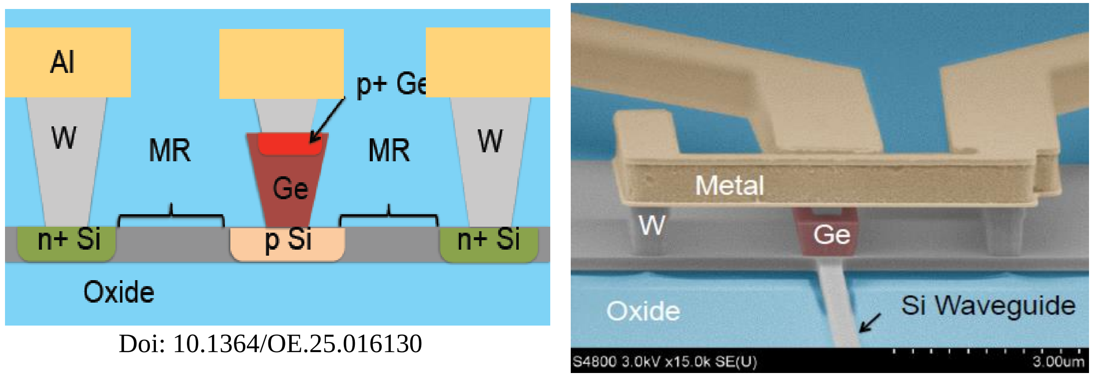


- ***<u>Important topic</u>*** in quantum photonics → ***<u>integration of photon source, manipulation and detection in the PICs</u>***.
- Possible approach:
  1. Si-based photonics (SWIR, e.g. 1550 nm photonics)
     - ❑ PIC integrated with SNSPD or TES: good performance but require cryogenic temperature operation

Introduction: Integrated quantum photonic circuits



Detector integration in quantum PIC



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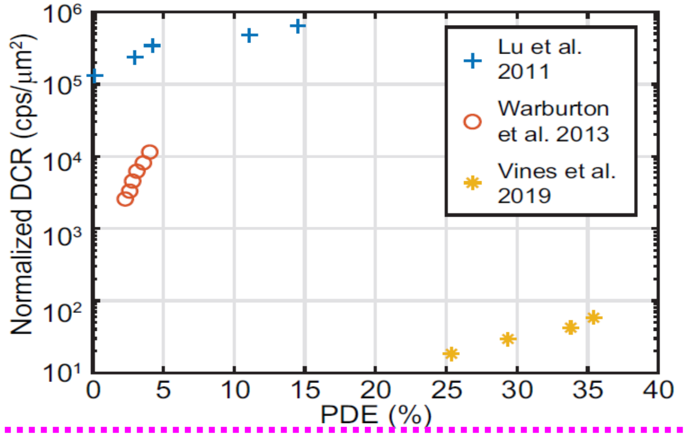
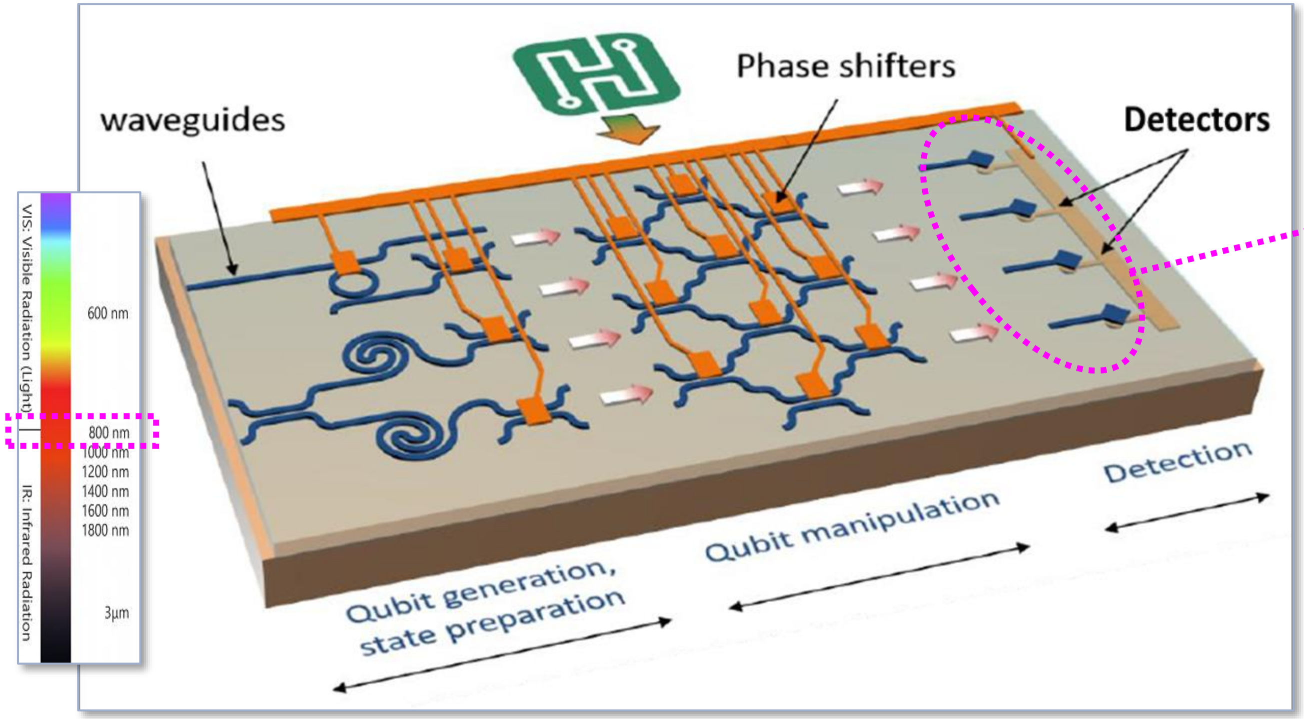


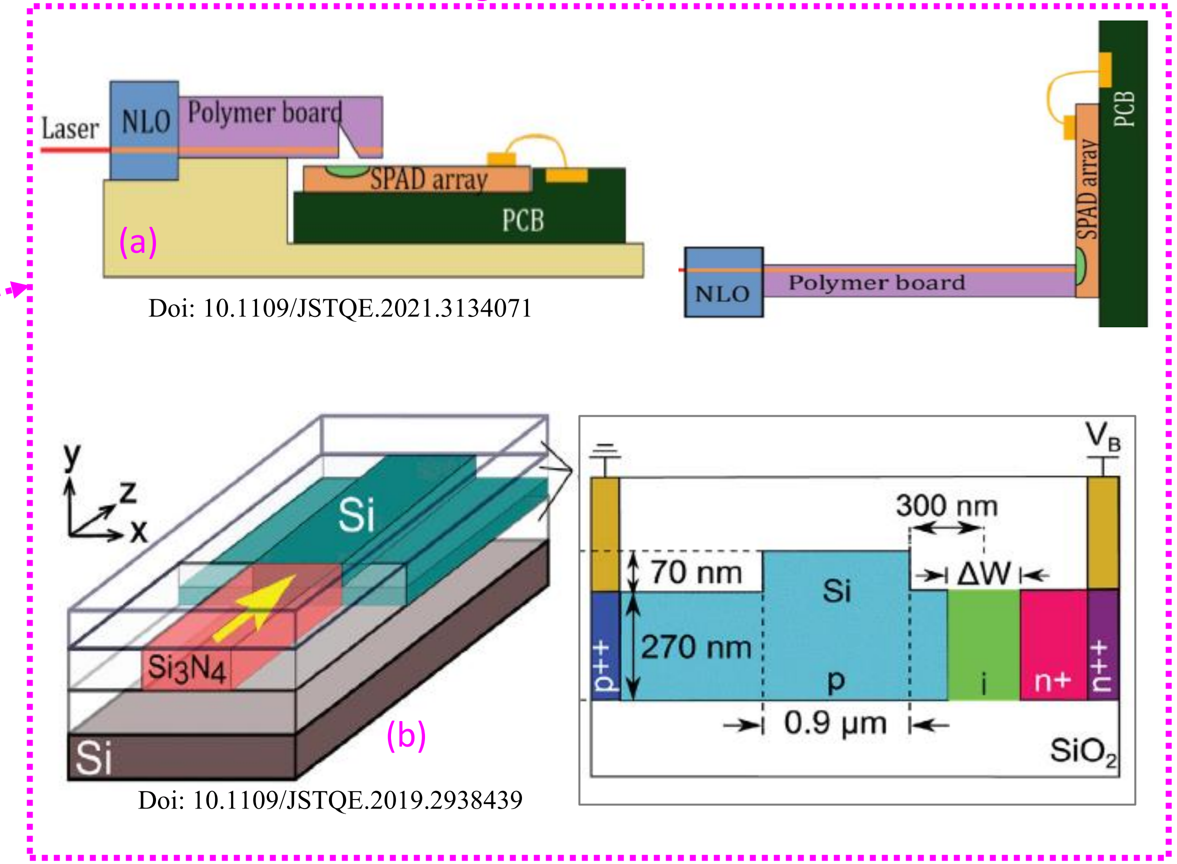
DOI: 10.1002/qute.202000102

- ***Important topic*** in quantum photonics → ***integration of photon source, manipulation and detection in the PICs***.
- Possible approach:
  1. Si-based photonics (SWIR, e.g. 1550 nm photonics)
     - ❑ Ge-on-Si detectors: interesting approach. R&D ongoing but DCR generally very high (even when cooled)

Introduction: Integrated quantum photonic circuits



Detector integration in quantum PIC

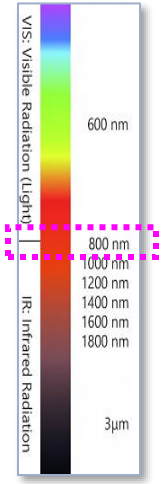


Doi: 10.1109/JSTQE.2021.3134071

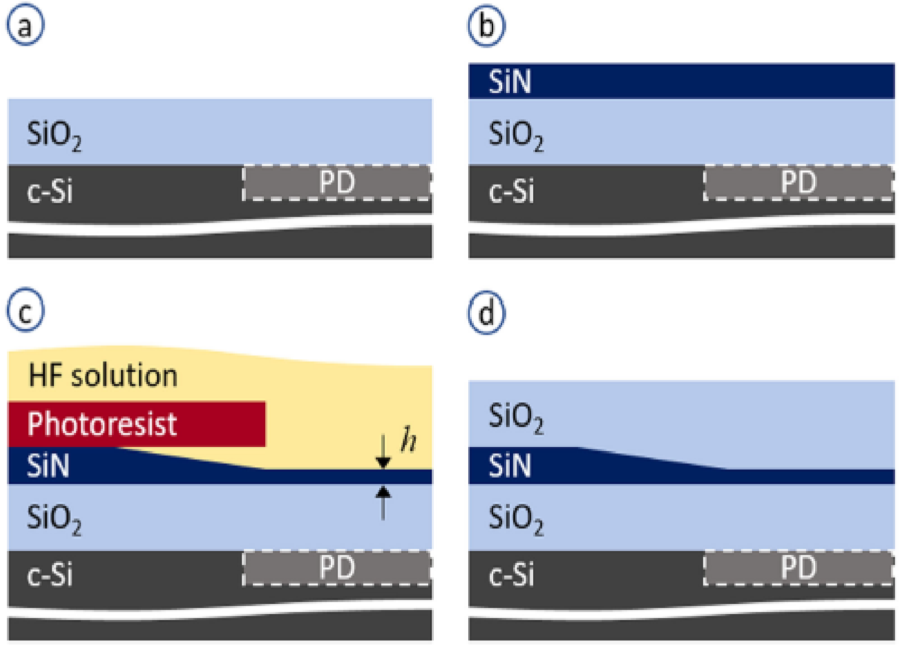
Doi: 10.1109/JSTQE.2019.2938439

- ***Important topic*** in quantum photonics → ***integration of photon source, manipulation and detection in the PICs***.
- Possible approach:
  2. SiN (or SiON) photonics (NIR photonics, e.g. 850nm)
     - ❑ Silicon-based detectors: (a) system-level integration, or (b) chip-level integration with different materials

FBK photonic/electronic integration: approach #1



Novel FBK approach



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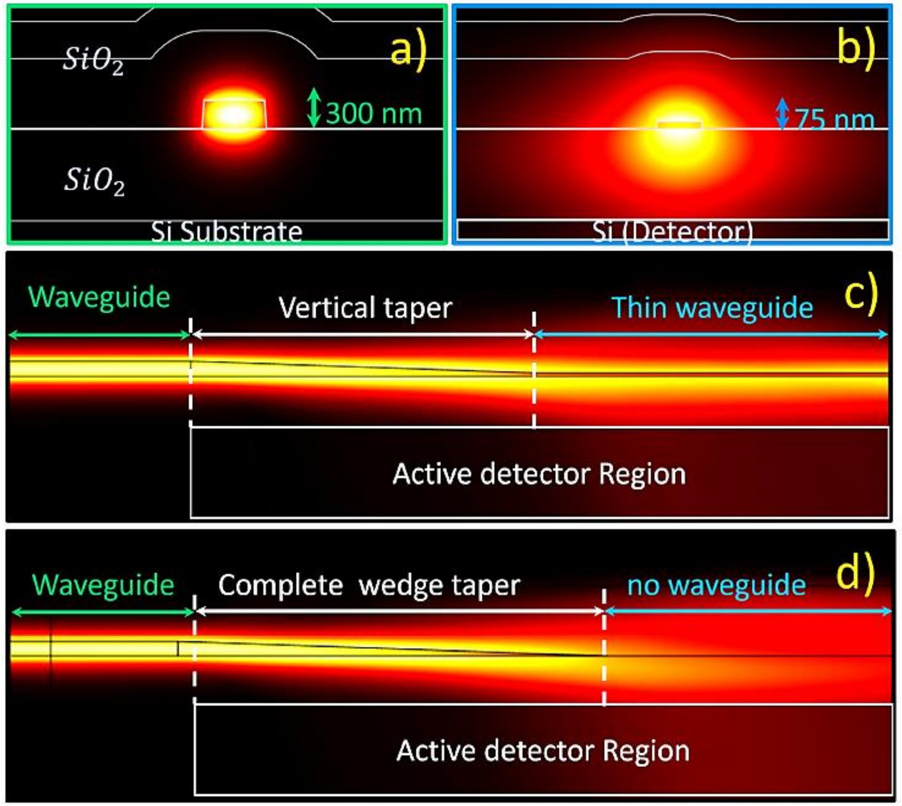
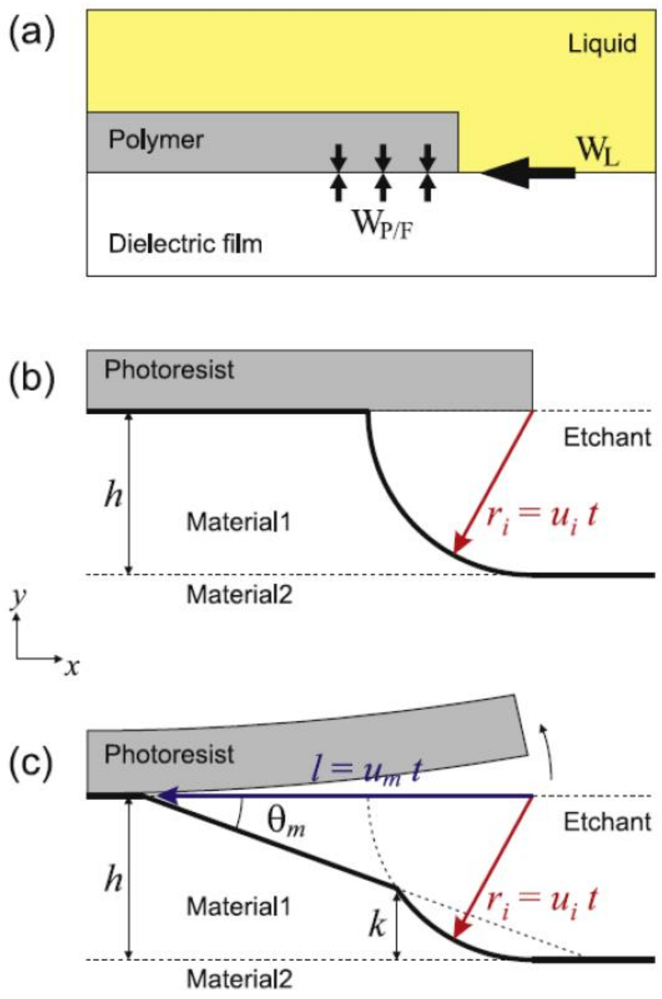
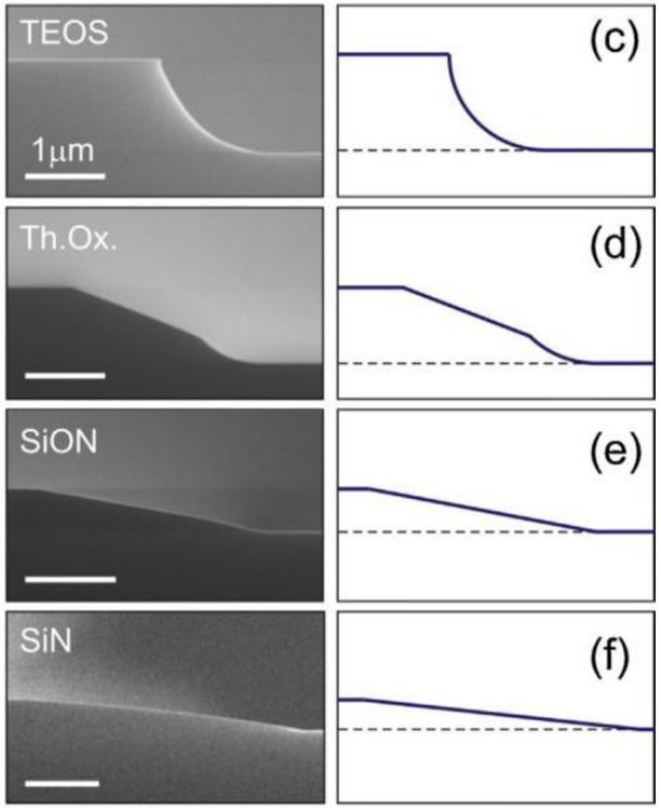


- **Waveguide (PIC) and detector fabricated on the same chip**: *BEOL region and FEOL region*
- *Approach: customized and precisely-controlled shaping of the waveguide thickness in the detector region*
- *Light is squeezed out of the waveguide, to be detected by the photodiode*

FBK photonic/electronic integration: *microfabrication technique*

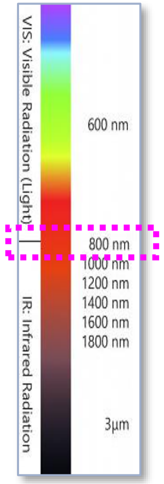




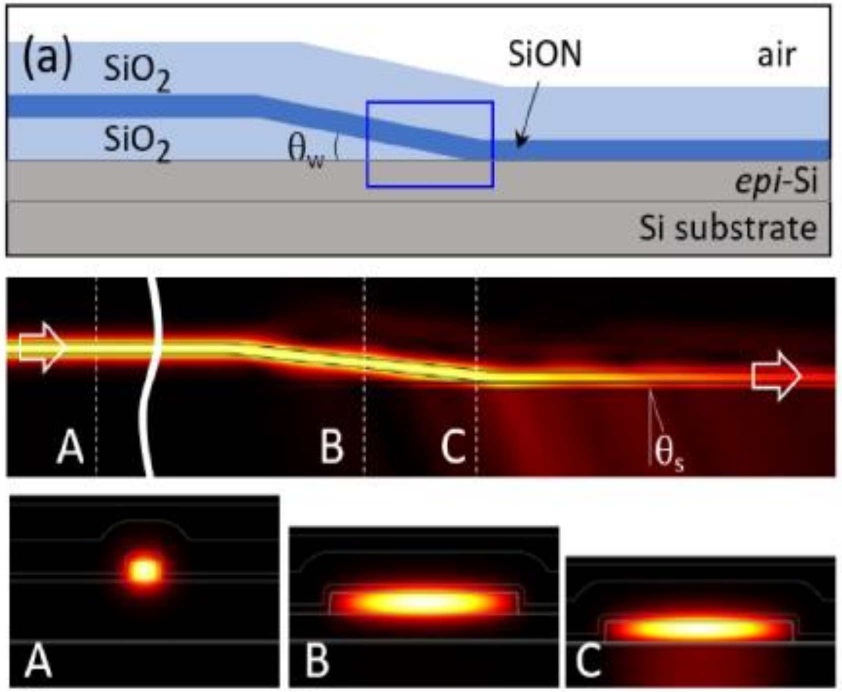
M. Ghulinyan, M. Bernard, R. Bartali, and G. Pucker, Appl. Surf. Sci. 359, 679 (2015).

- the wedge profile is generated by the superposition of the circular isotropic etch fronts, when the peeling (moving object) results into a lateral etching rate u_m, faster than the isotropic one u_i
- Formally, the dynamics of a wedge profile formation is analogues to the formation of a shock wavefront (sonic booms) → the so-called Mach cone.
- *Model* of the phenomena can be used to *precisely-tune and customize the profile*.

FBK photonic/electronic integration approach #2



Novel FBK approach



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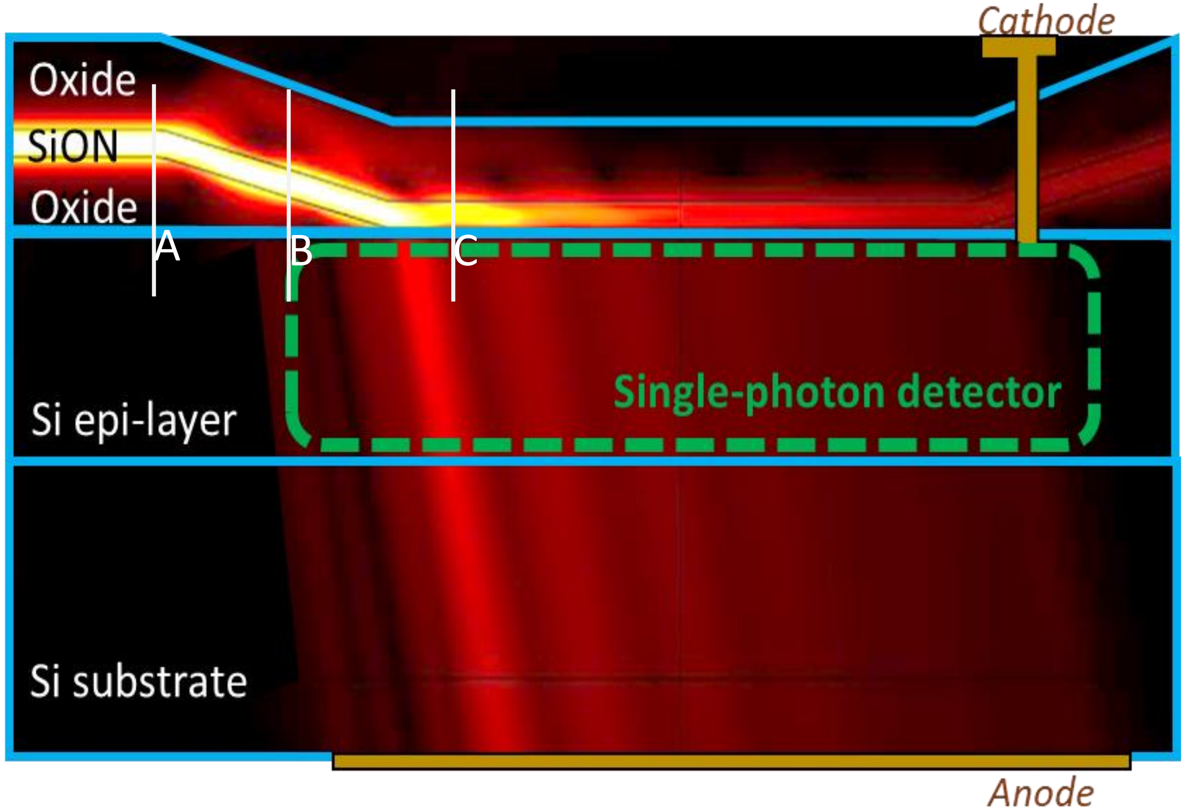
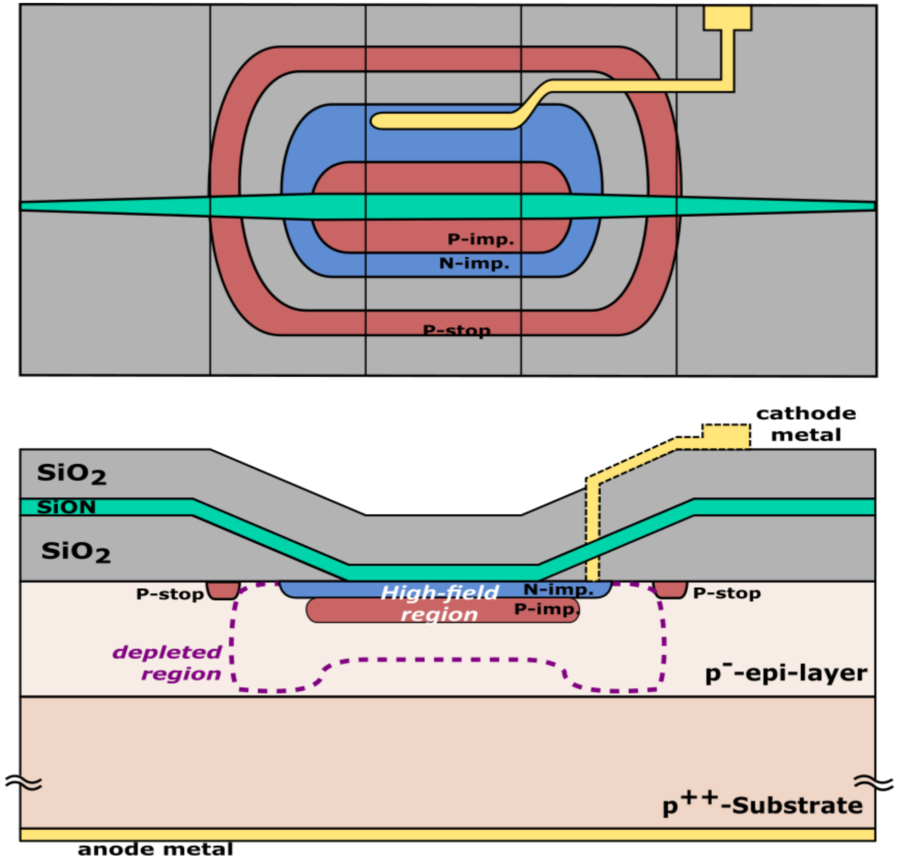


- **Waveguide (PIC) and detector fabricated on the same chip**: *BEOL region and FEOL region*
- ***<u>New efficient top-down evanescent coupling approach (#2)</u>***
  - Precise shaping of the cladding below the Waveguide and of the Waveguide width
  - Efficient evanescent coupling when the WG touches the silicon epi-layer

FBK photonic/electronic integration approach #2



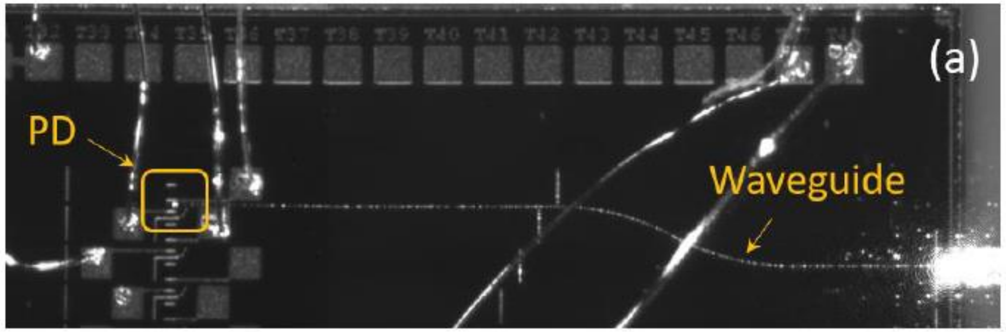
DOI: 10.1109/JLT.2023.3342031

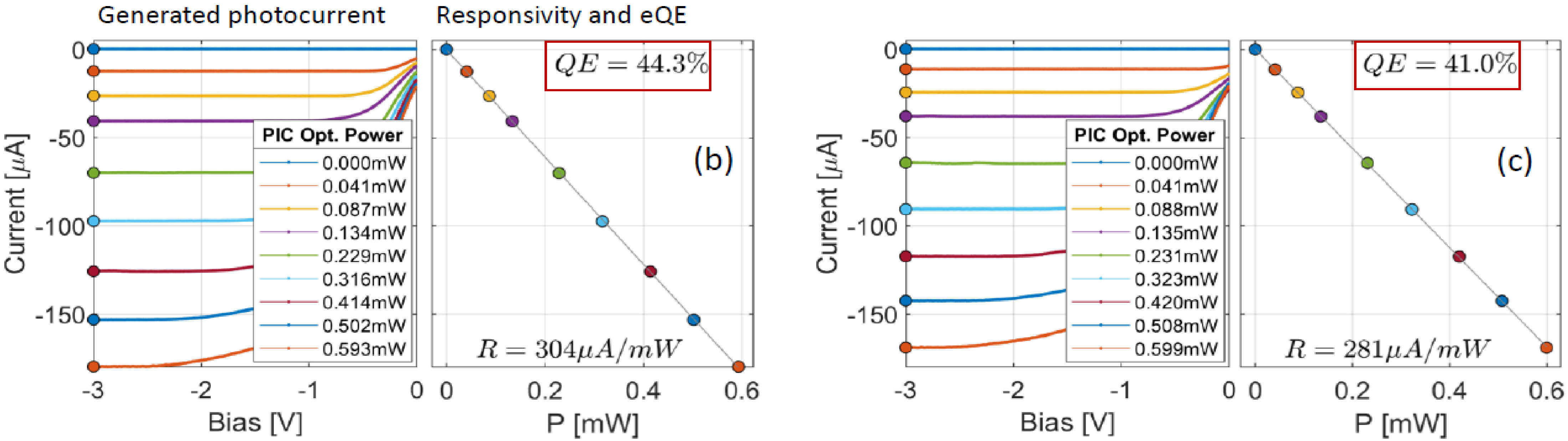
Novel FBK photonic/electronic integration approach

- Advantages:
  1. *PIC/SPADs can operate at room temperature*
     - Si-SPADs: with state-of-the-art DCR
     - No cooling is needed
  2. *Completely CMOS compatible*
     - Material are all already used in CMOS processes (e.g. Silicon, SiO_2, SiNx)
  1. *Do not require alignments*, butt coupling, …etc…
     - *Minimized coupling-losses*
     - No complex structures
     - No additional materials to be grown / patterned
  2. *SPAD design: no particular constraints*
     - Layout of the SPADs tailored for better performances
     - No constraint given by the photonic integration

FBK photonic/electronic integration approach #2

Doi: 10.1364/OPTICA.441496

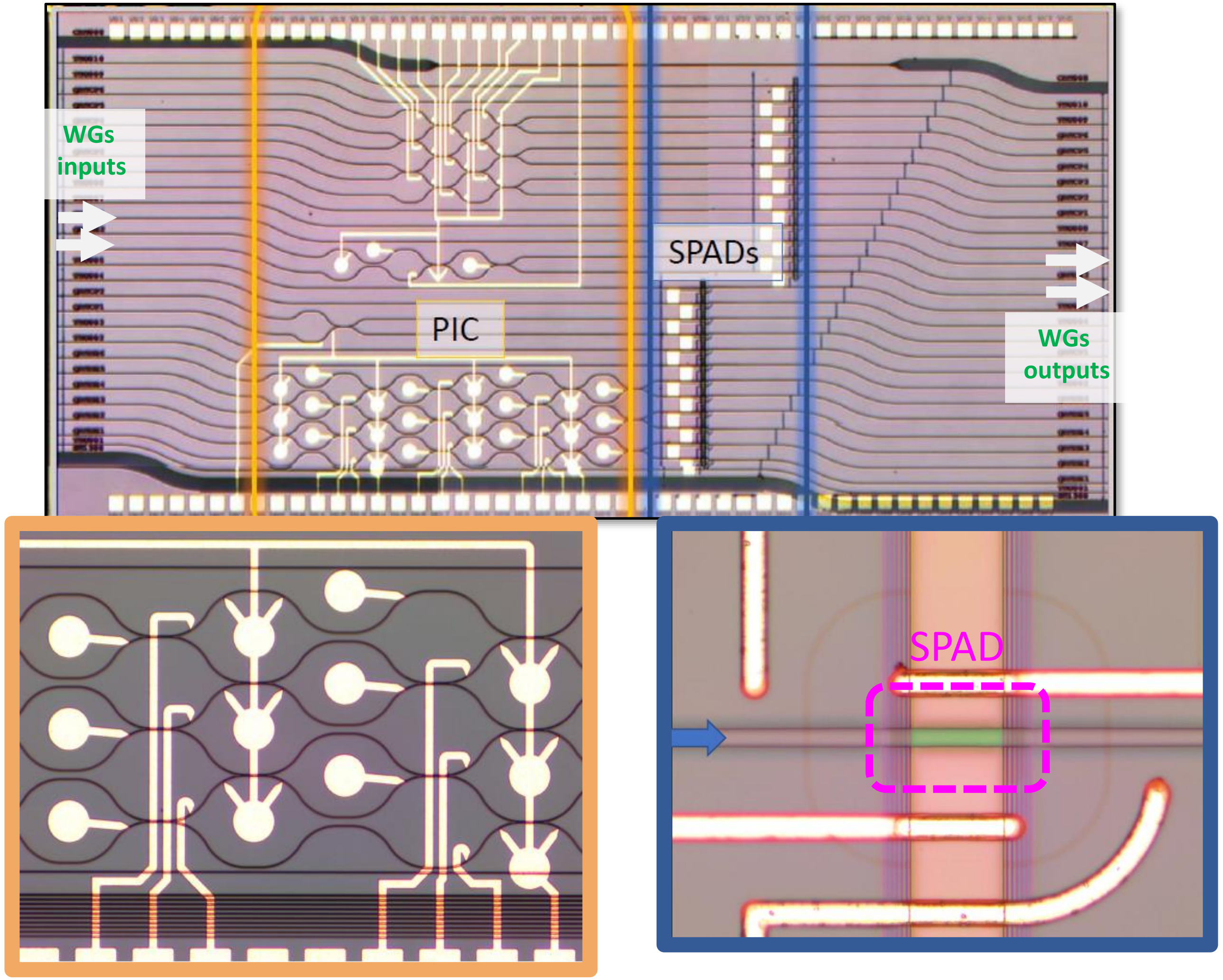




- **First tests on linear-mode photodiodes**
  - PIC working in classical-light regime, with moderate light power injected.
  - Measured quantum efficiency: ~41÷44 %

Test chip #1: PIC+SPADs → *photon manipulation and detection*

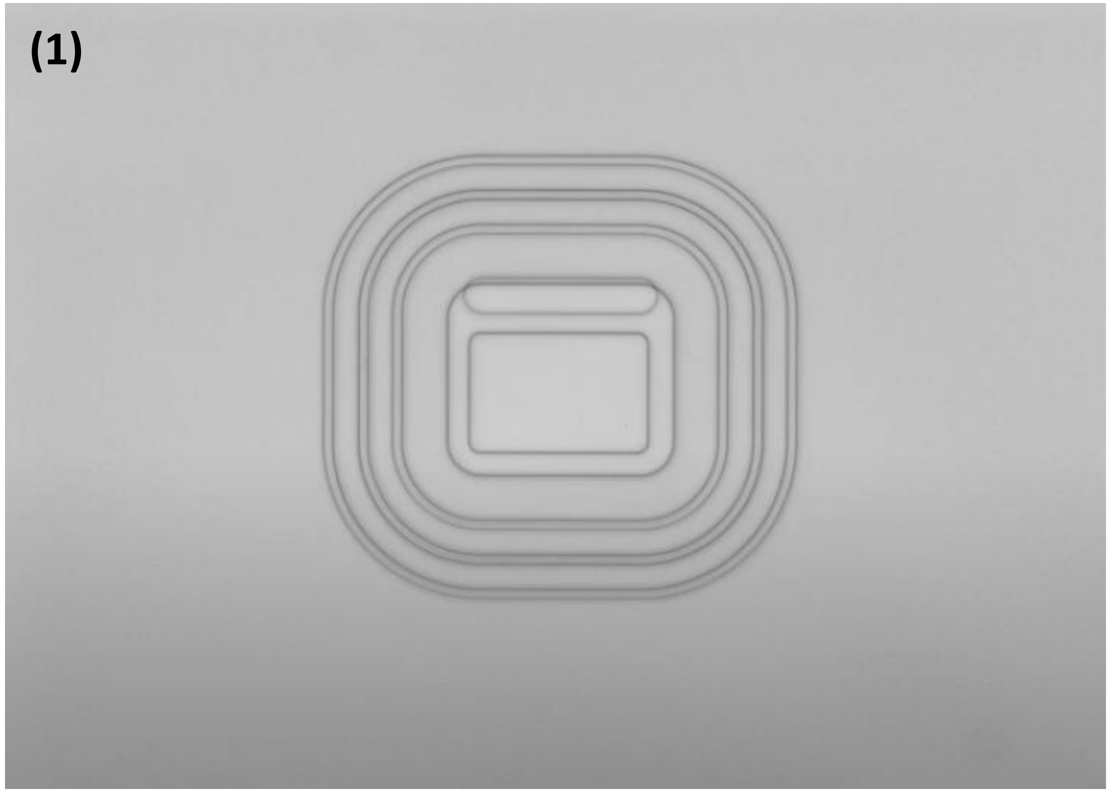
Test chip: PIC + SPADs (dimensions: 5mm x 10mm)

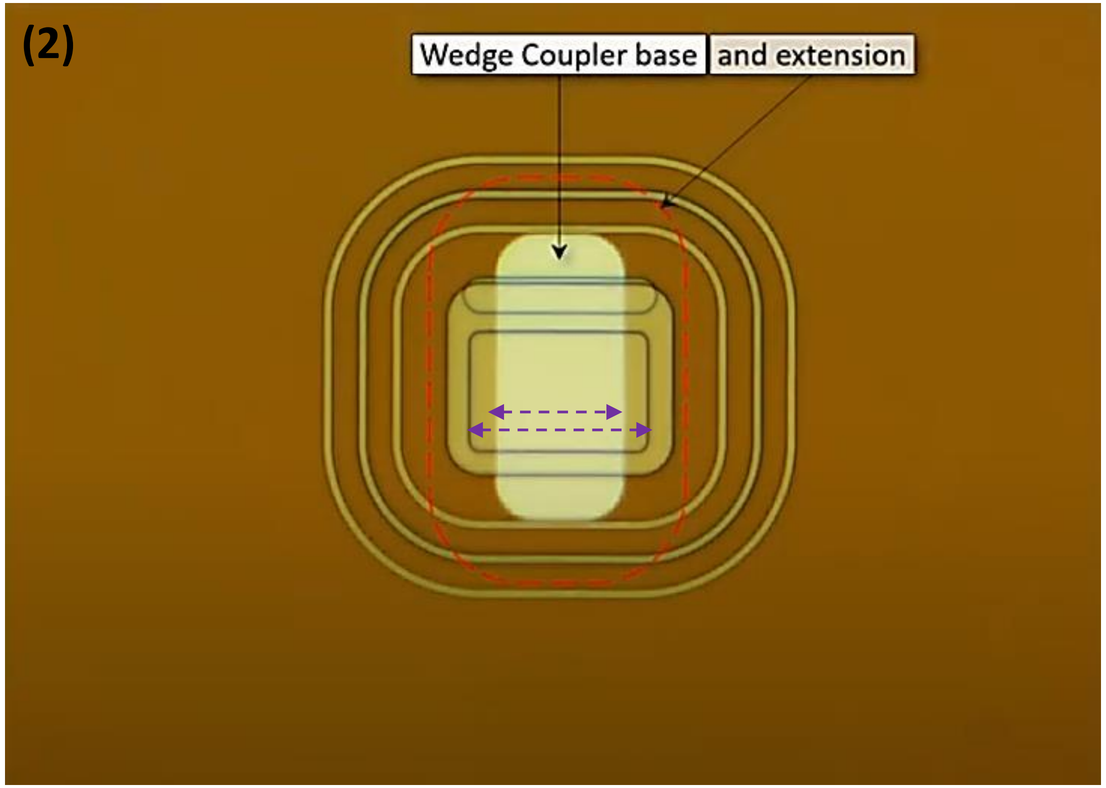


Grant agreement # 899368

- ***First implementation of quantum PIC+SPAD***
- Several waveguides:
  - Inputs and outputs on opposite facets,
  - Each WG coupled to 1 SPAD
- Manipulation:
  - MZI, based on heaters
- Detection:
  - Si SPADs
  - *FBK "RGB" technology* *(n-on-p junction type, p-type epi/substrate)*

Fabrication of integrated chip: PIC+SPADs



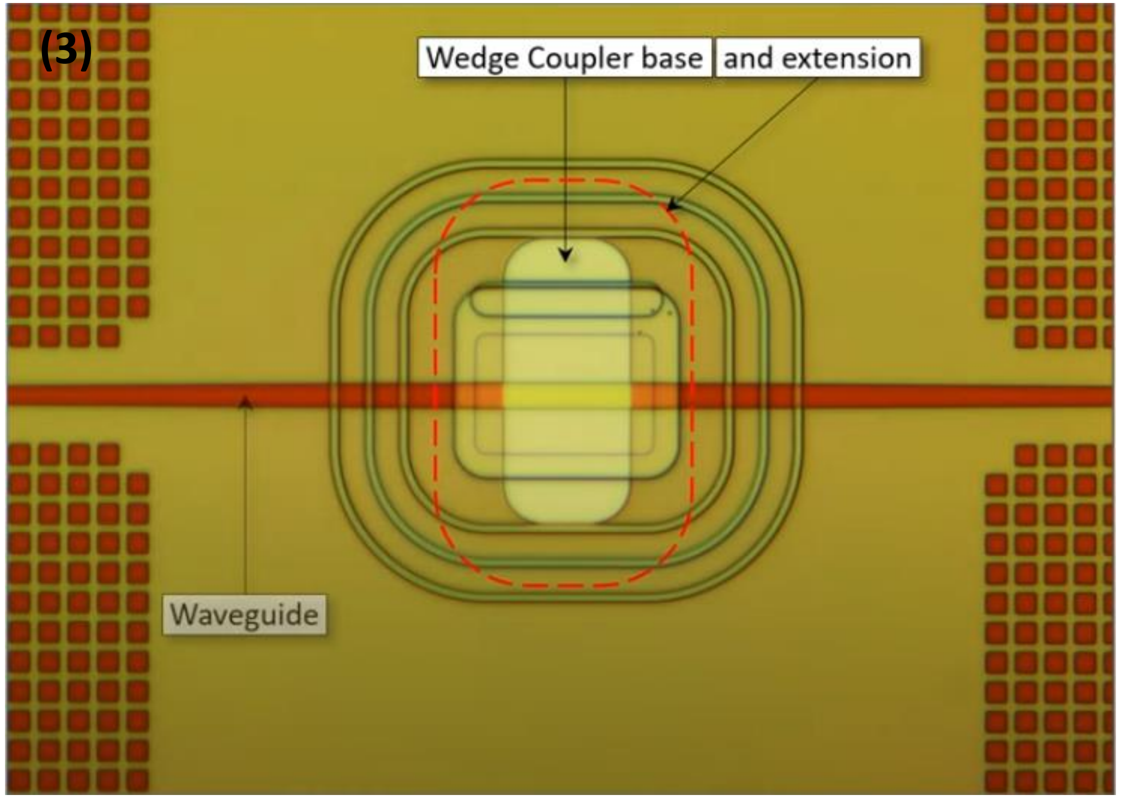


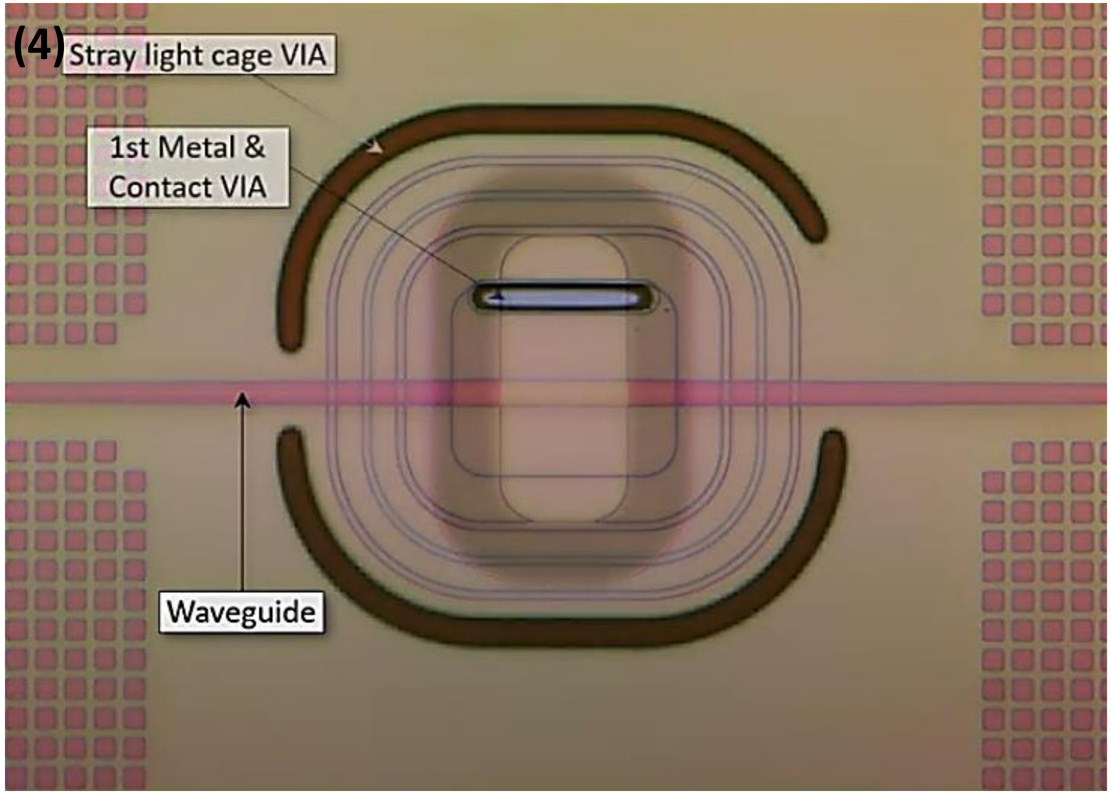
- Litho and *implants* on Silicon wafers
- *SPAD and diode formation*
  - N-on-p (p-epi) junction type
  - FBK "RGB" SPAD and SiPM technology

- *Wedge coupling region* definition
- *smaller than SPAD region*
  - To compensate for E-field edge effects
  - To compensate for partial light leakage

https://www.linkedin.com/company/epiqus-h2020/posts/?feedView=all

Fabrication of integrated chip: PIC+SPADs





- Deposit BEOL: SiN (or SiON)
- Litho and *Waveguide (WG) definition*
  - *Larger footprint on coupling region*

- *VIA opening* and 1st metal deposition:
  - Electric contacts
- Creation of *light cage structures*
  - *Stray-light and optical crosstalk mitigation*

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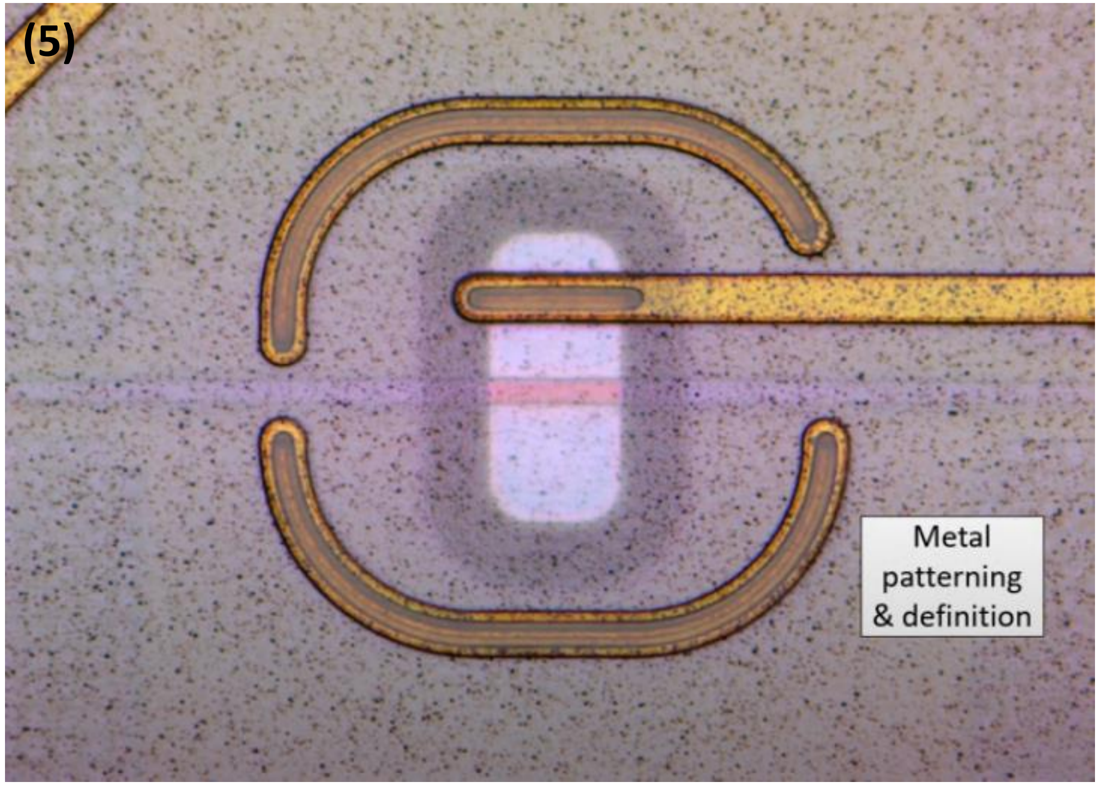
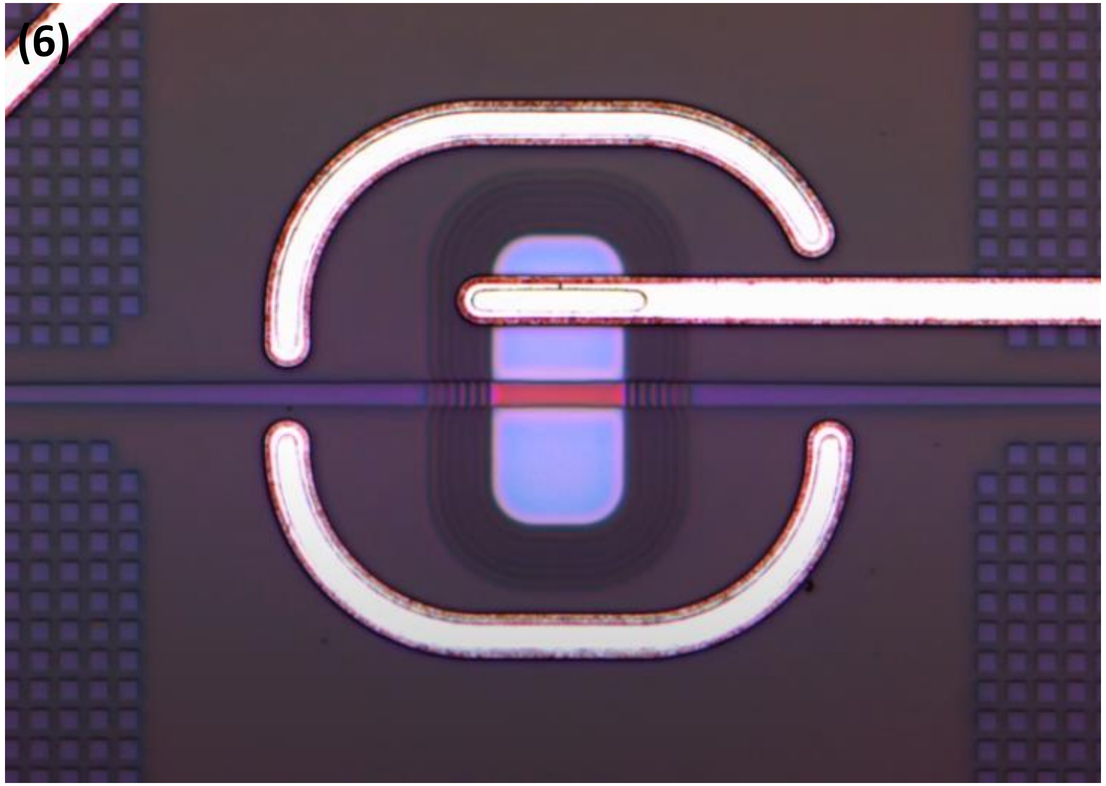
Fabrication of integrated chip: PIC+SPADs





- 2nd *metal deposition*
- Patterning and definition

- *Overglass deposition*
- PAD openings

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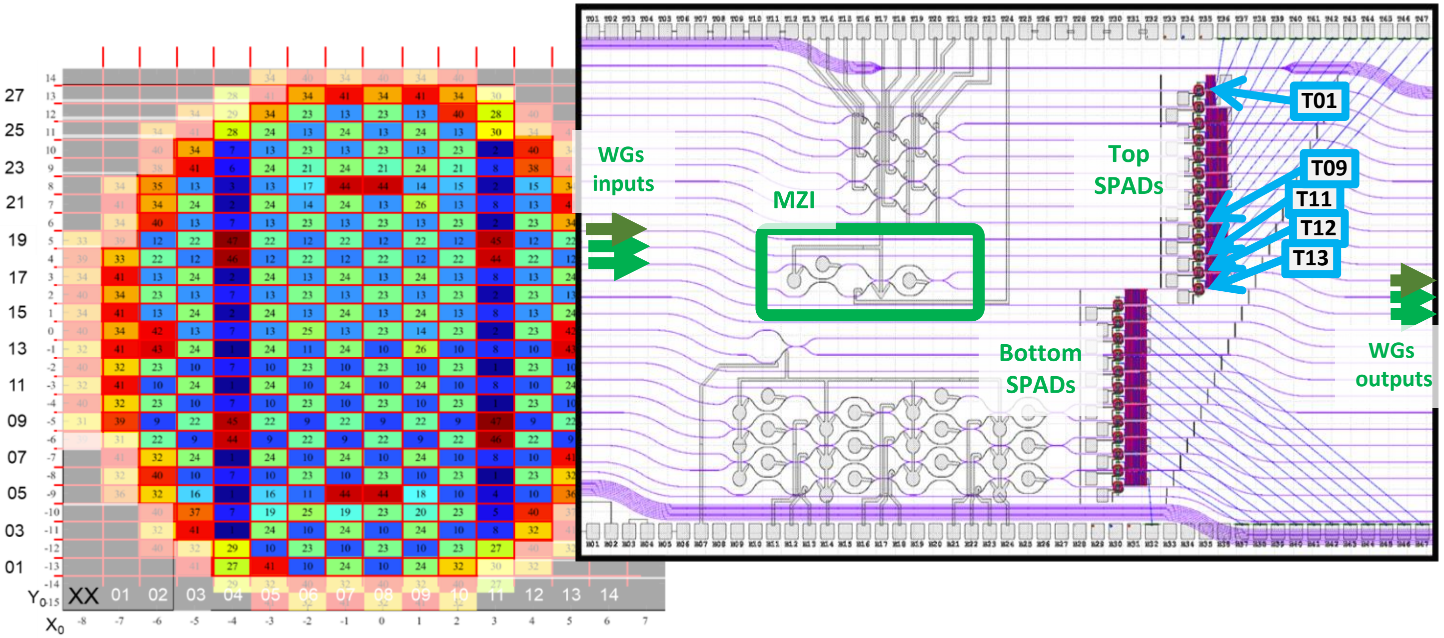
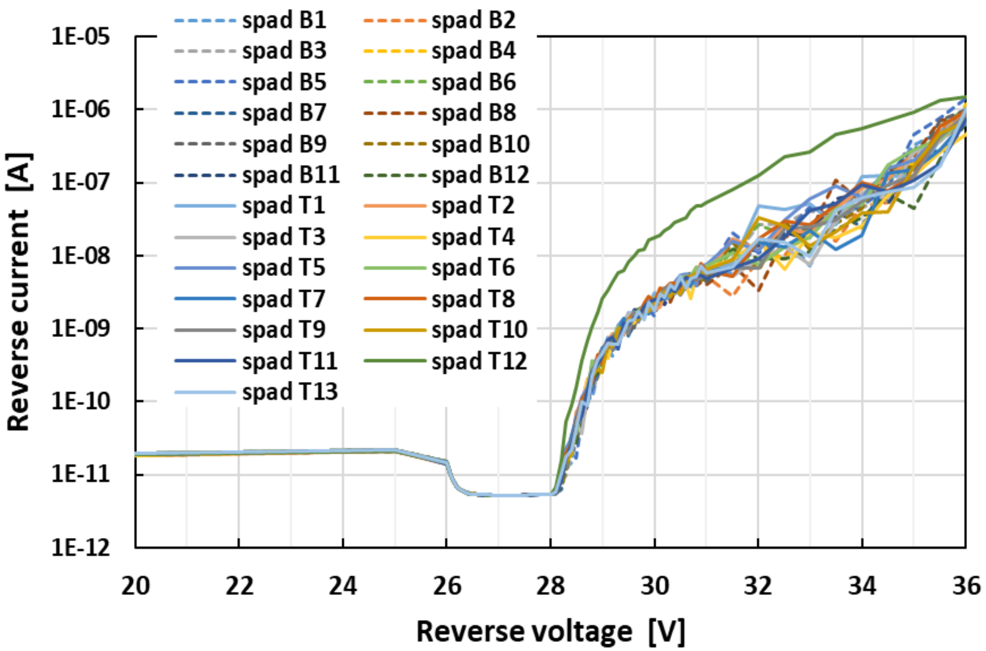
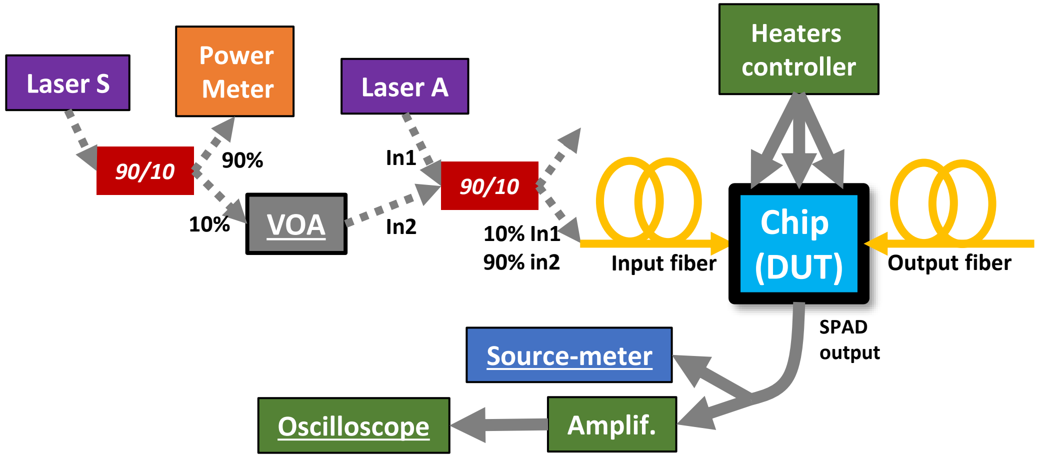
Test chip #1: wafer-level electrical characterization

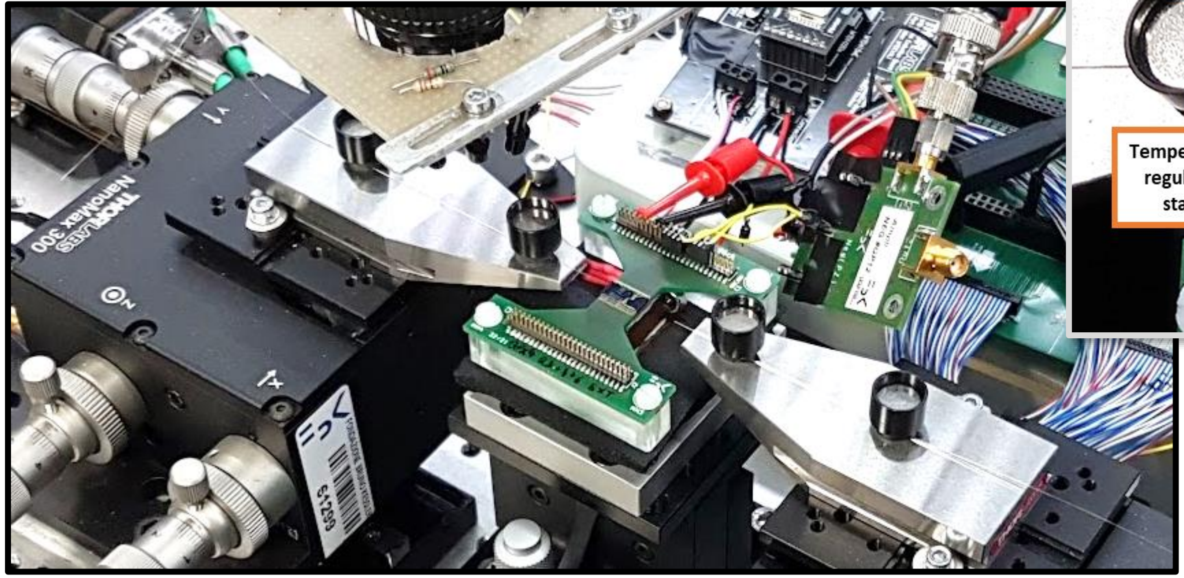


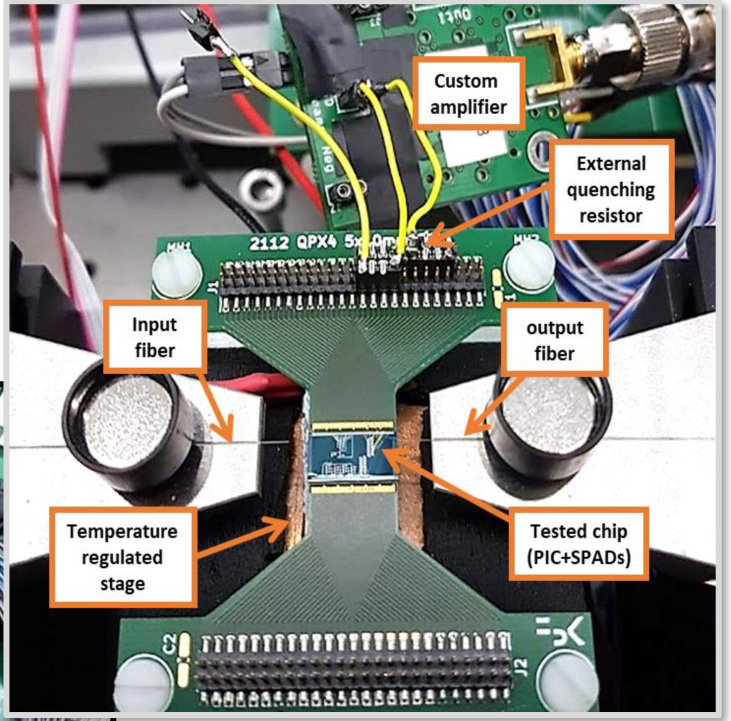


- ***Wafer level electrical testing → measurements of fw and reverse IV curves of diodes and SPADs***
  - 6” wafers → Several chip tested
  - Good uniformity in breakdown voltage in the SPADs (~28V)
  - *Relatively low yield because of process-related issue → to be solved in future production*

Test chip #1: Photonic/optoelectronic characterization

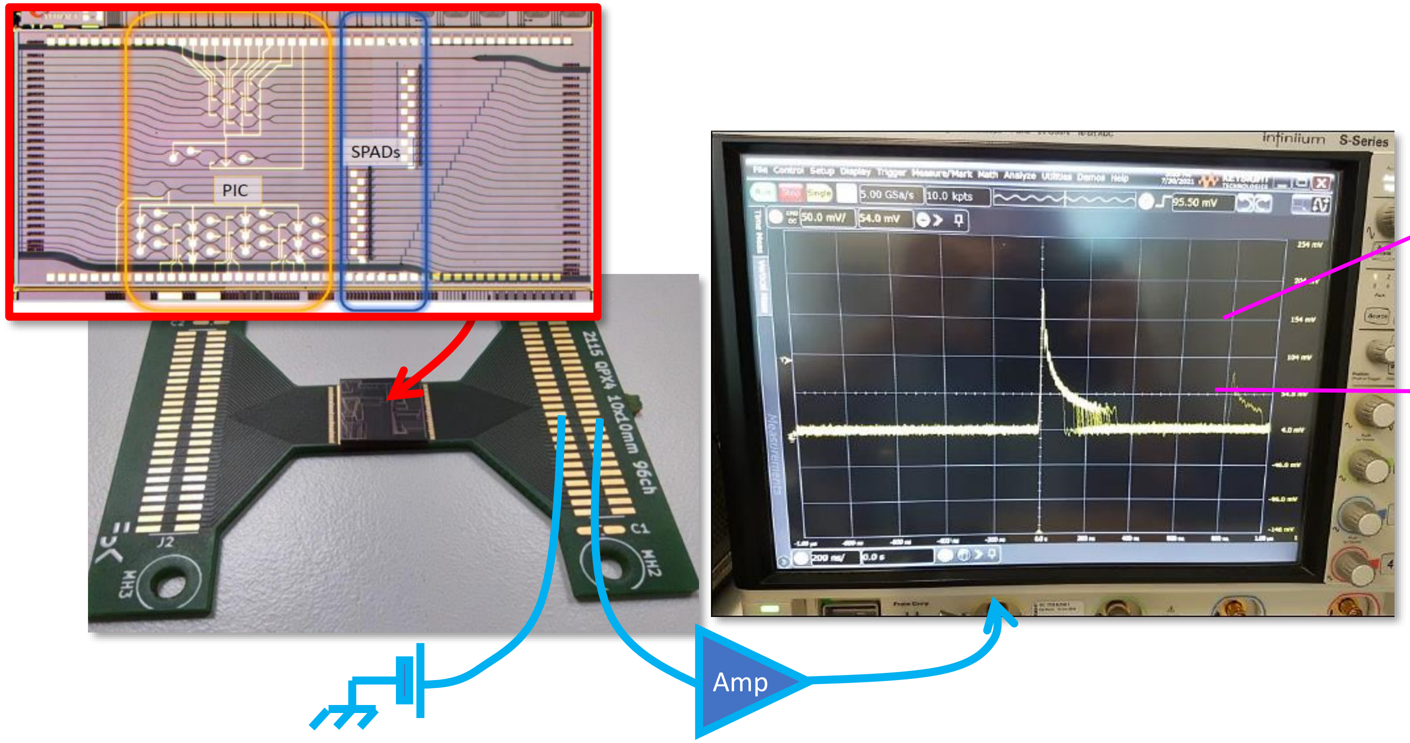


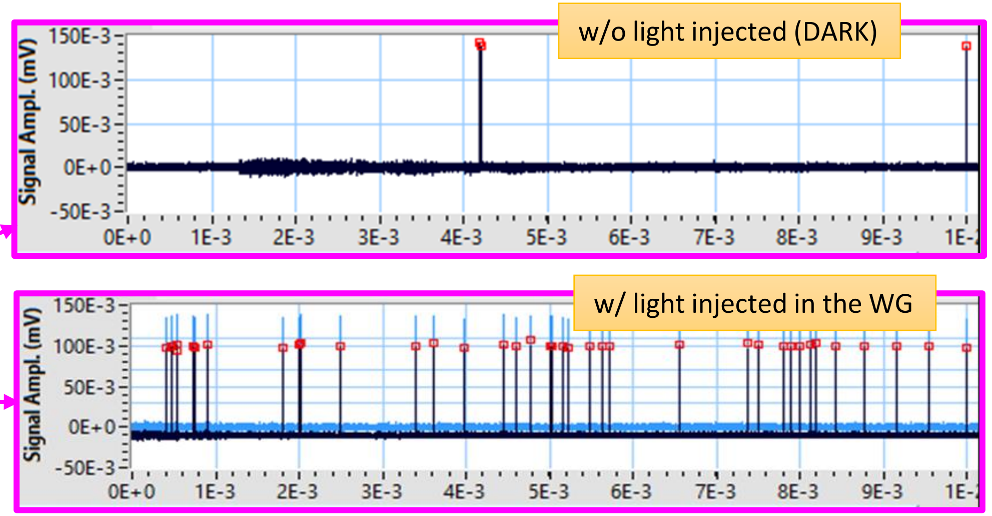


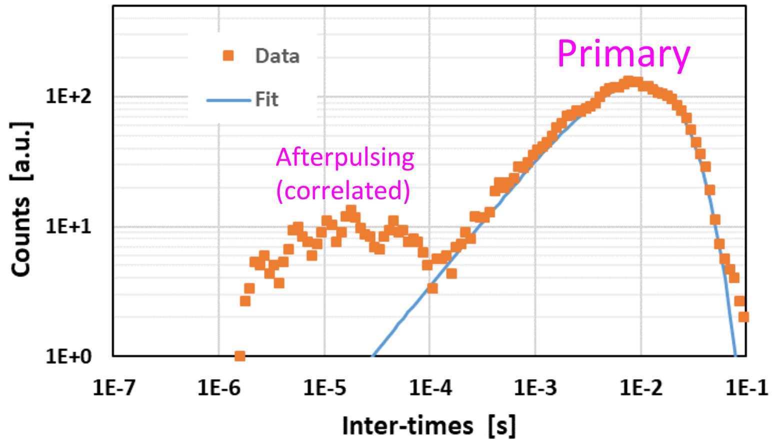


- Source laser (850 nm)
- Alignment laser
- Multiple variable optical attenuators:
  - Pre-calibration: with high light intensity
  - Use: to single-ph. Level
- *TEC cooling*
- SPADs:
  - External quench. resistors
  - Custom sig. amplifier

Pulse-counting performance

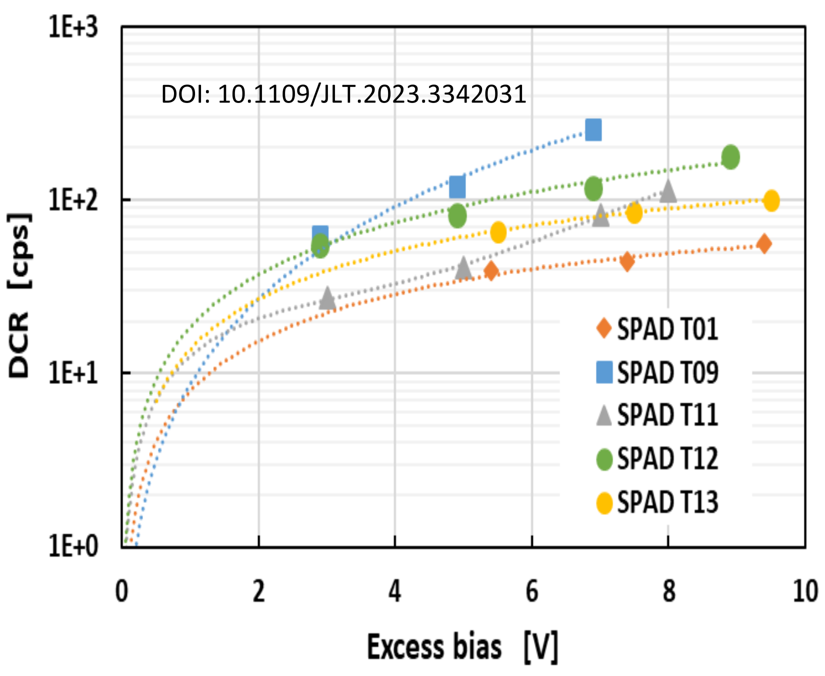


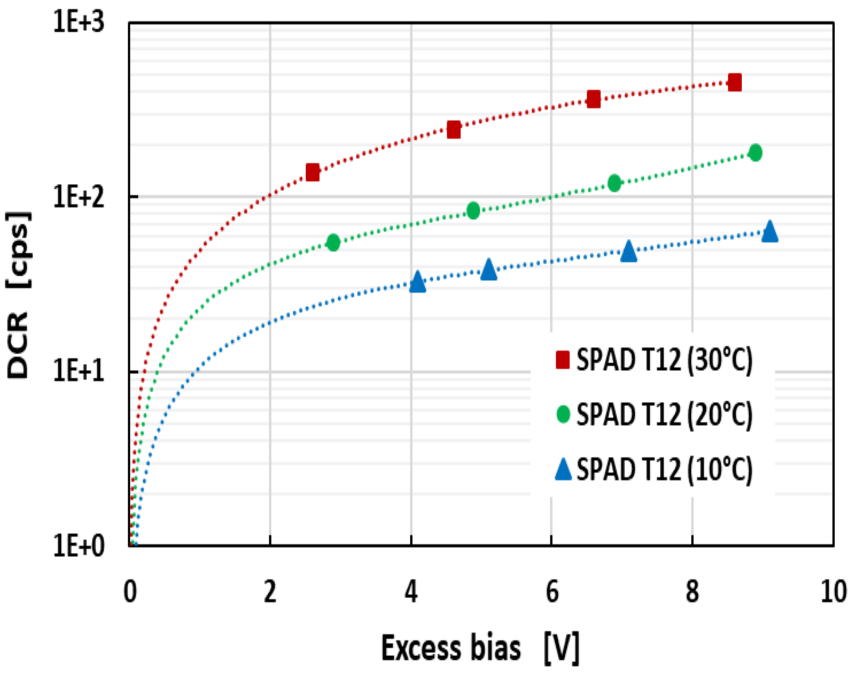


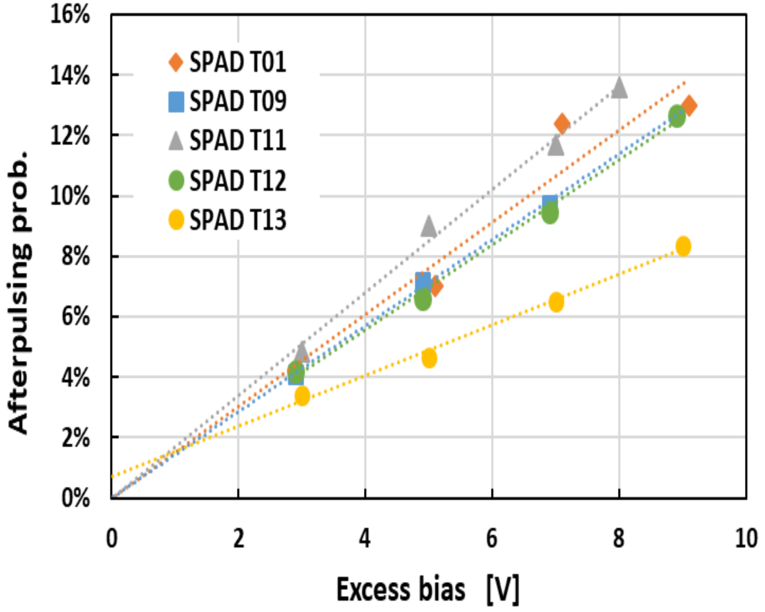


- ➢ SPAD pulse rate: proportional to the injected light intensity
- ➢ Inter-times between pulses → exponential statistics
  → extraction of primary and correlated events

Pulse-counting performance

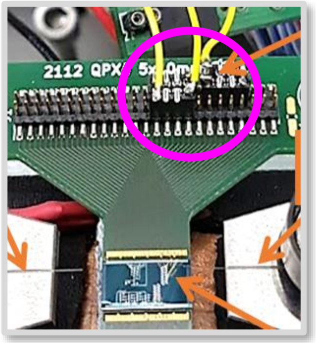




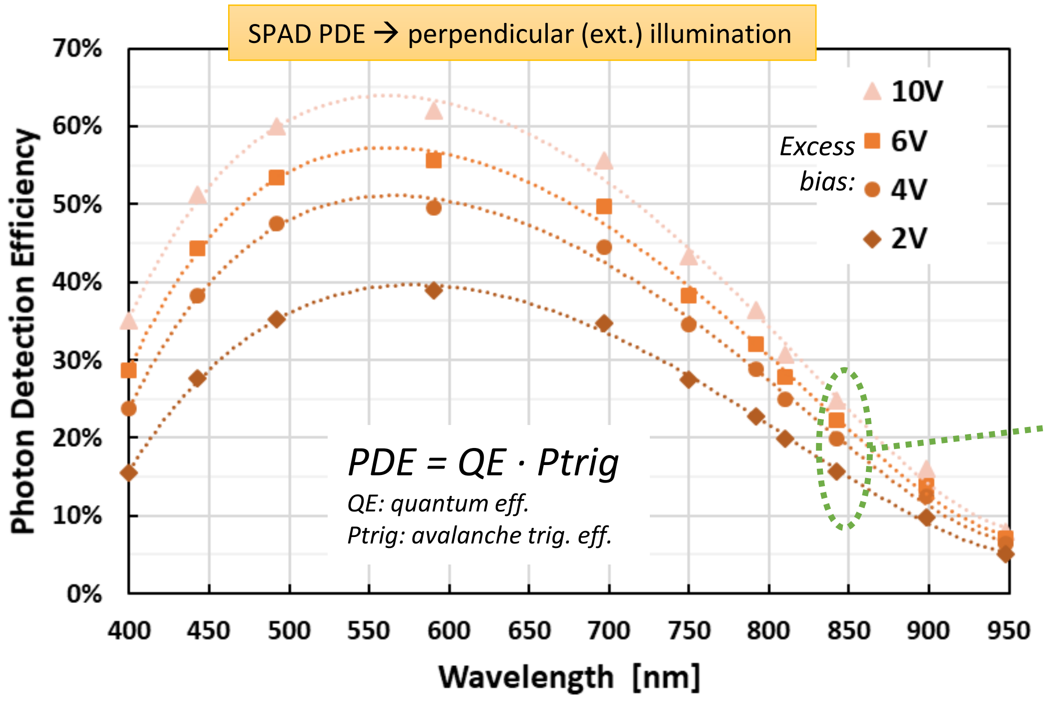


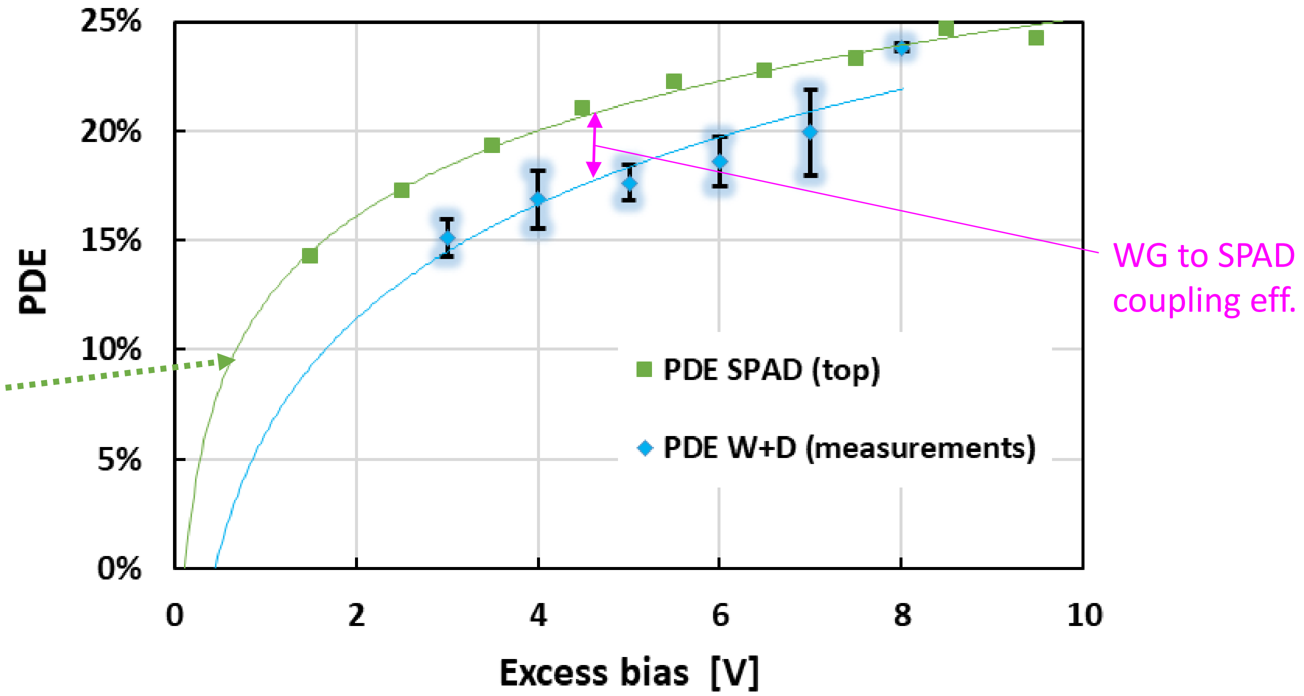
Excess bias: bias above the breakdown voltage

- Dark count rate (primary noise)
  - ~100 counts per second (cps) @ 20°C
  - in line with state-of-the-art Si-SPAD (commercial product)
- Temperature dependence: DCR halved about every 10°C
- Afterpulsing relatively high → *because of the external quenching (not optimized)(not the operative conditions)*



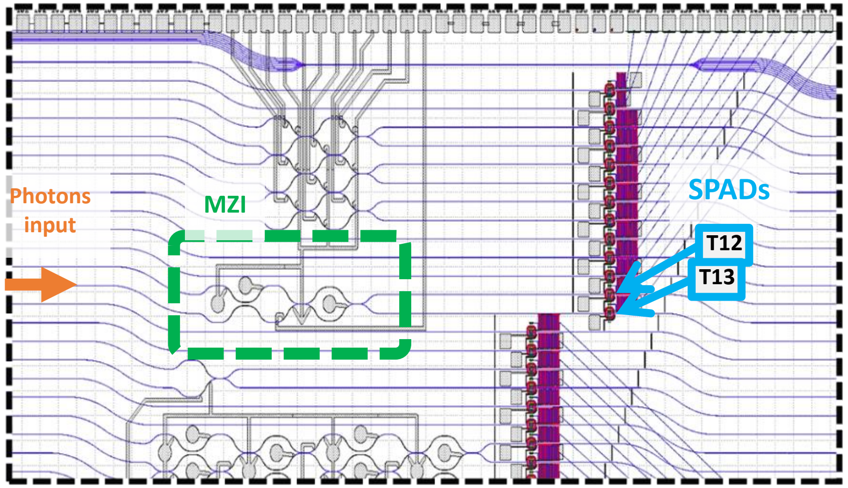
Detection efficiency and light-coupling efficiency

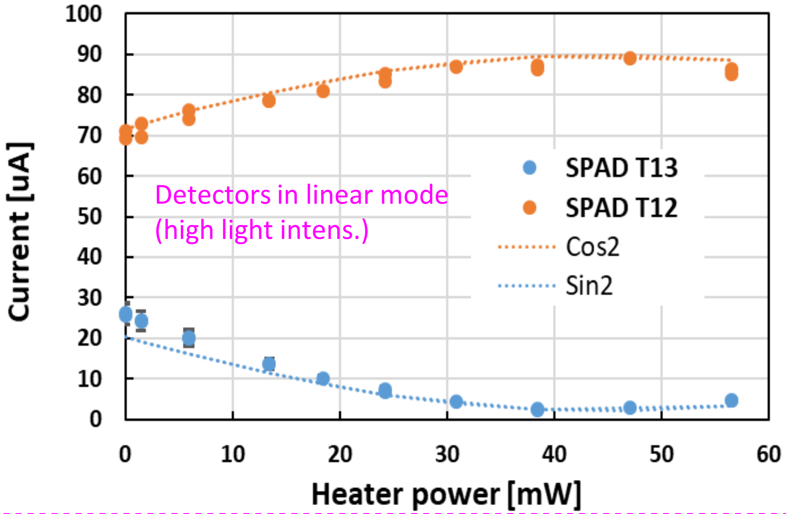


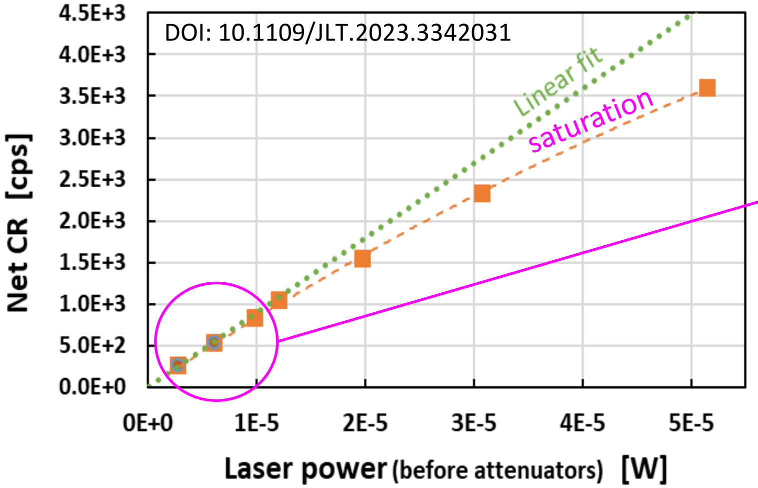


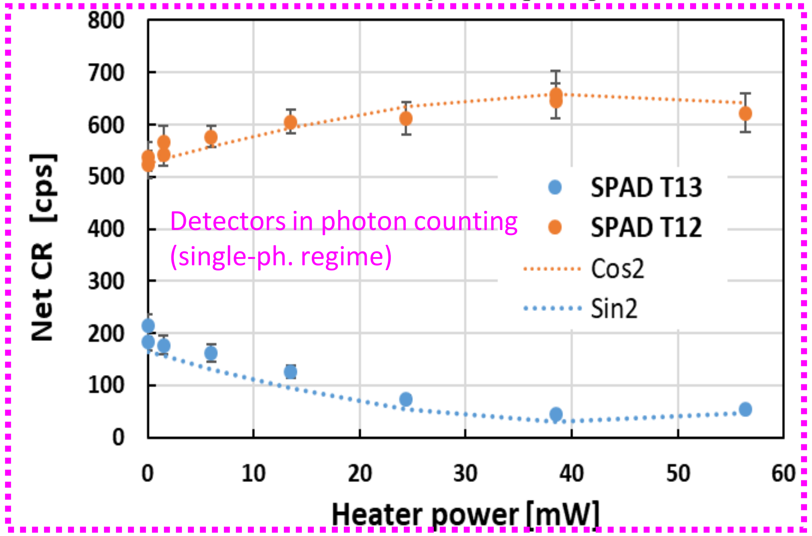
- Si-SPAD measurement with external light:
  - PDE peaked in the green wavelength region → ~20% ÷ 25 % at 850nm
- laser light injected into WG + detection by SPAD:
  - *Detection efficiency= ~17% ÷ 20 % at 850nm* → *WG-to-SPAD coupling efficiency= ~ 76% ÷ 85%*

Light modulation with MZI









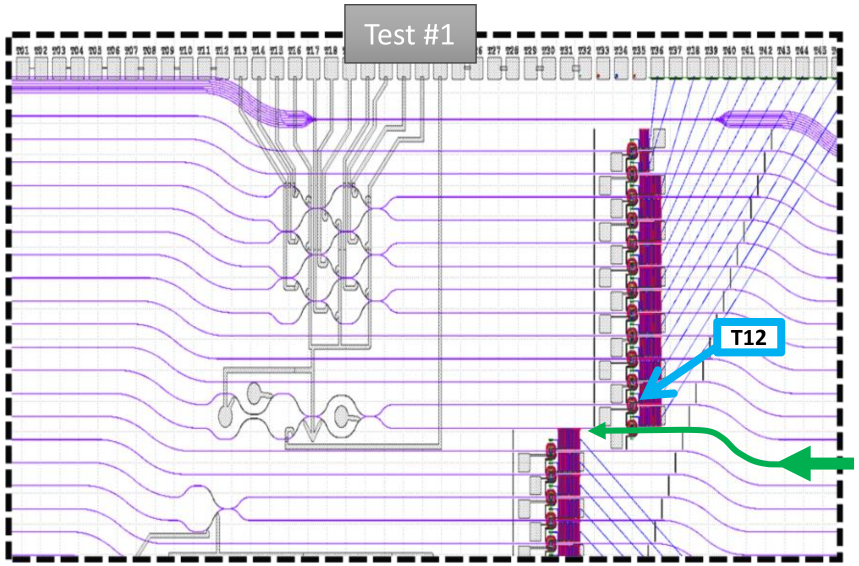
- ***<u>Direct test of photon manipulation and detection</u>***

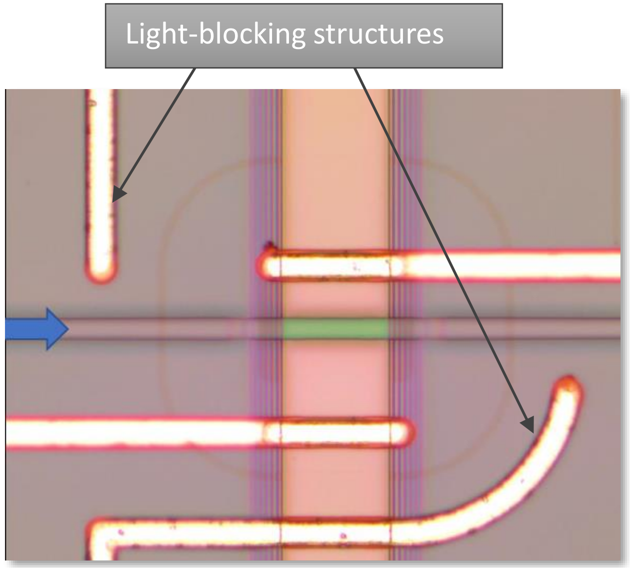
- Single photons injected.
- MZI (driven by heaters)
- 2 SPAD detectors

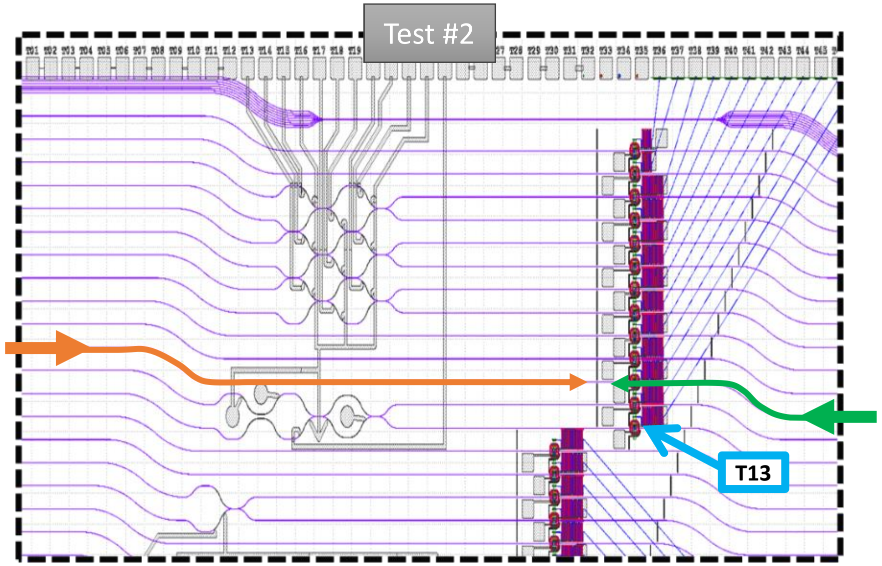
Procedure:

1. Selection of non-saturated power range
2. Heater power modulation
3. Count rate measurements (in the 2 SPADs)
4. *<u>Good agreement:</u>* *<u>photon counting behavior vs linear-mode behavior</u>*

Stray-light estimation

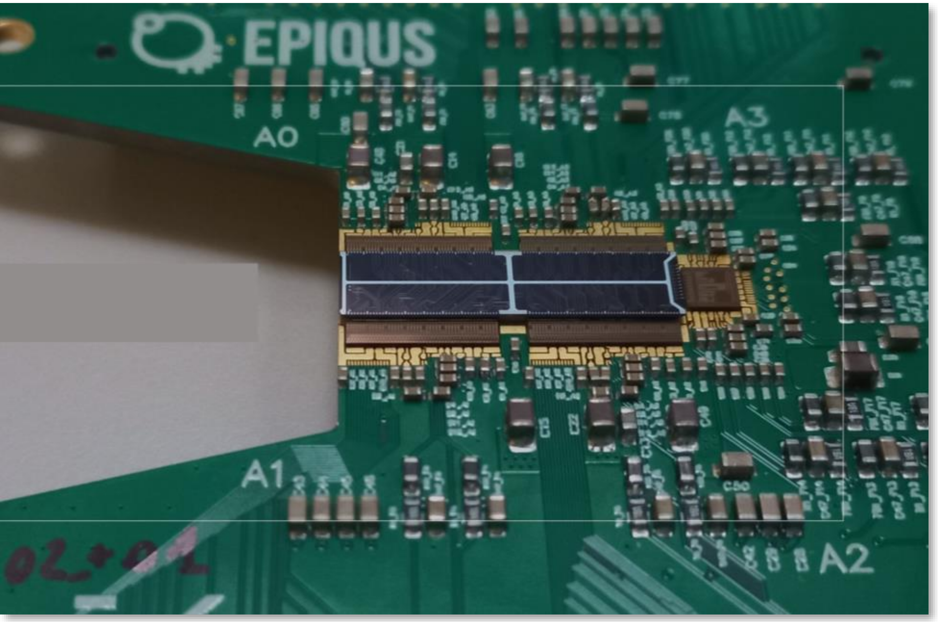






- ➢Test #1: light from the right side WG associated to SPAD T13, monitoring SPAD T12.
  - ➢we estimated a detection efficiency of about ***0.04%***.
- ➢Test #2: light from left or right side of WG associated to SPAD T11, monitoring SPAD T13
  - ➢detection efficiency around ***0.03%*** (first case) and ***0.16%*** (second case).
- ➢***Minor stray-light → thanks to light blocking structures***

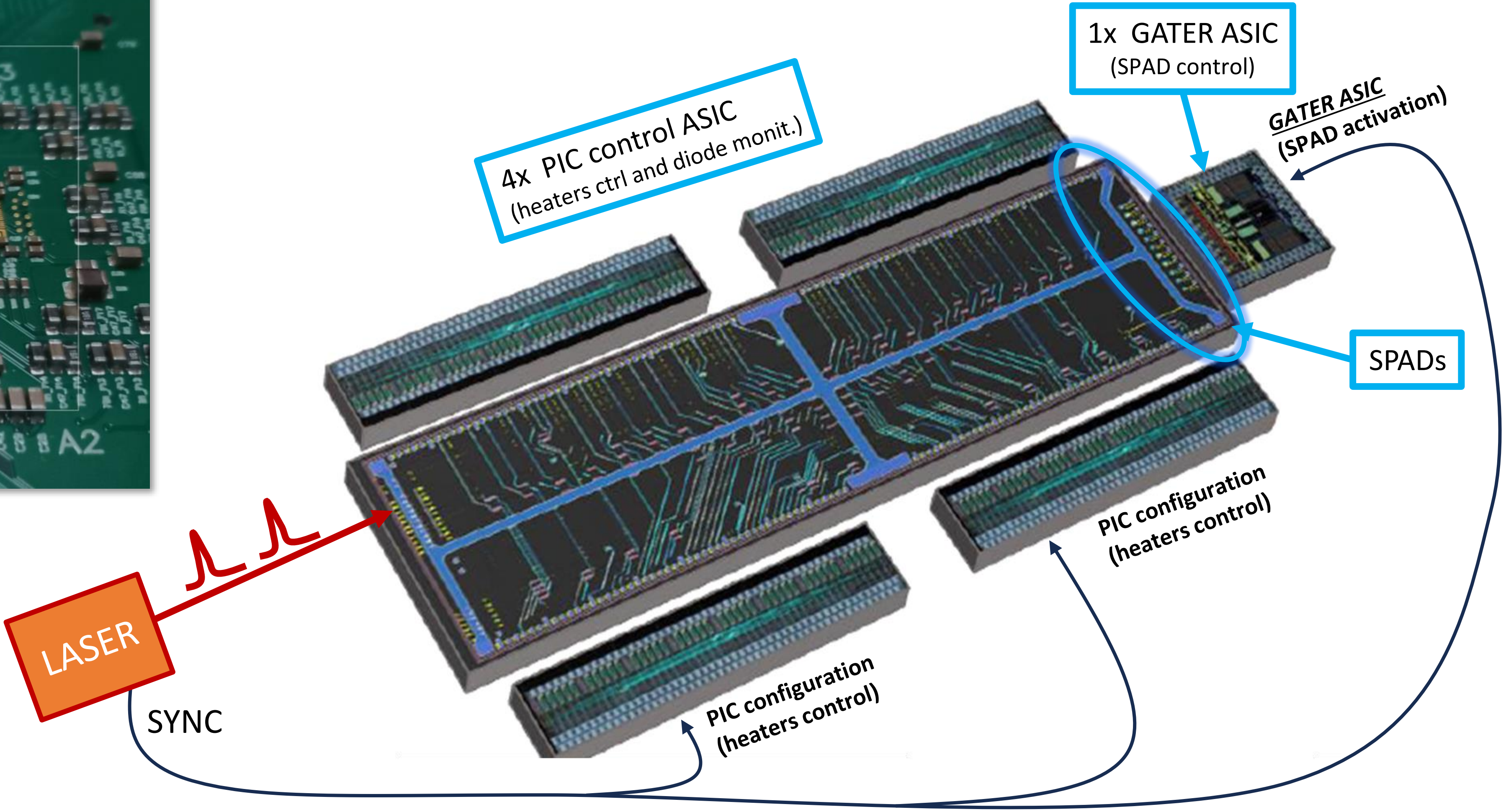
Next: complete quantum simulator (EPIQUS project)



EPIQUS

Grant agreement # 899368

European Commission
Horizon 2020
European Union funding
for Research & Innovation



- *Periodic PIC and SPAD configuration/enabling, synchronous with input light pulses*

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Conclusions

- New ***CMOS compatible top-down evanescent approach for monolithic electronic-photonic integration***
  - ✓ material all CMOS compatible,
  - ✓ it does not require alignments, butt coupling, or two waveguides made in different materials,
  - ✓ it can be operated at room temperature,
  - ✓ design of the SPADs does not have particular restrictions.

- Fabricated the first PICs with integrated silicon SPADs:
  - moderately low dark count rate
  - Good photon detection probability (improvable in future runs)
  - SPADs well appropriate for short gating pulses in a photonic quantum simulator.
  - system detection efficiency (i.e. PIC+SPAD), being between 17% and 20%
  - Waveguide-to-detectors coupling efficiency ~ 80%.

- Direct test of photon manipulation and detection:
  - Modulation of photons propagation between two adjacent waveguides and detection.

- Promising technology for future developments at FBK.

- *Future runs: improvement of detection efficient (light trapping)*

FONDAZIONE
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Silicon SPAD monolithically integrated with SiON-based photonic circuit

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