GHENT
UNIVERSITY

15th October 2024

Waveguide-Coupled Photodetectors and Light Sources Based on Colloidal Quantum Dots: From Building Blocks to Advanced Demonstrators

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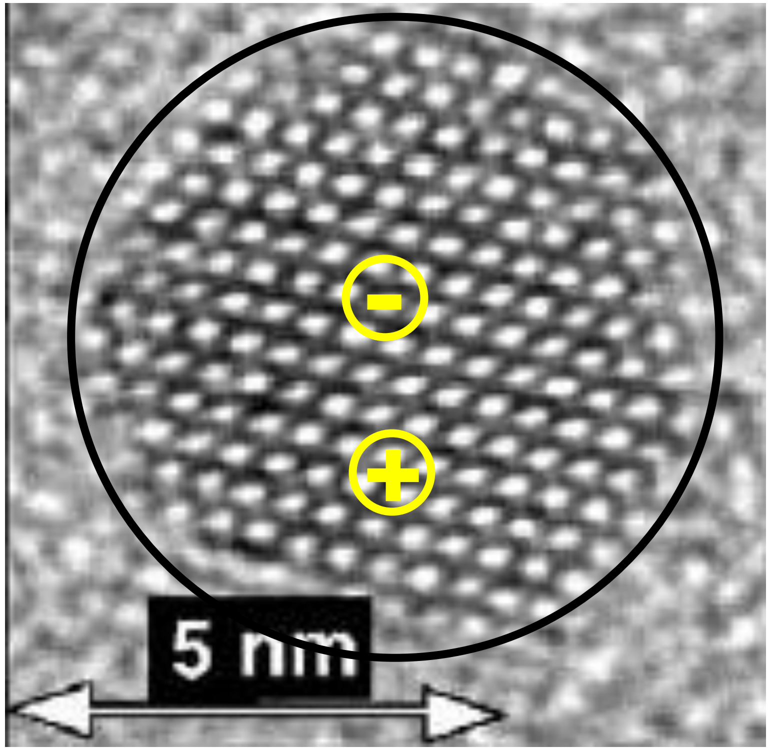
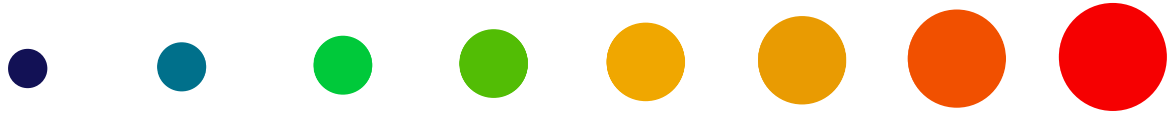
Supervisors: Dries Van Thourhout, Pieter Geiregat, Zeger Hens

imec PCN PHOTONICS RESEARCH GROUP

Colloidal **Quantum Dots**

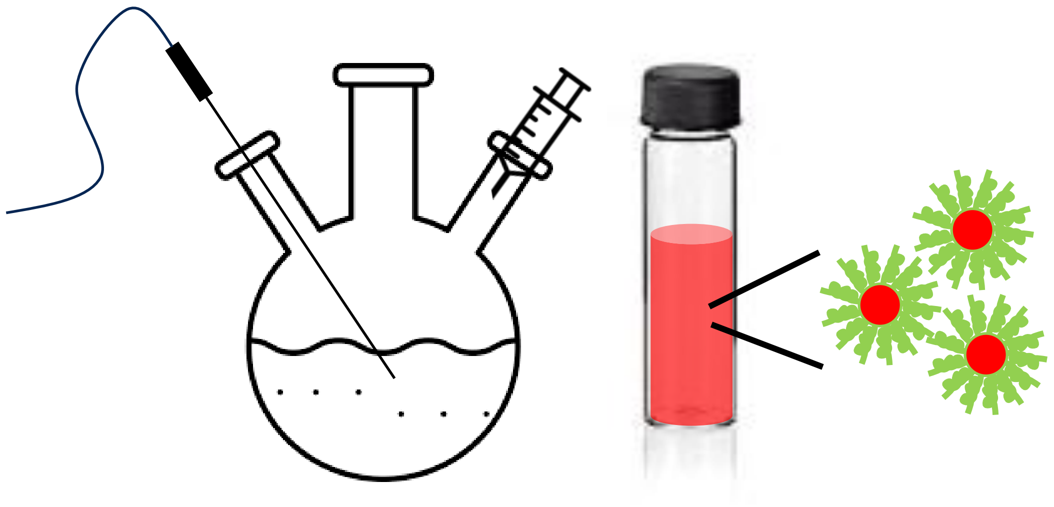


Nanocrystals, 1 nm – 20 nm



Spectral tunability through quantum confinement effect

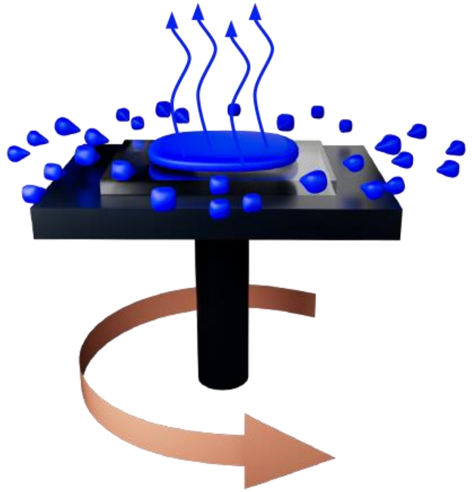
Colloidal Quantum Dots



Deposition

Spray coating

Spin coating



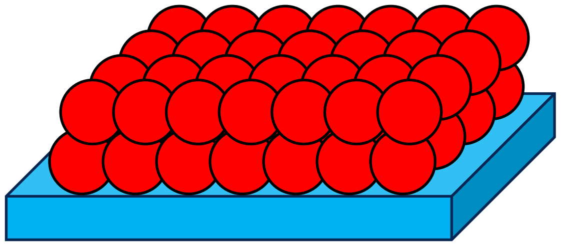
Synthesized with wet chemical method

Stable dispersion in solvent

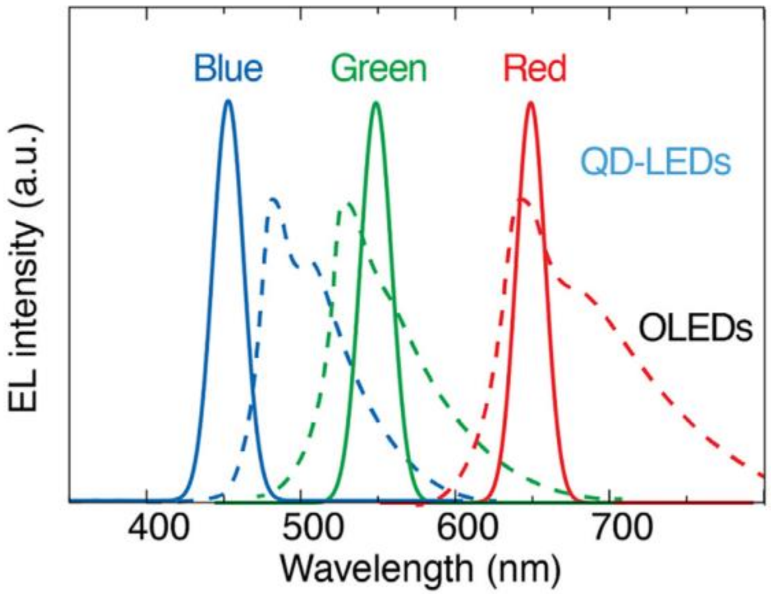
Easy deposition

→ Low-cost material

QD solid film



Colloidal Quantum Dots: Good Light Emitters



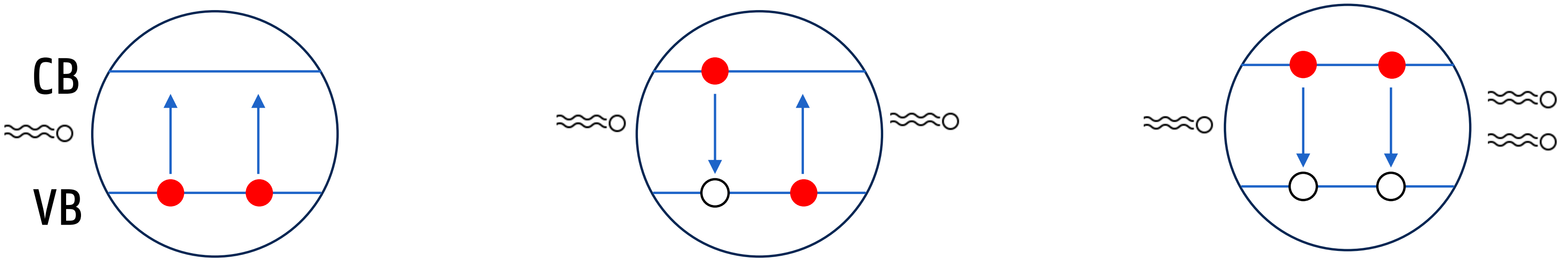
Z. Yang, Materials Today 2019.

Excellent color purity

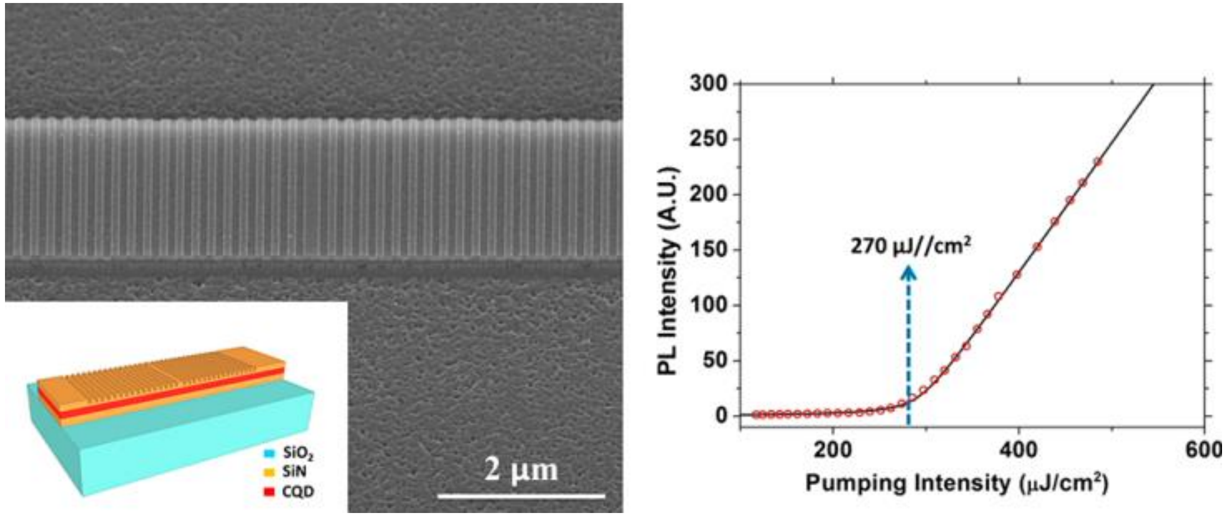
High emission efficiency

Stable

Colloidal Quantum Dots: Potential Gain Material

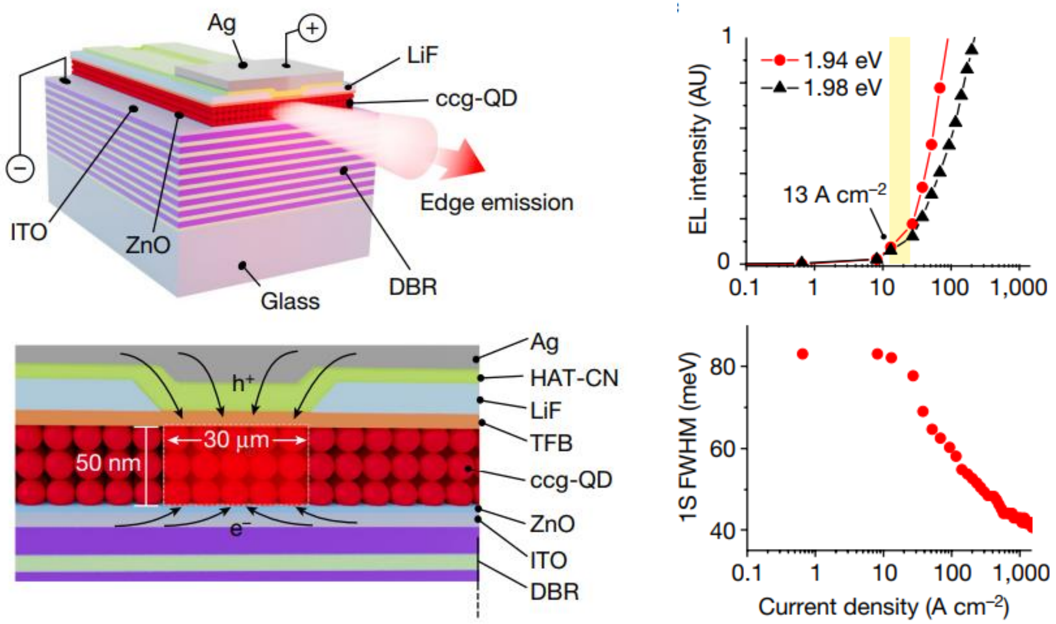


ns-optical-pump integrated laser



Y. Zhu, ACS Photonics, 2017

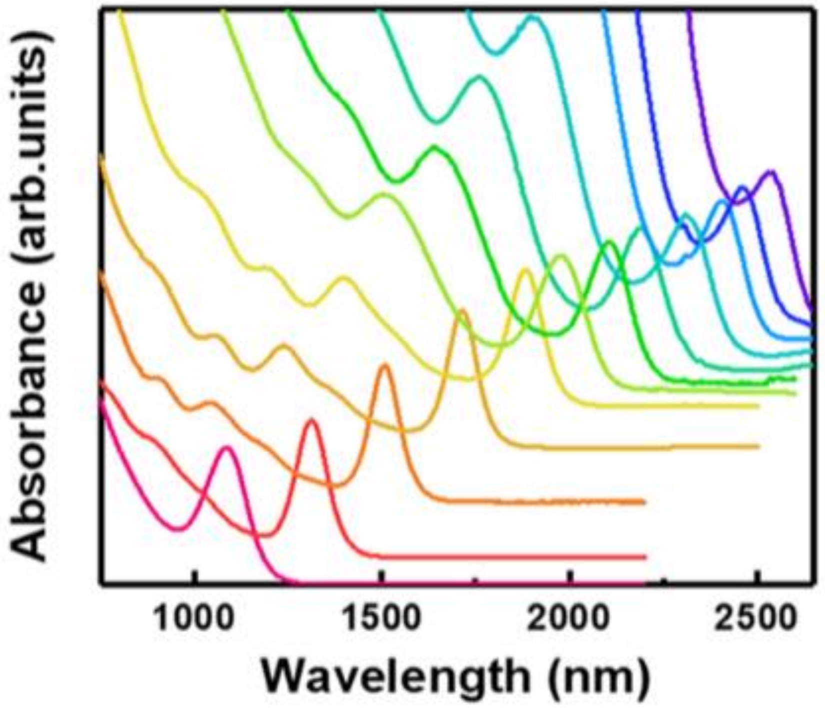
Electrical-pump Amplified Spontaneous Emission



N. Ahn, Nature, 2023.

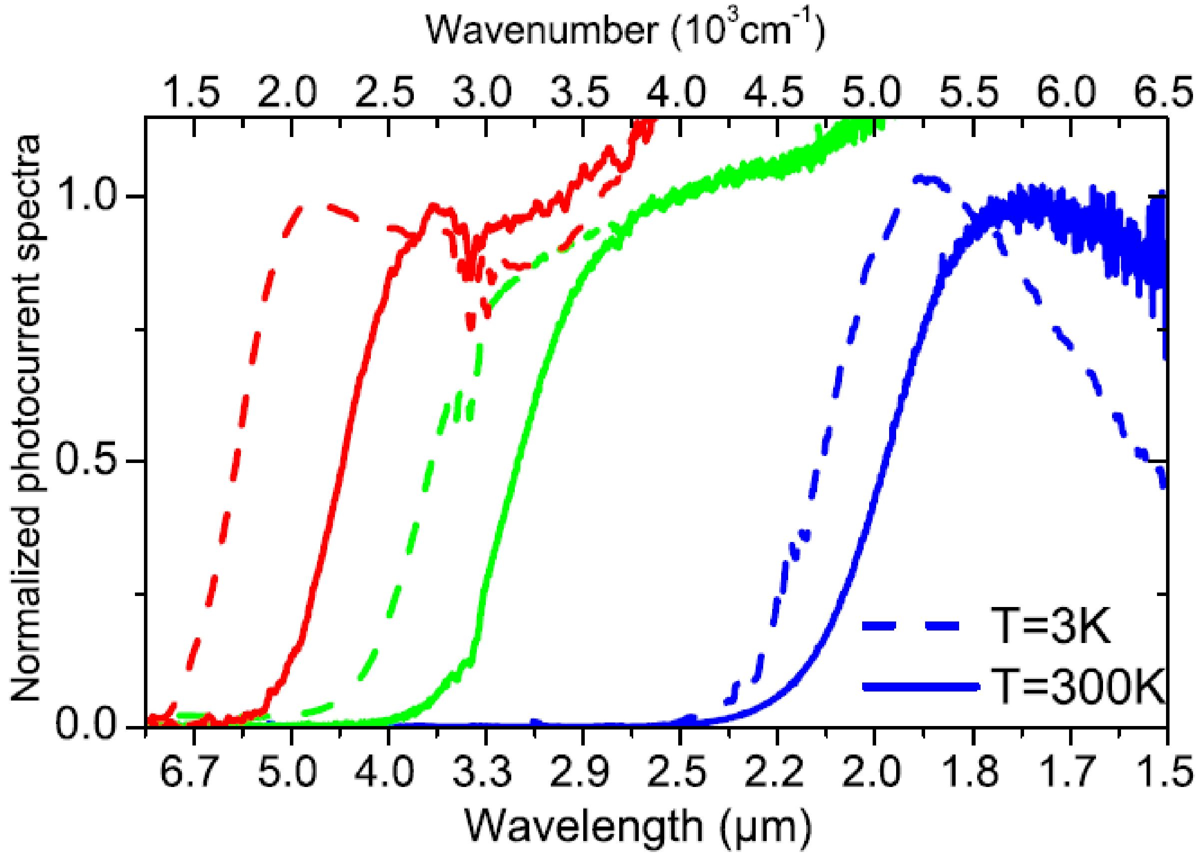
Colloidal Quantum Dots: Good Infrared Absorbers

PbS QDs



C. Dong, ACS applied materials & interfaces, 2019.

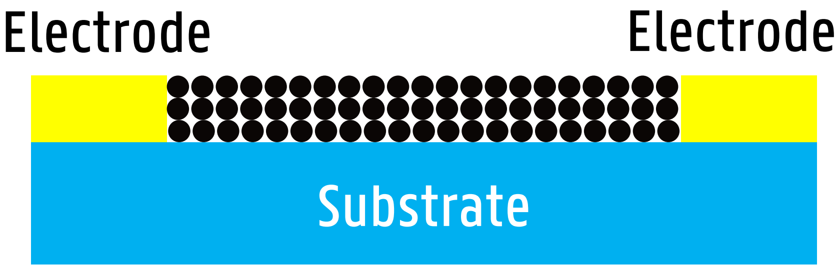
HgTe QDs

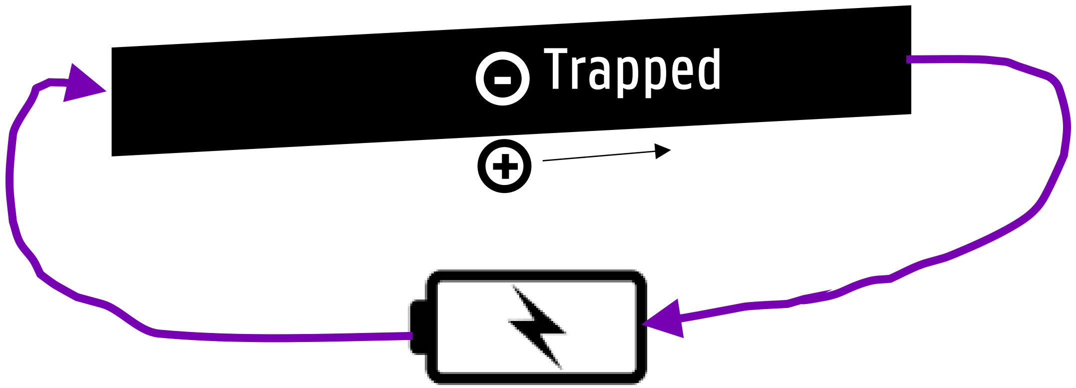


E. Lhuillier, Nanotechnology, 2012.

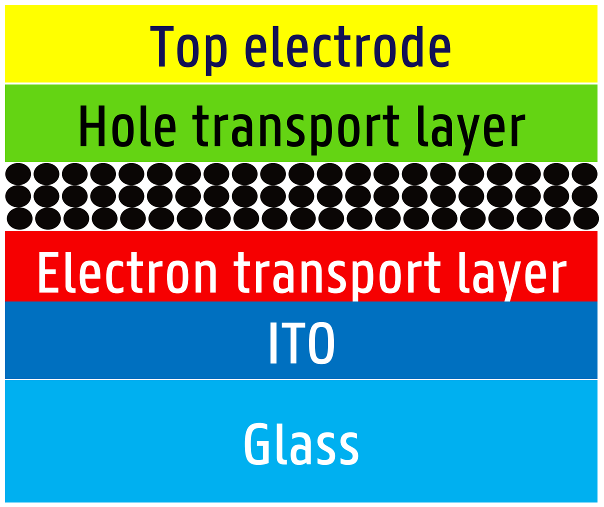
Colloidal Quantum Dots: Infrared Photodetectors

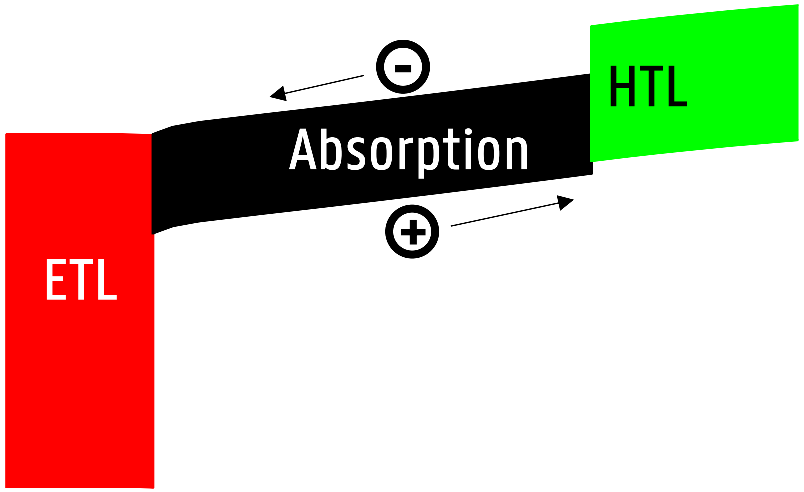
Photoconductors



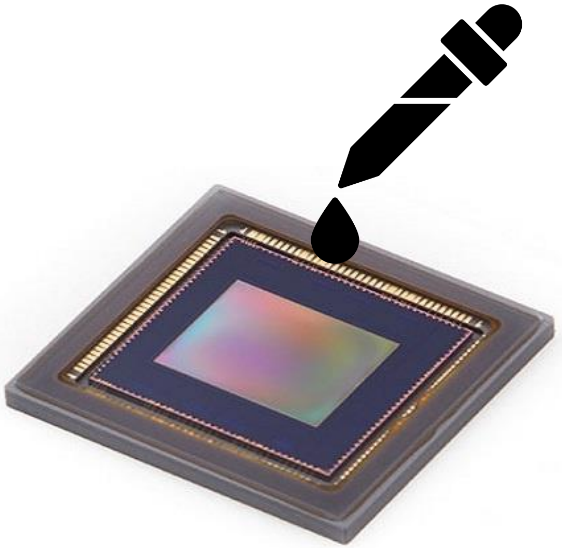


Photodiodes





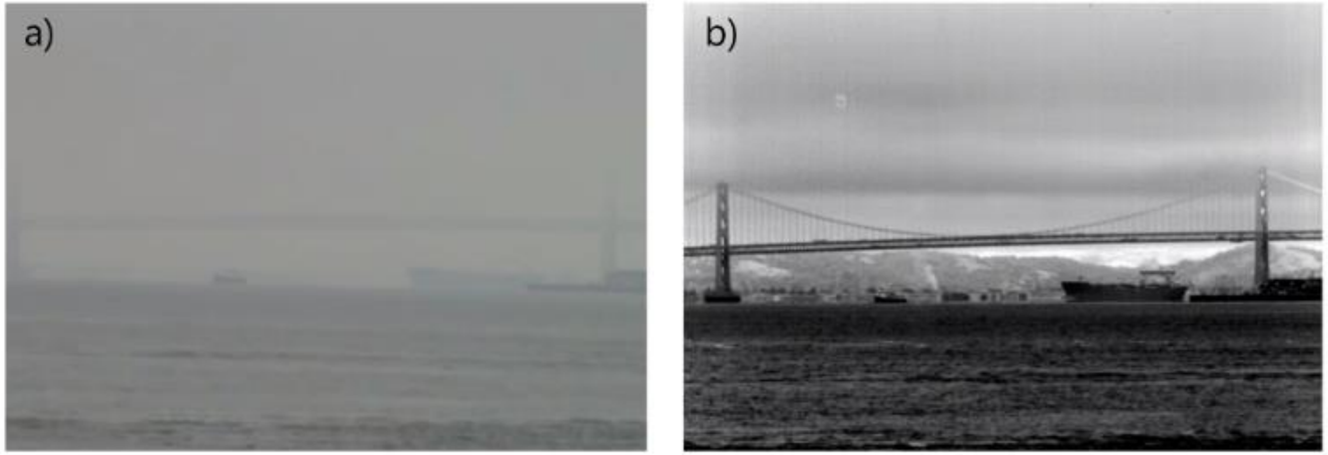
Colloidal Quantum Dots: Cost-effective Infrared Imagers



Read-out integrated circuits

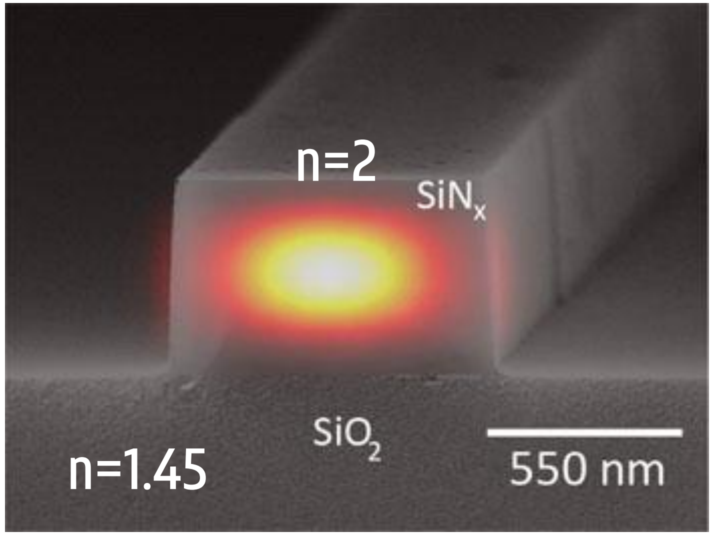
Visible

Infrared

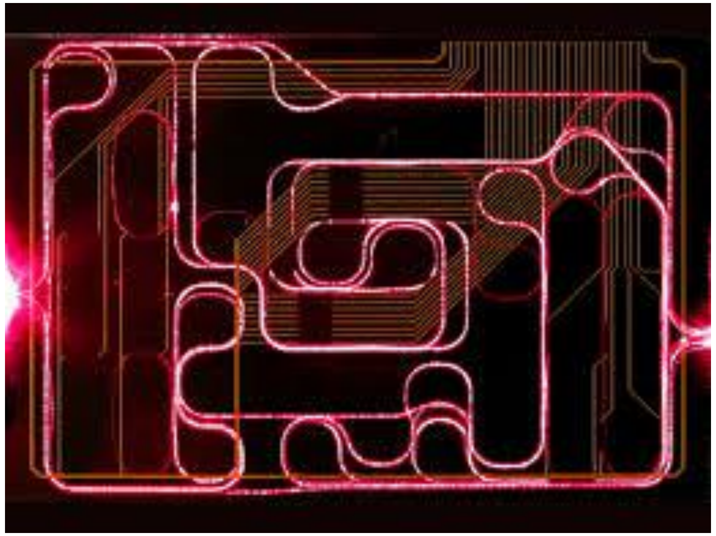


Photonic Integrated Circuits

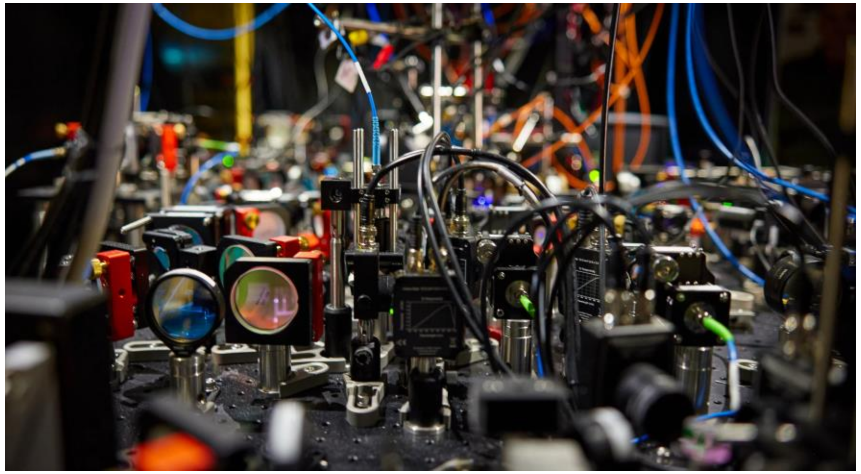
Waveguide: confine light tightly

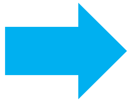


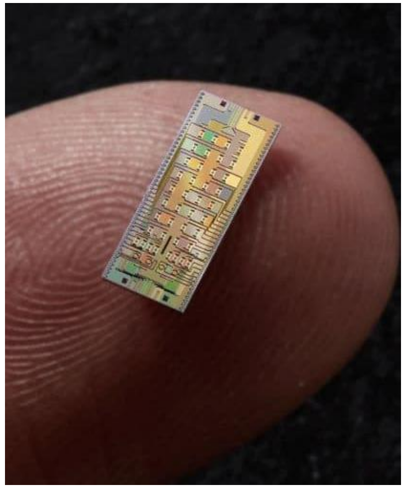
Guide and manipulate light on chip



LioniX



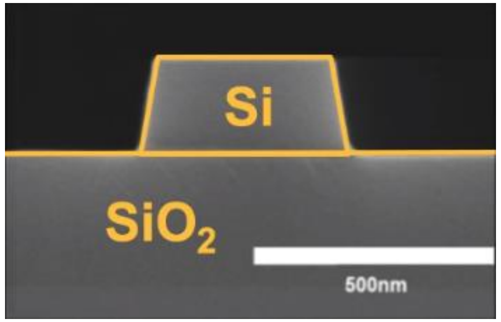




Xanadu

Silicon Photonics

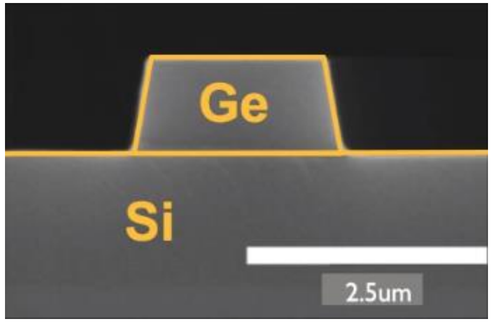
Use CMOS infrastructures developed for electronic integrated circuits!



1.1 µm — 3.7 µm

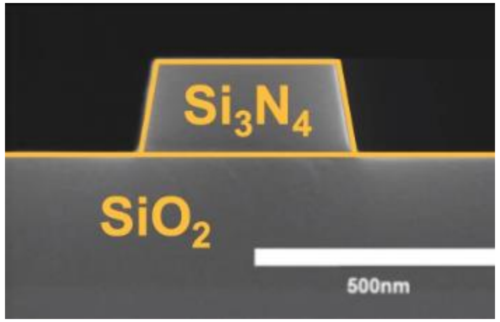
Dense integration

Modulation



1.6 µm — 8 µm

Detector



0.4 µm — 3.7 µm

Visible transparency

Low Loss, high power, ...

Intrinsic incapability

Light emission

Photodetection beyond 1.6 µm

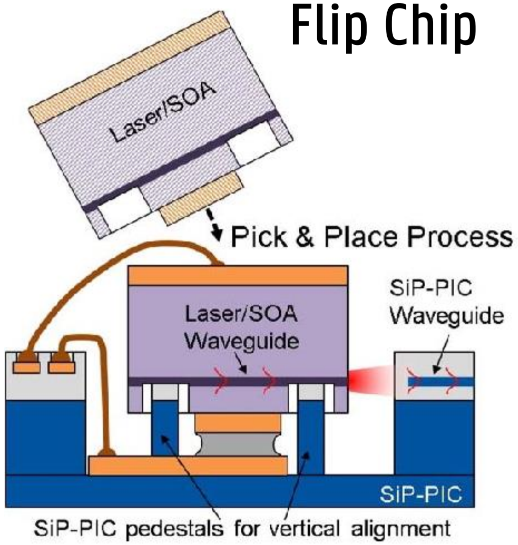
Photodetection

Modulation

Silicon Photonics: Add Active Components (III-V)

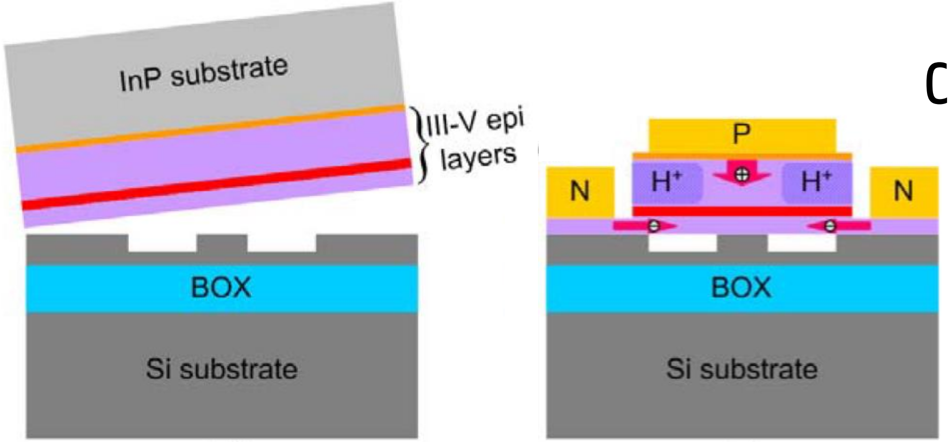
Flip Chip

Manufacturing
Throughput



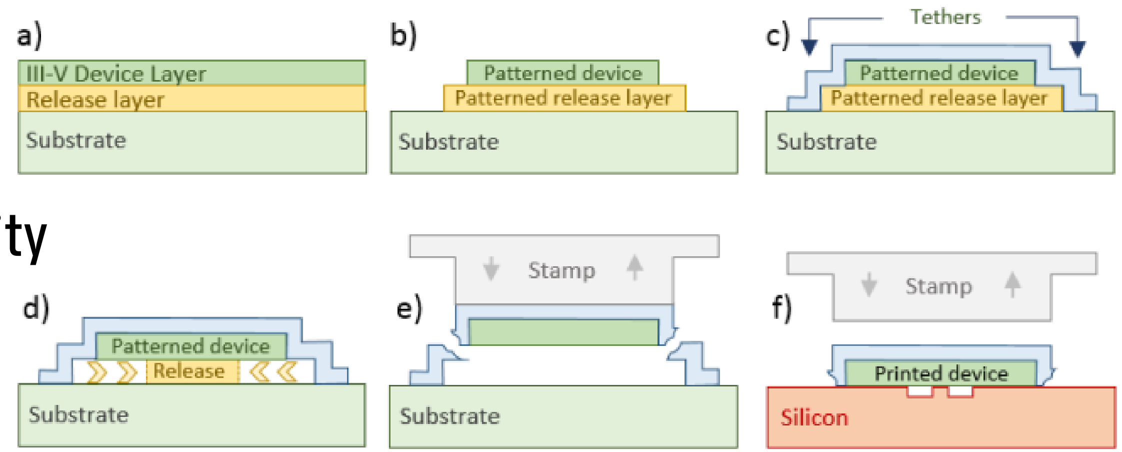
Bonding

Cost



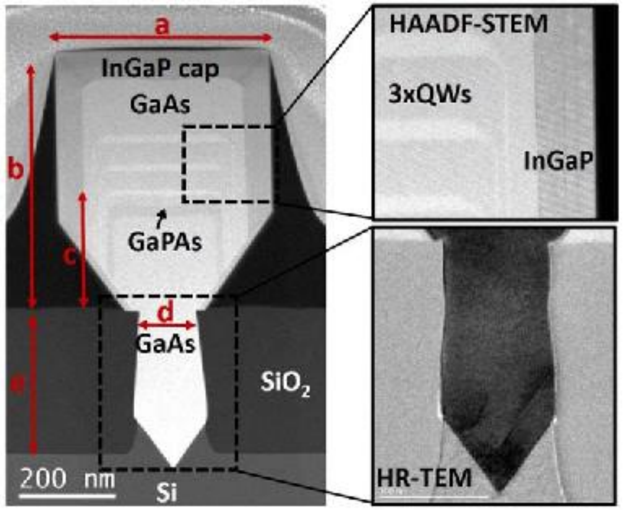
Transfer printing

Complexity

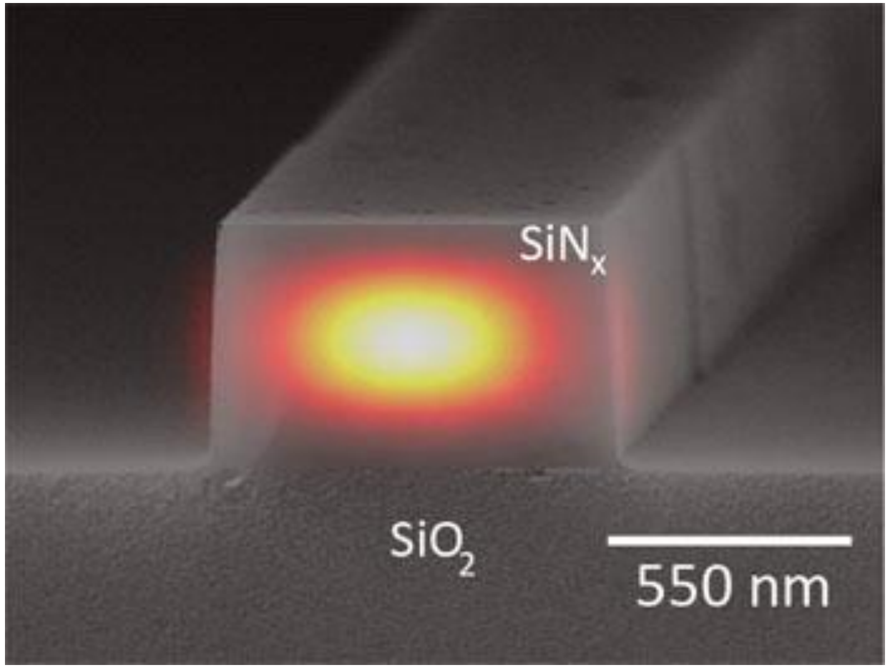


Monolithic growth

Challenging



Colloidal Quantum Dots for Photonic Integrated Circuits

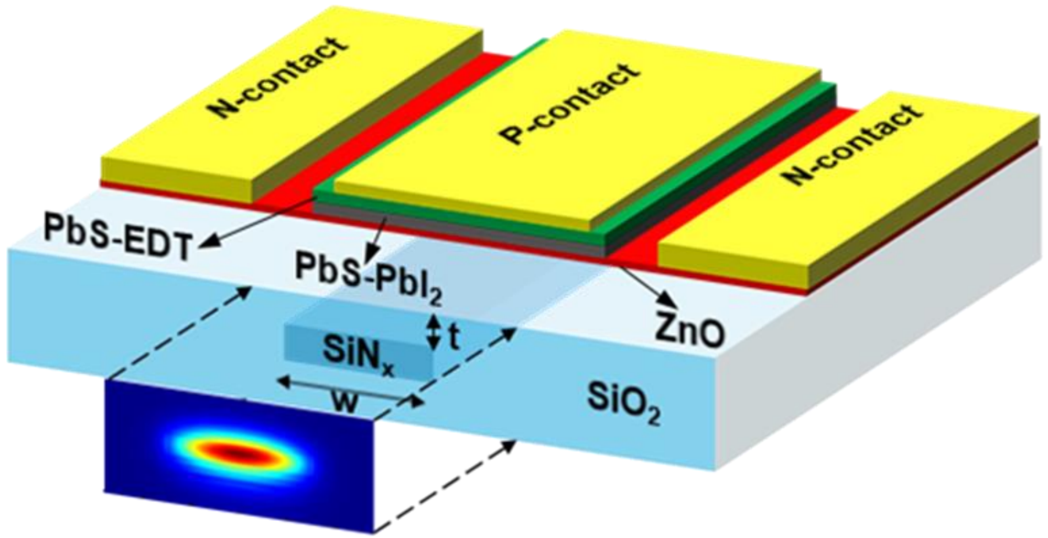


Cost-effective building blocks:

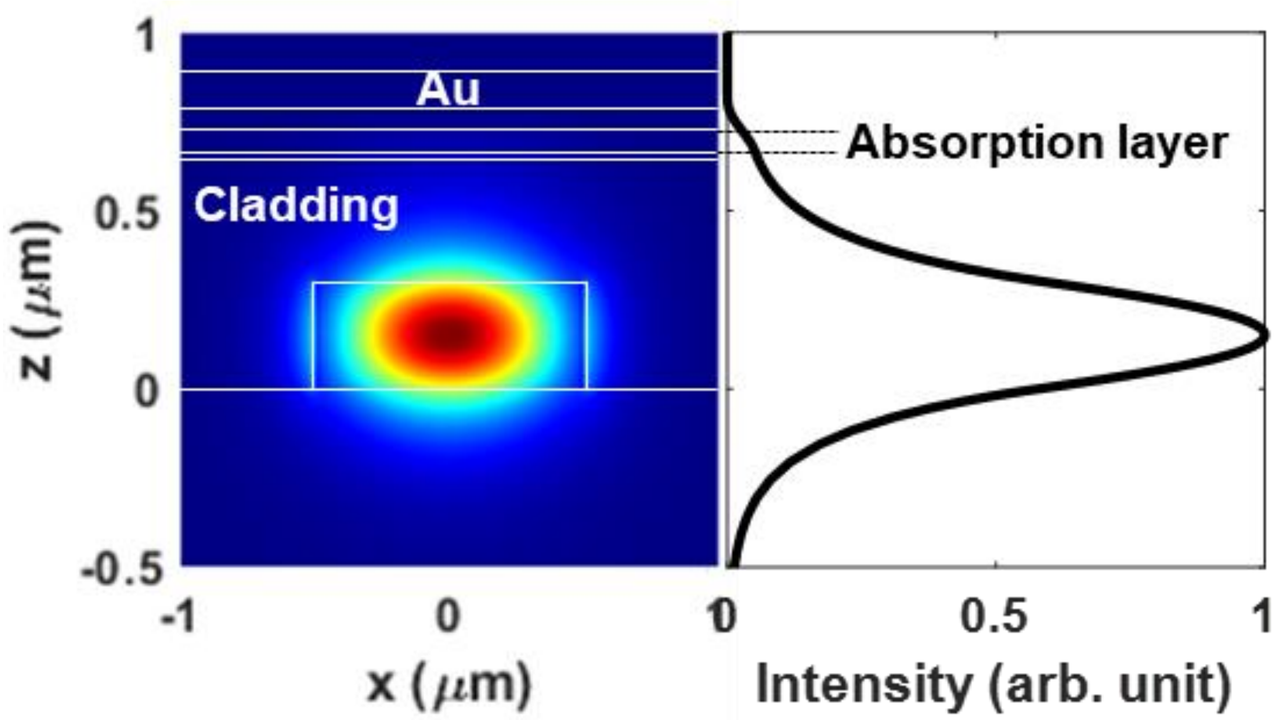
Colloidal QD Photodetectors

Colloidal QD Light sources

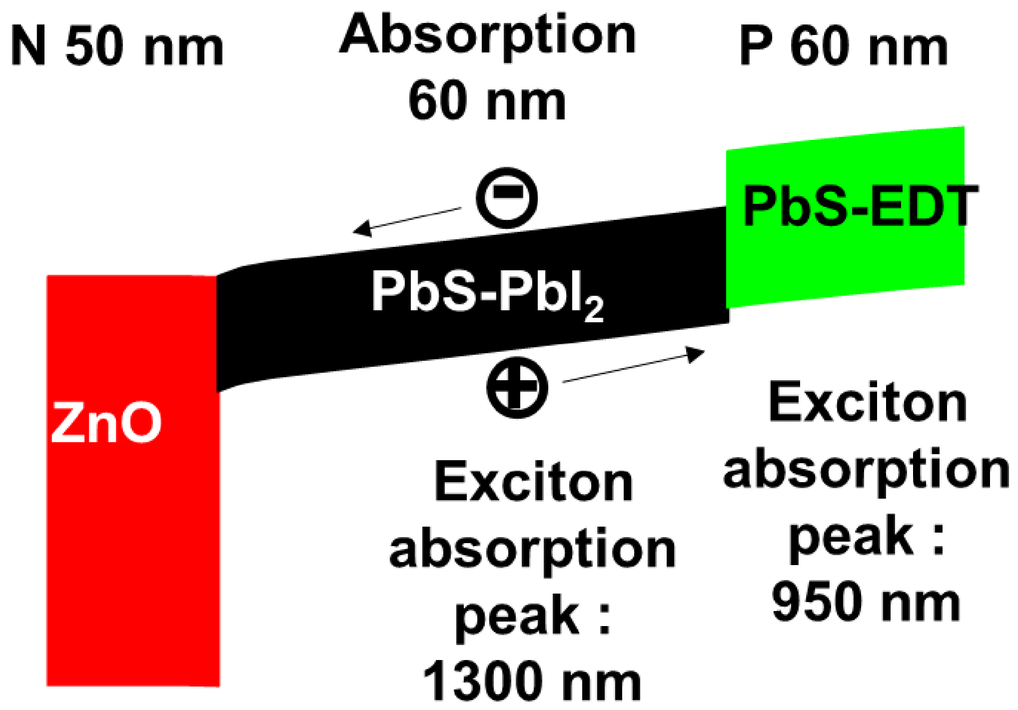
1.3 µm waveguide-coupled QDPD on SiN

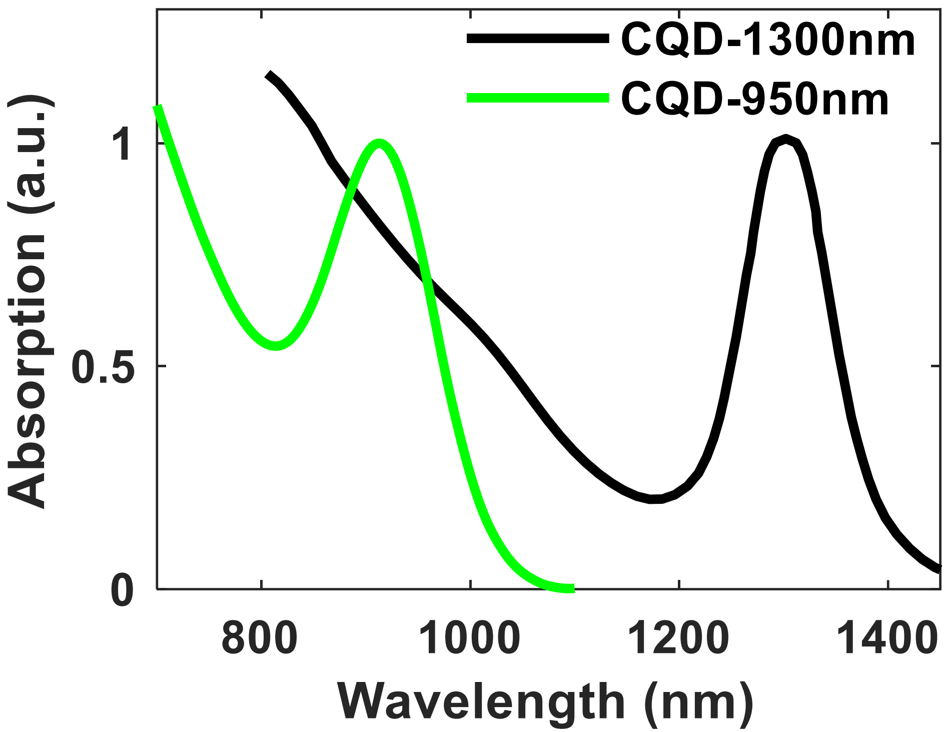


Evanescent absorption

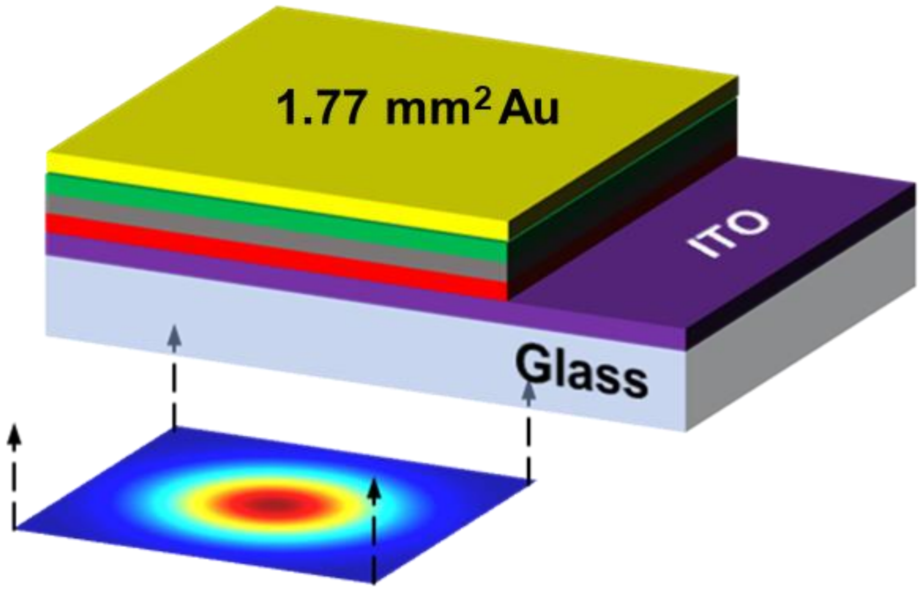


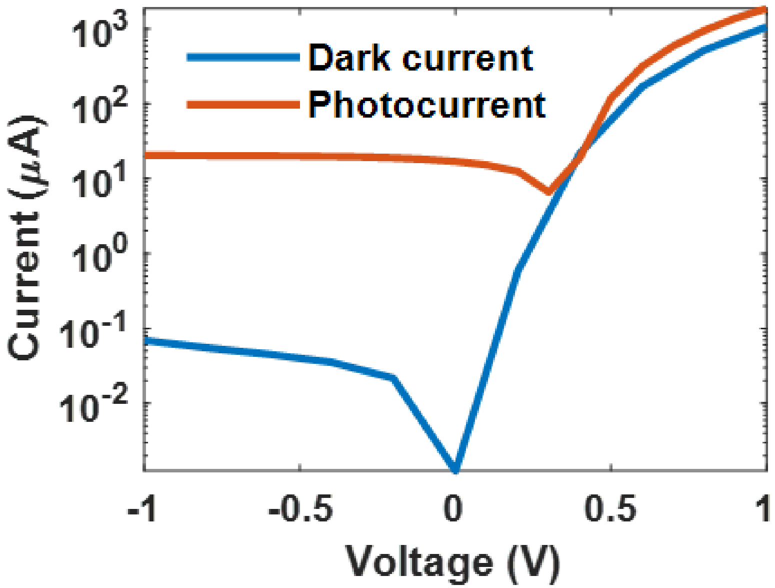
What Materials used for QDPD Stack?

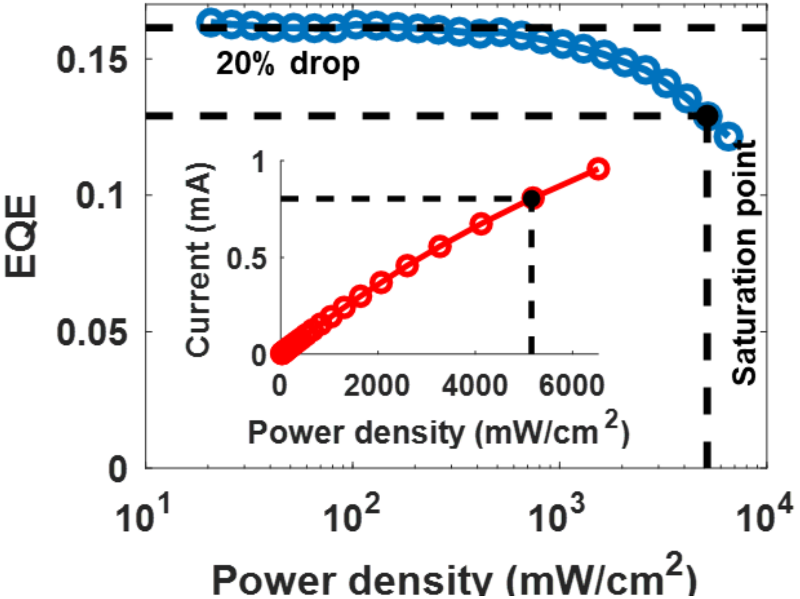




What is the performance of QDPD stack?





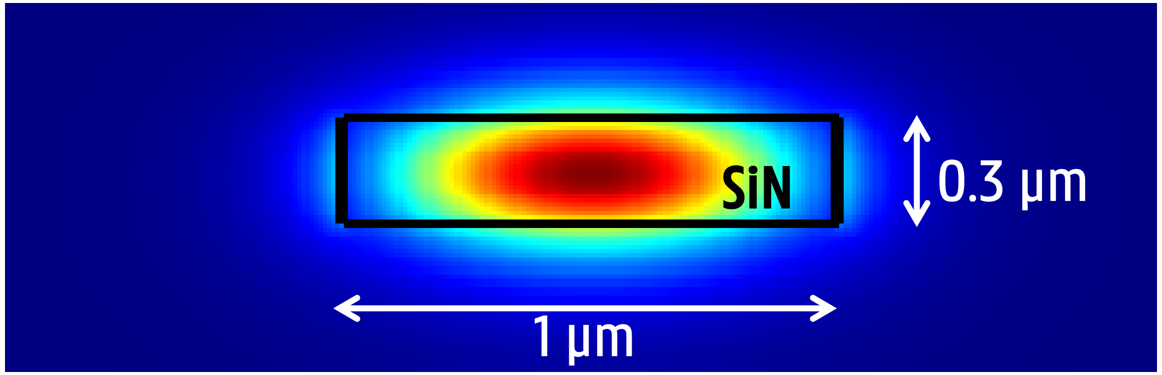


Saturation power density: 5.2 W/cm^2

Be careful!

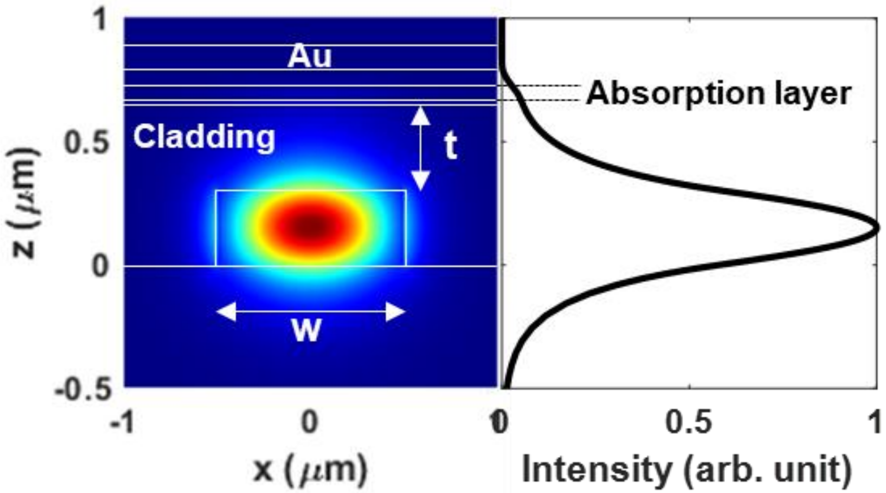
Design

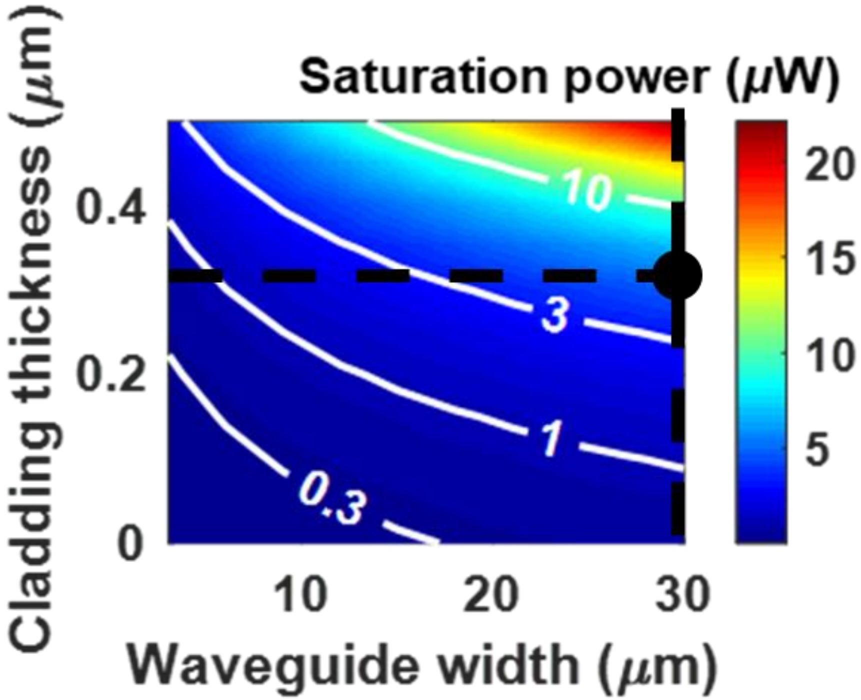
5.2 W/cm² Not high!



Cross-section < 1 µm²

1 µW ~ 100 W/cm²



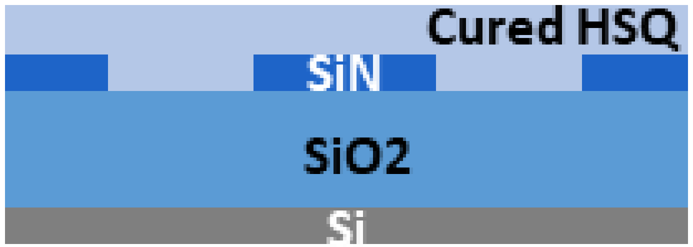


t = 350 nm ⟷ Saturation power ~ 6.9 µW

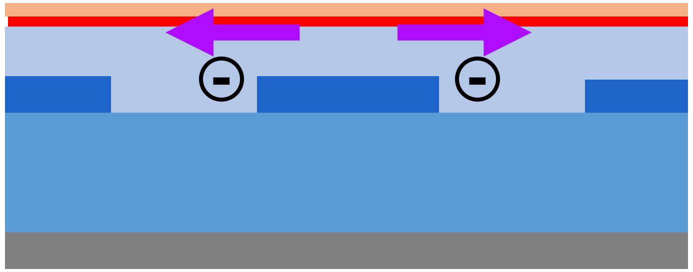
w = 30 µm

Develop a Process Flow in House

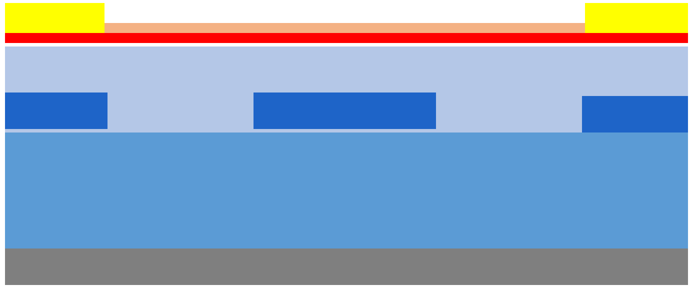
Passive waveguide



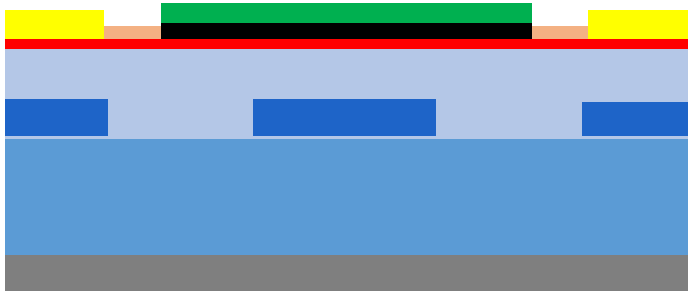
ALD ZnO + Al2O3



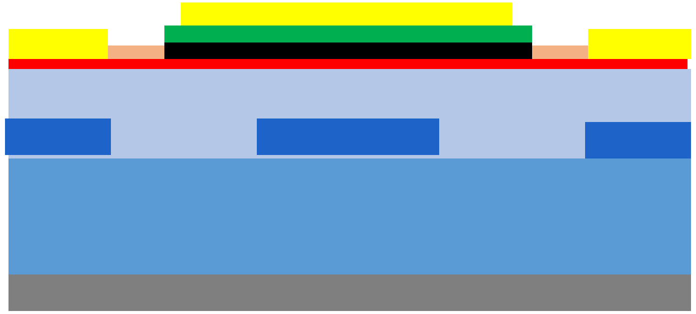
Ti + Au N-contact



PbS-PbI + PbS-EDT CQDs

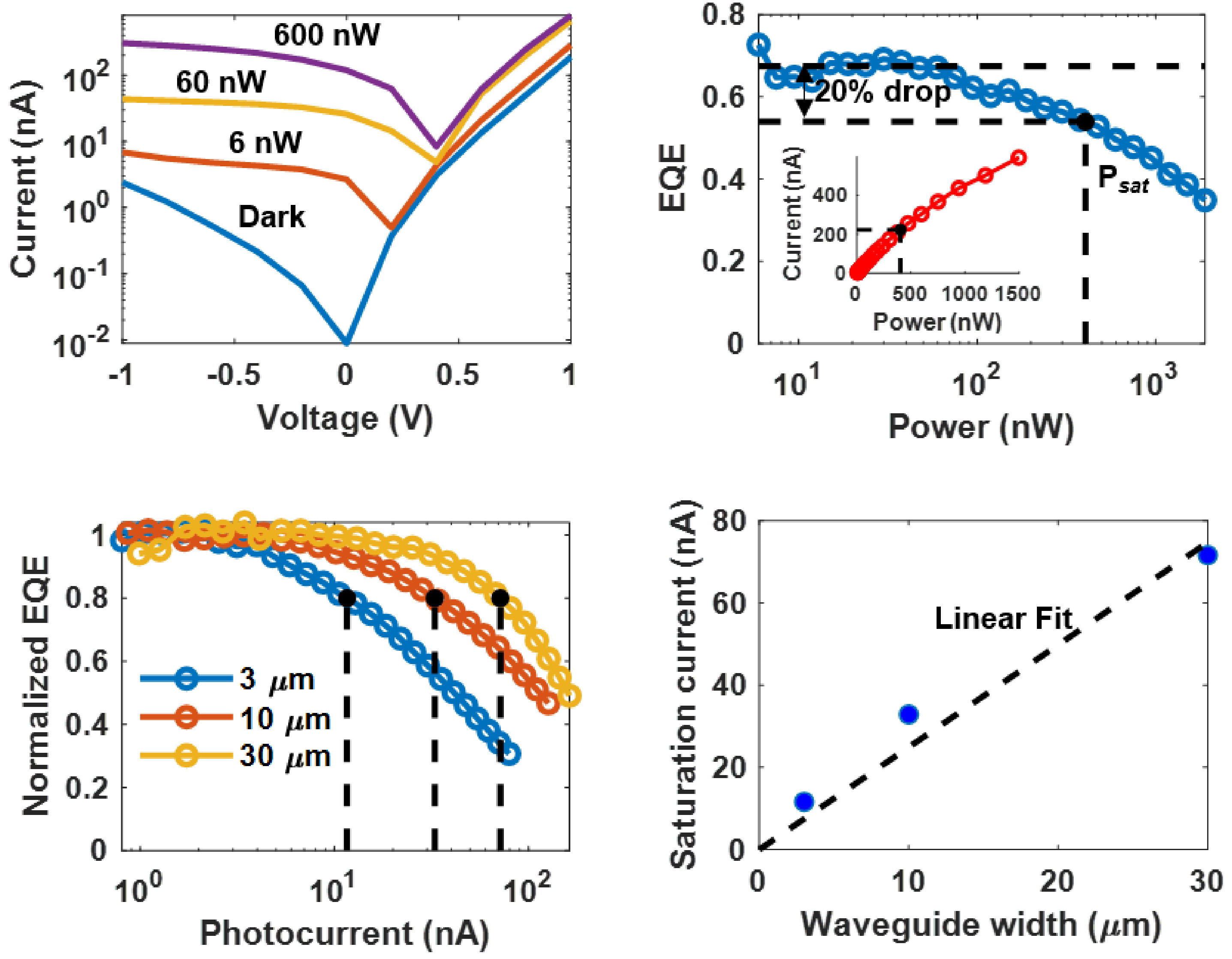


Au P-contact



Top view

Performance of 1.3 µm WG-QDPD

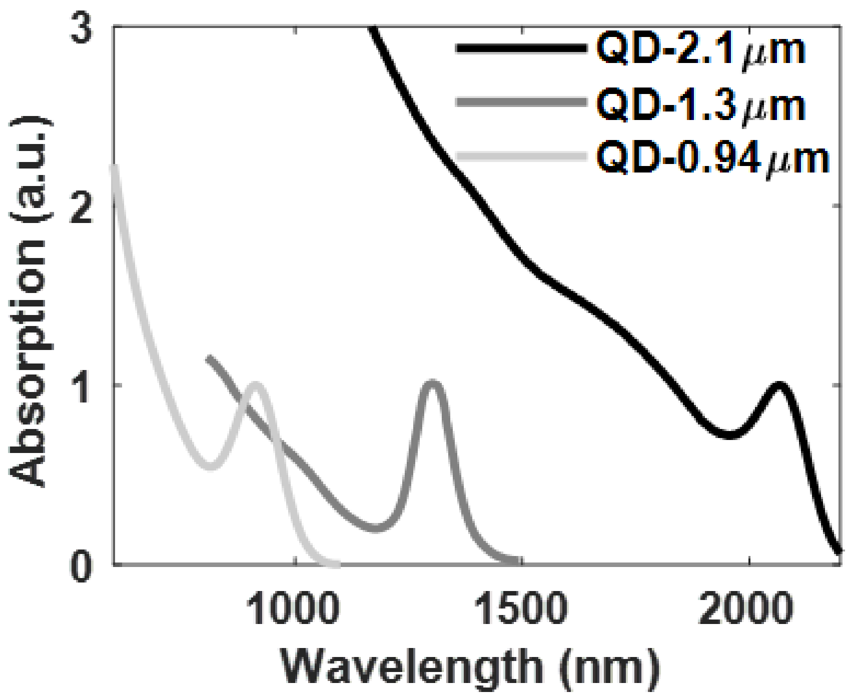


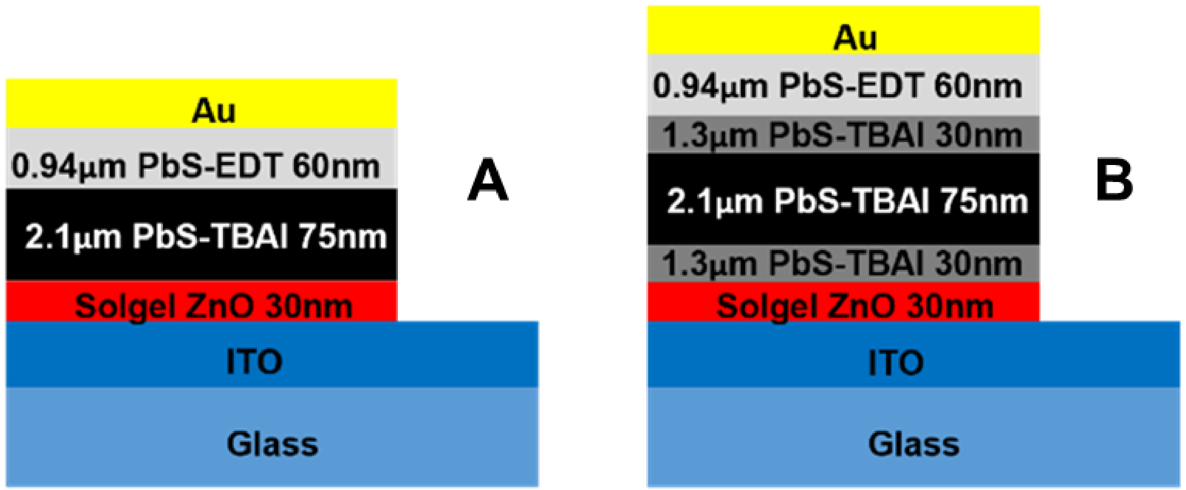
Performance at wavelength of 1275 nm, bias of -1 V:

- Dark current: 2.4 nA
- EQE: 67.5%
  Responsivity 0.69 A/W
- Linear response up to 400 nW

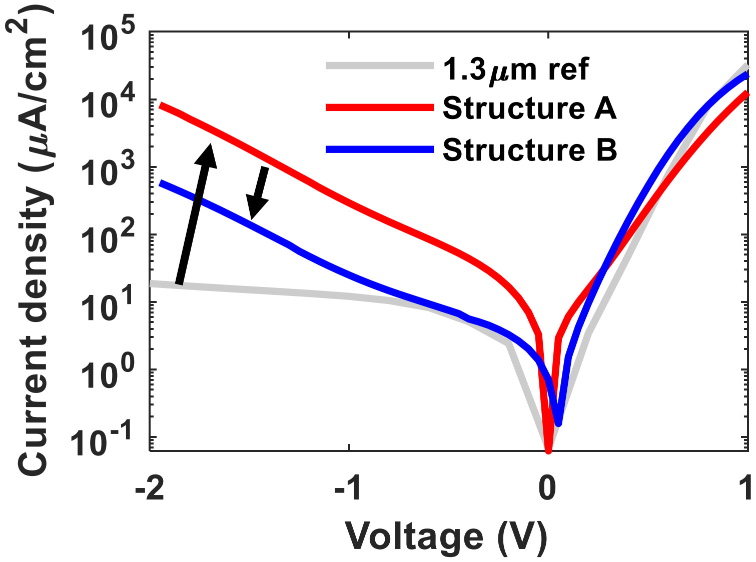
Power density control important!

2.1 µm waveguide-coupled QDPD on Si





Dark current suppression >10 times



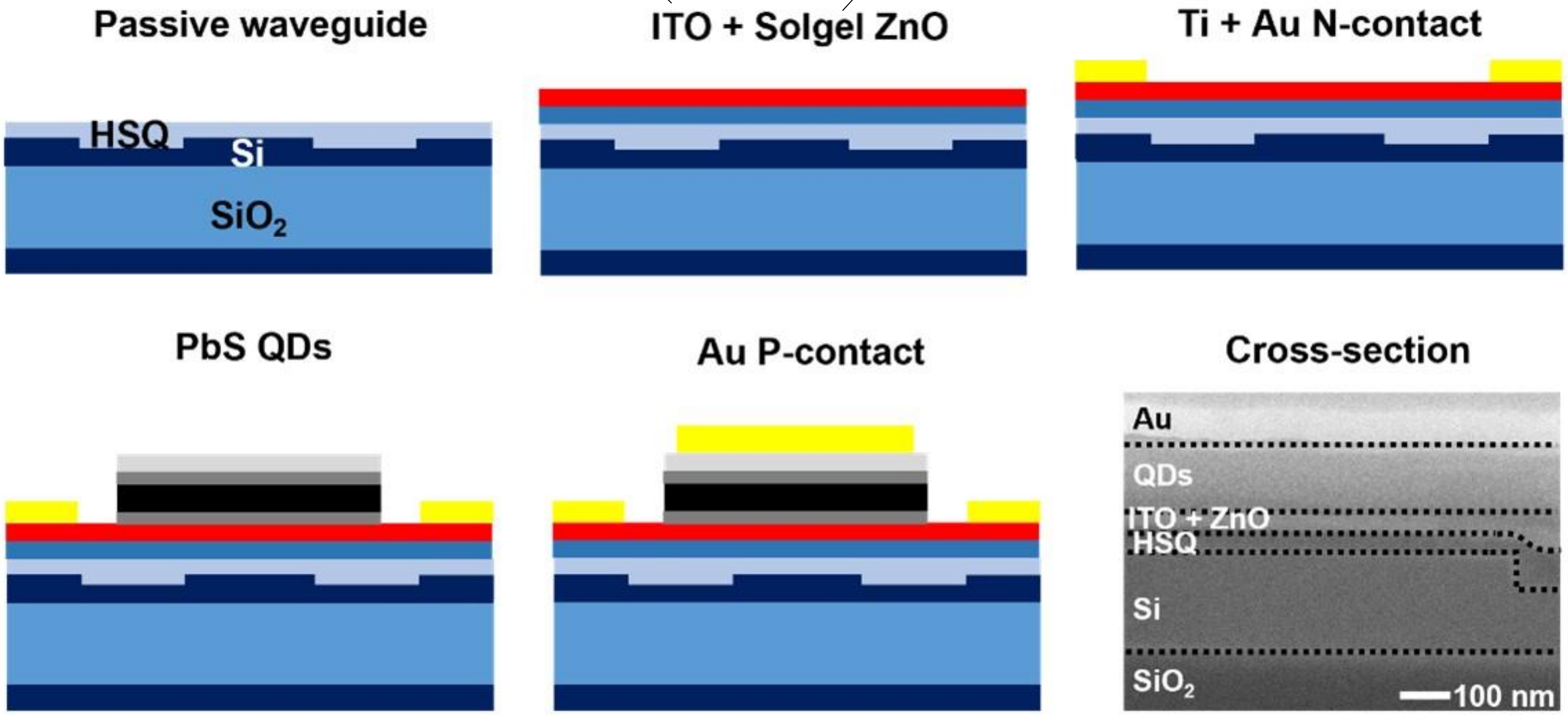
C. Pang et al., "A silicon photonics waveguide-coupled colloidal quantum dot photodiode sensitive beyond 1.6 µm," APL Photonics, 2024.

2nd Generation Process Flow

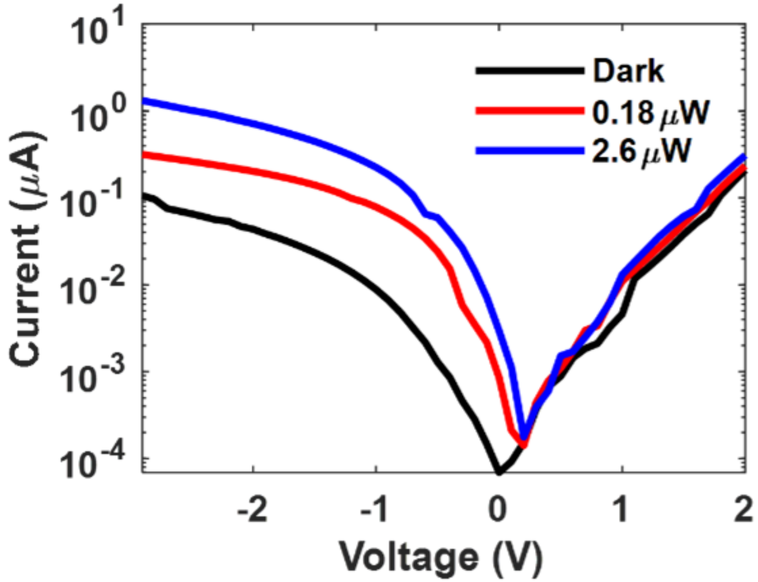
Electron transport

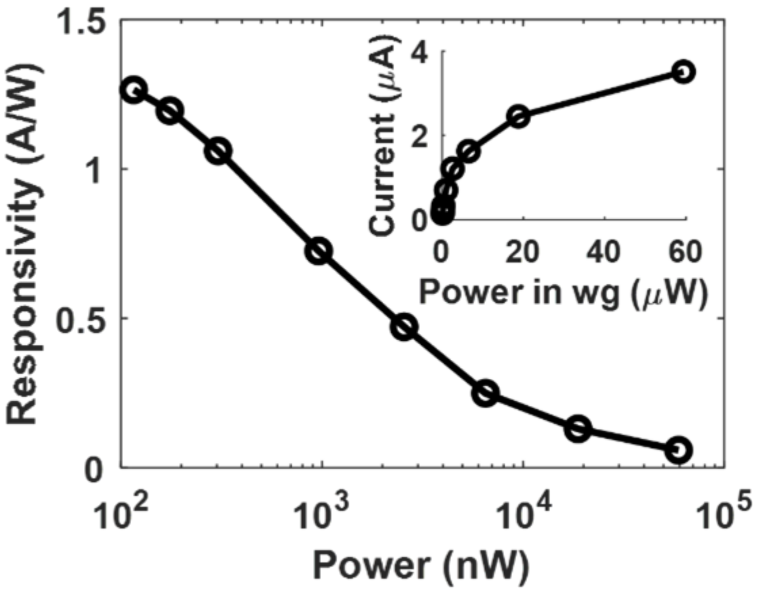
Good heterojunction

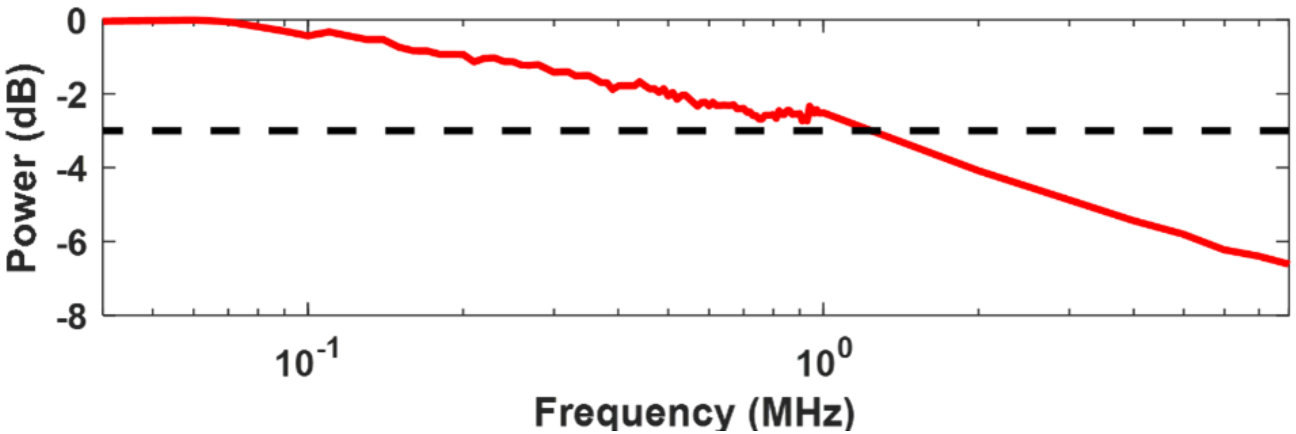
Suppress dark current



Performance of 2.1 µm WG-QDPD





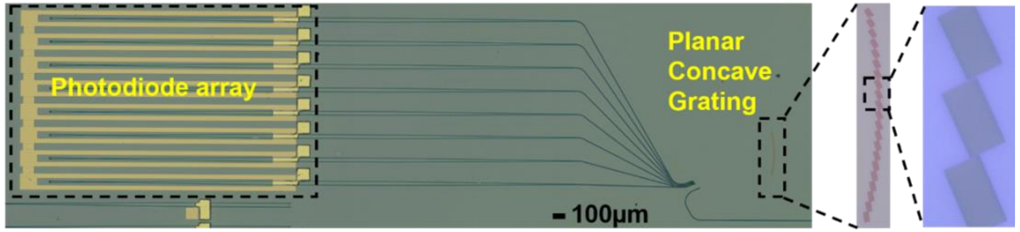


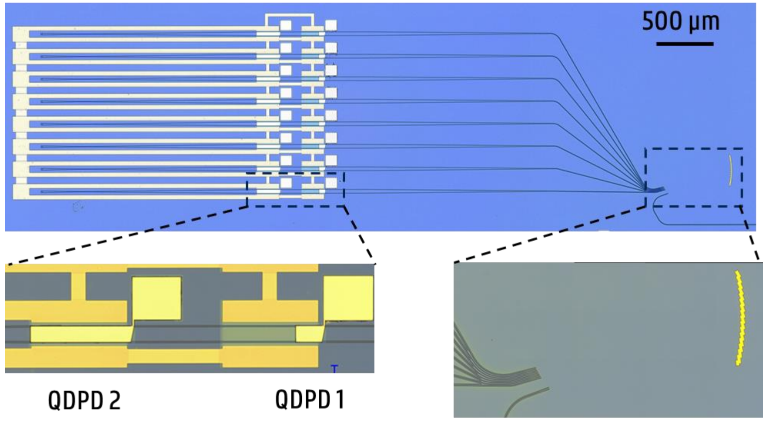
Performance at bias of -3 V

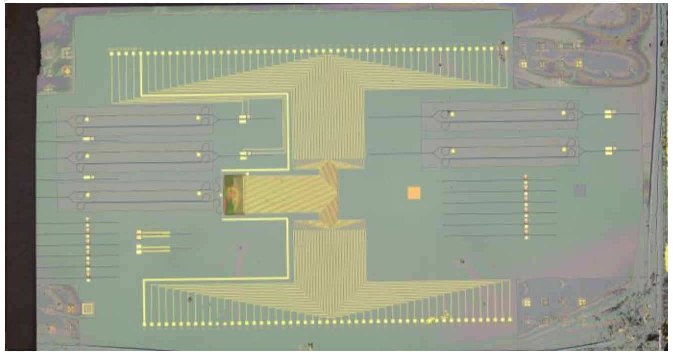
- Dark Current: 106 nA
- Responsivity: 1.3 A/W (EQE 74.8%) @ 116 nW, 2.1 µm
- Bandwidth: 1.1 MHz

Demonstrations based on WG-QDPD Blocks

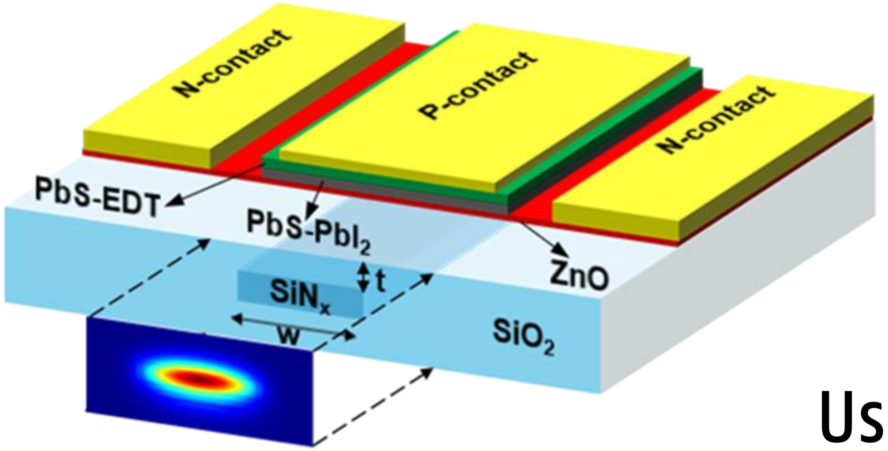
On-chip spectrometers







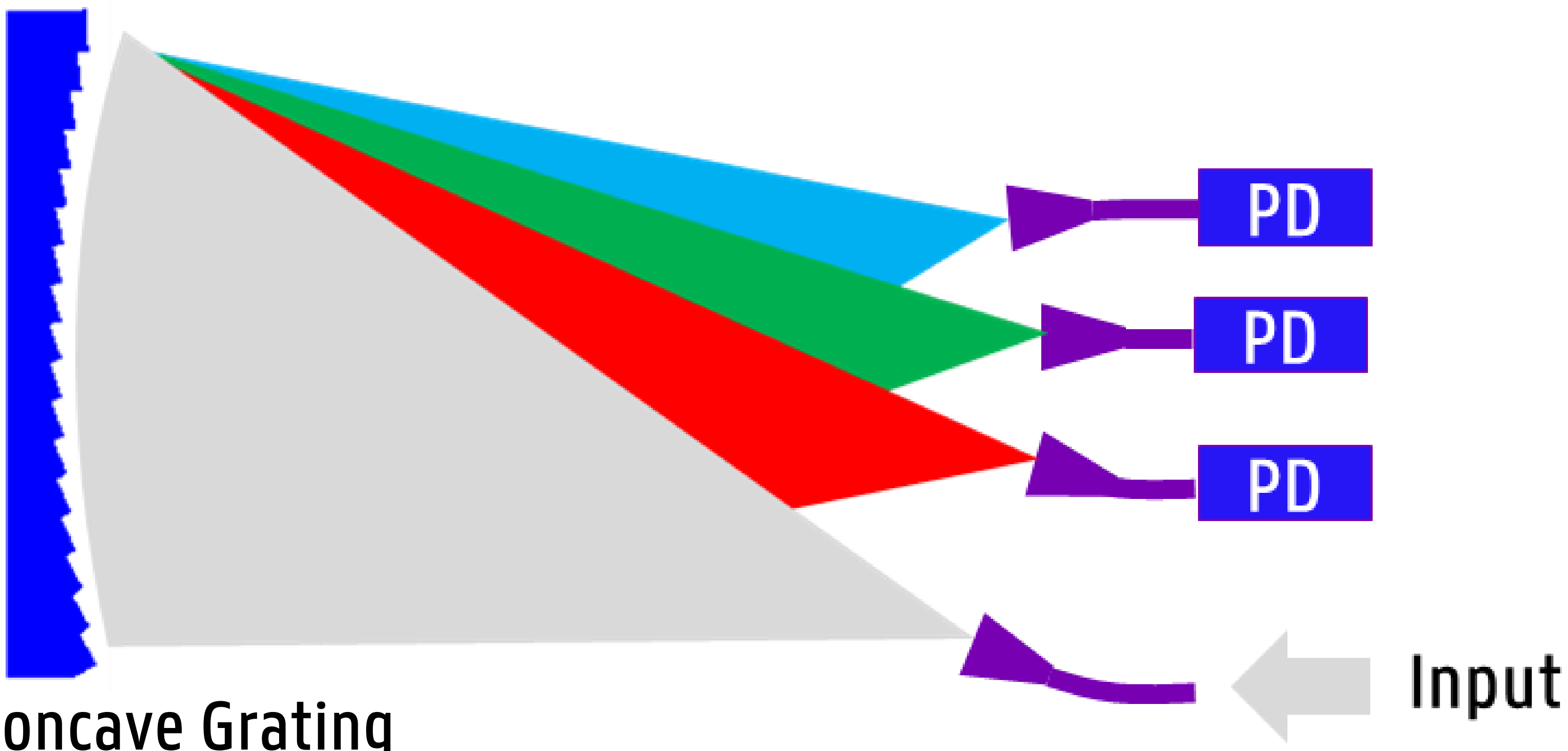
WG-QDPD unit



Useful?

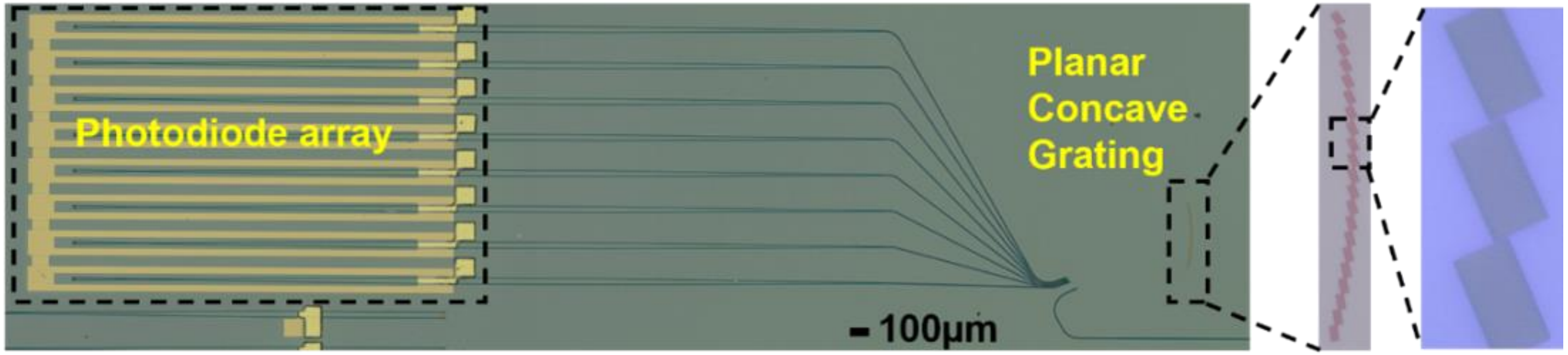
Classic On-chip Spectrometer

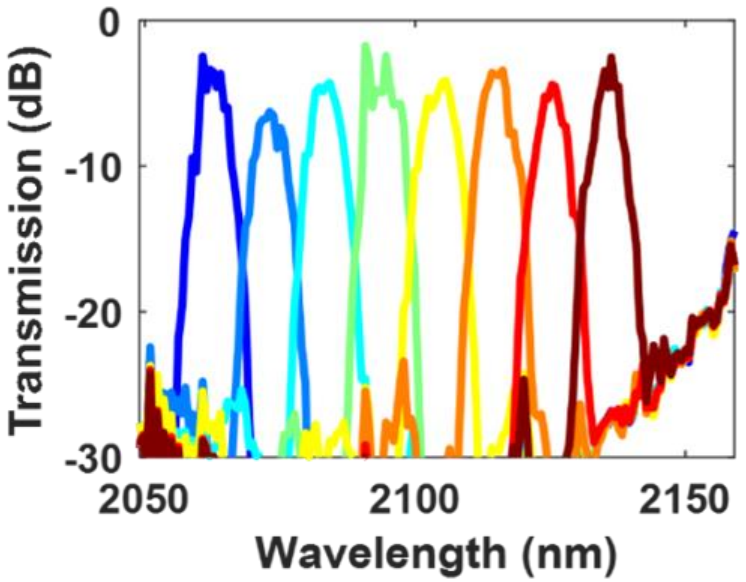
Dispersive optics + PD array

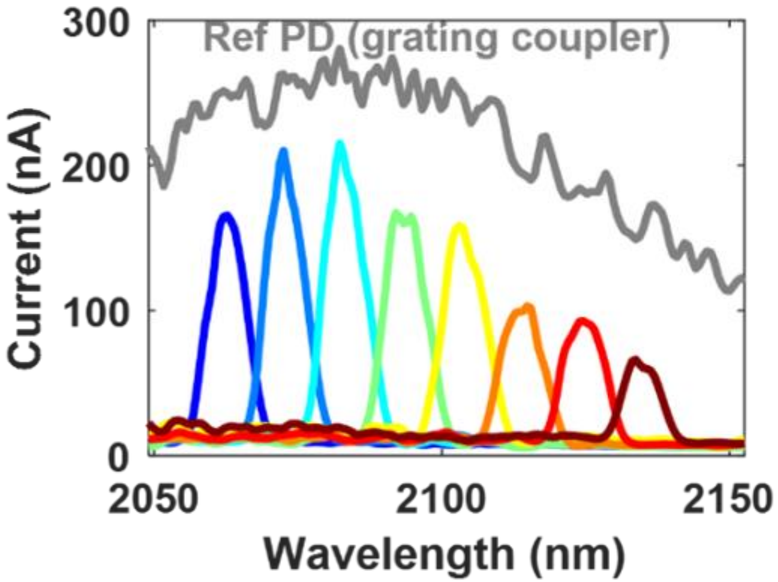


Planar Concave Grating

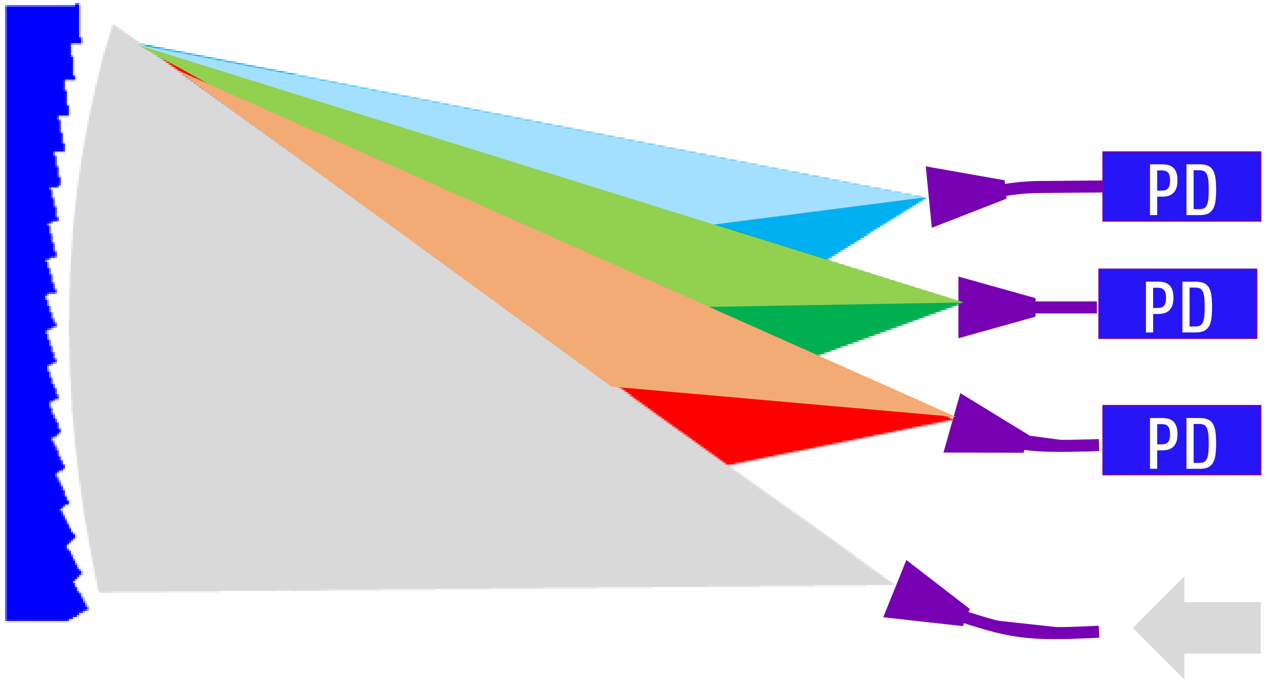
Compact spectrometer working around 2.1 µm



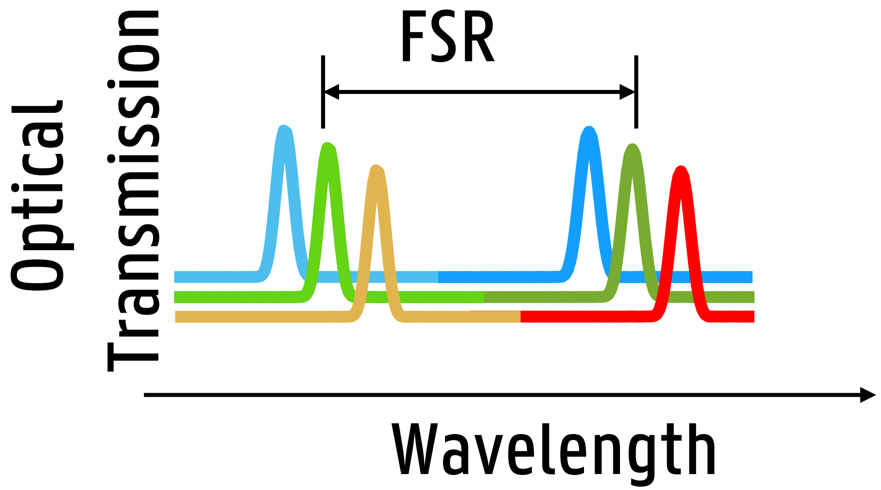




Limit of Classic On-chip Spectrometer

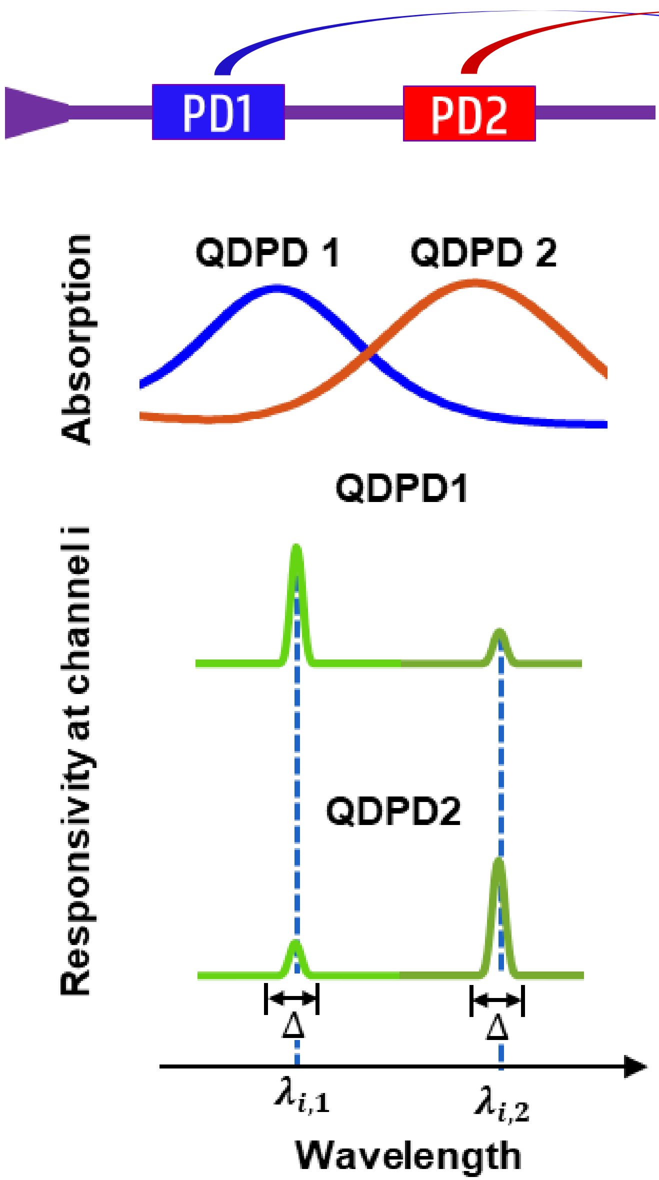


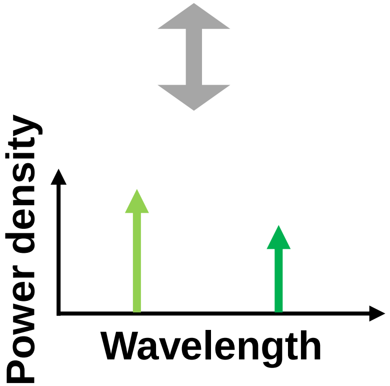
Many diffraction orders:



Sensing bandwidth
limit to a single FSR

How about Using Multi Photodetectors?





Sensing bandwidth Beyond single FSR!

$$\begin{bmatrix} I_{i,1} \\ I_{i,2} \end{bmatrix} = \begin{bmatrix} m_{i,11} & m_{i,12} \\ m_{i,21} & m_{i,22} \end{bmatrix} \begin{bmatrix} P_{in}(\lambda_{i,1}) \\ P_{in}(\lambda_{i,2}) \end{bmatrix}$$

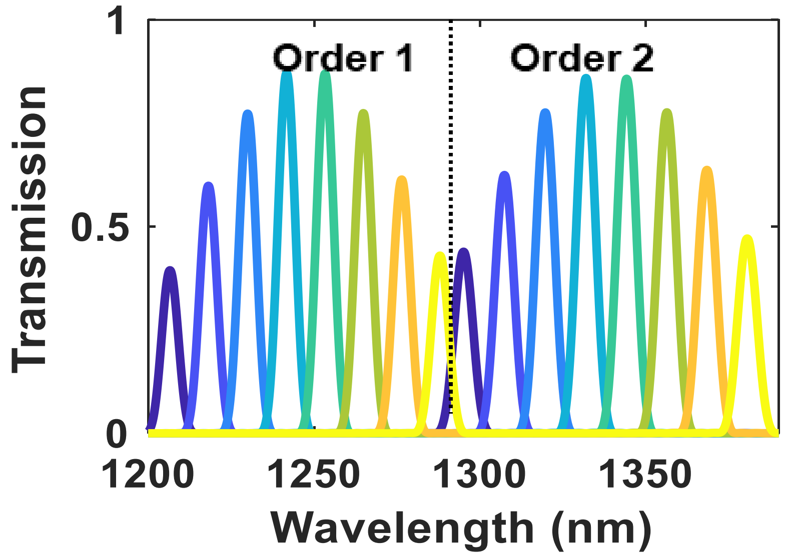
$$\mathbf{I}_i \quad = \quad \mathbf{M}_i \quad \mathbf{P}_i$$

$$m_{i,jk} = \int_{\lambda_{i,k}-\frac{\Delta}{2}}^{\lambda_{i,k}+\frac{\Delta}{2}} R_{i,j}(\lambda)d\lambda$$

For unknown input:

Reconstruct : $\mathbf{P}_i = \mathbf{M}_i^{-1}\,\mathbf{I}_i$

Spectrometer based on multi-color cascaded WG-QDPDs



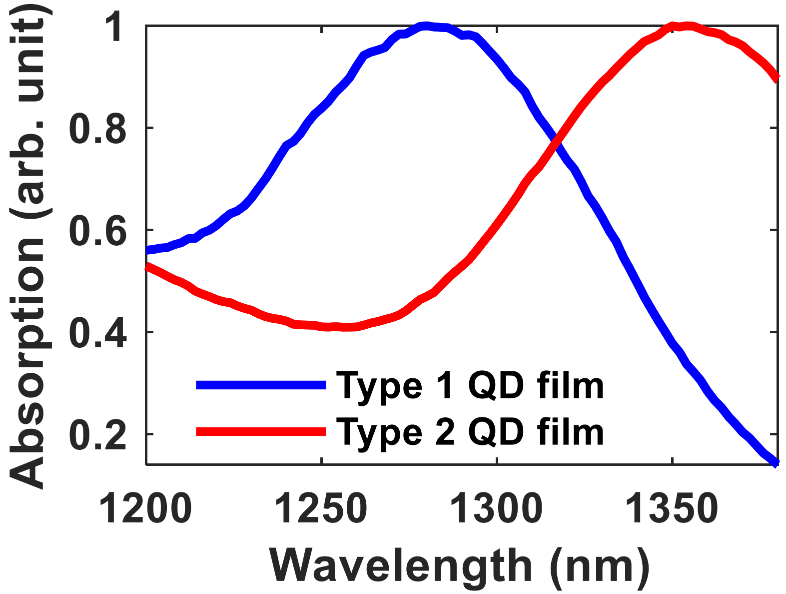
Transmission spectrum of planar concave grating

1200 nm to 1380 nm

FSR 90nm =

Number of channels (8) ×

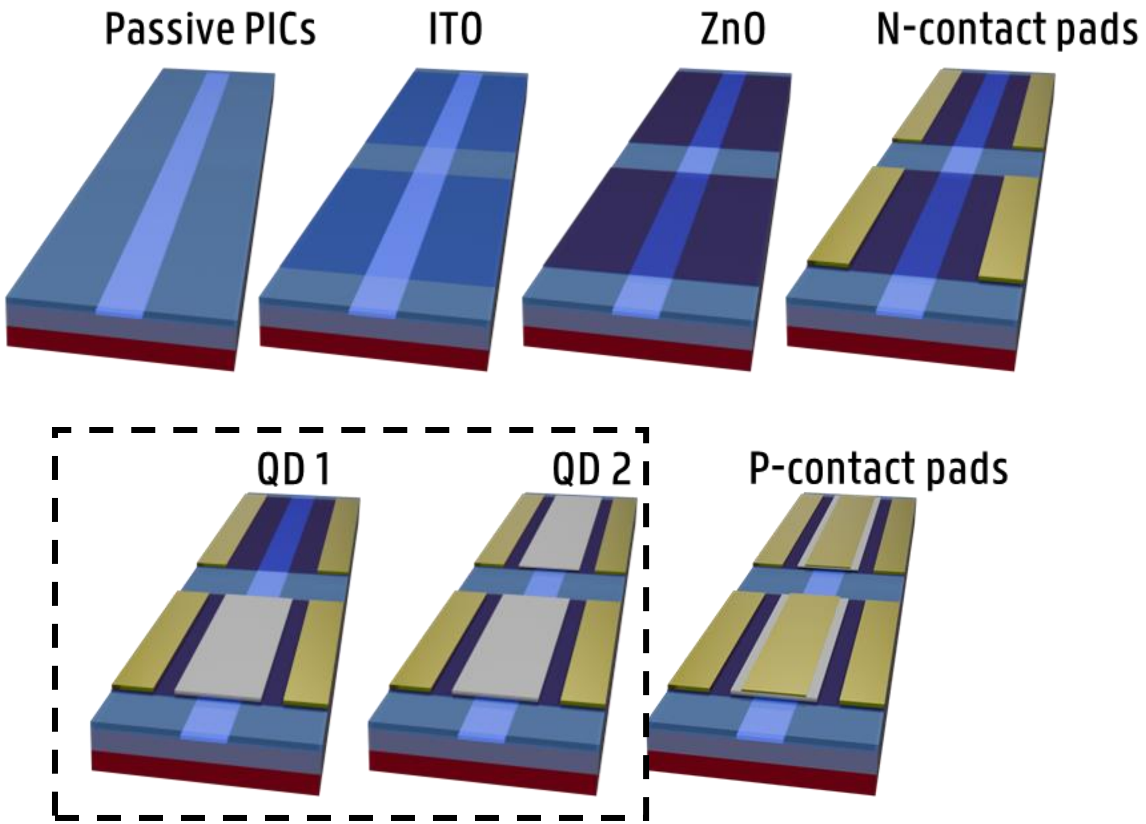
channel spacing (11.25 nm)

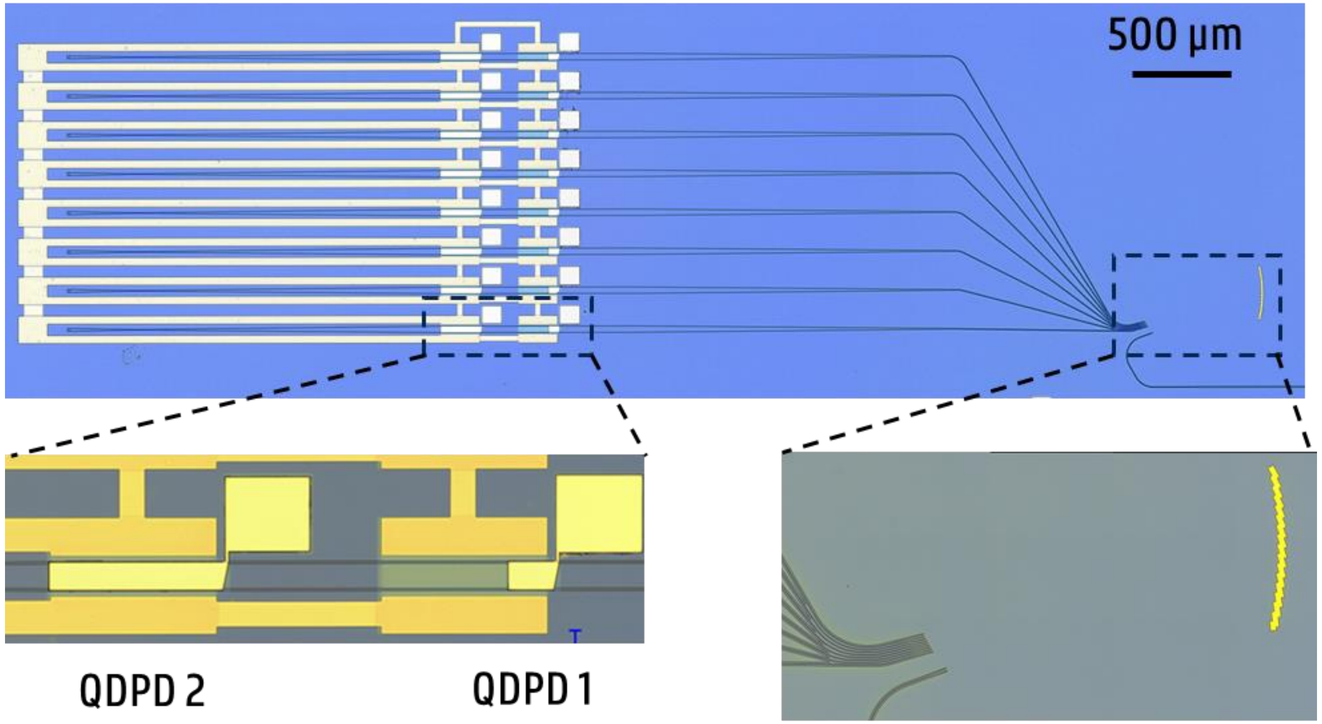


Absorption spectra of QDPD

Distinct responses to different orders

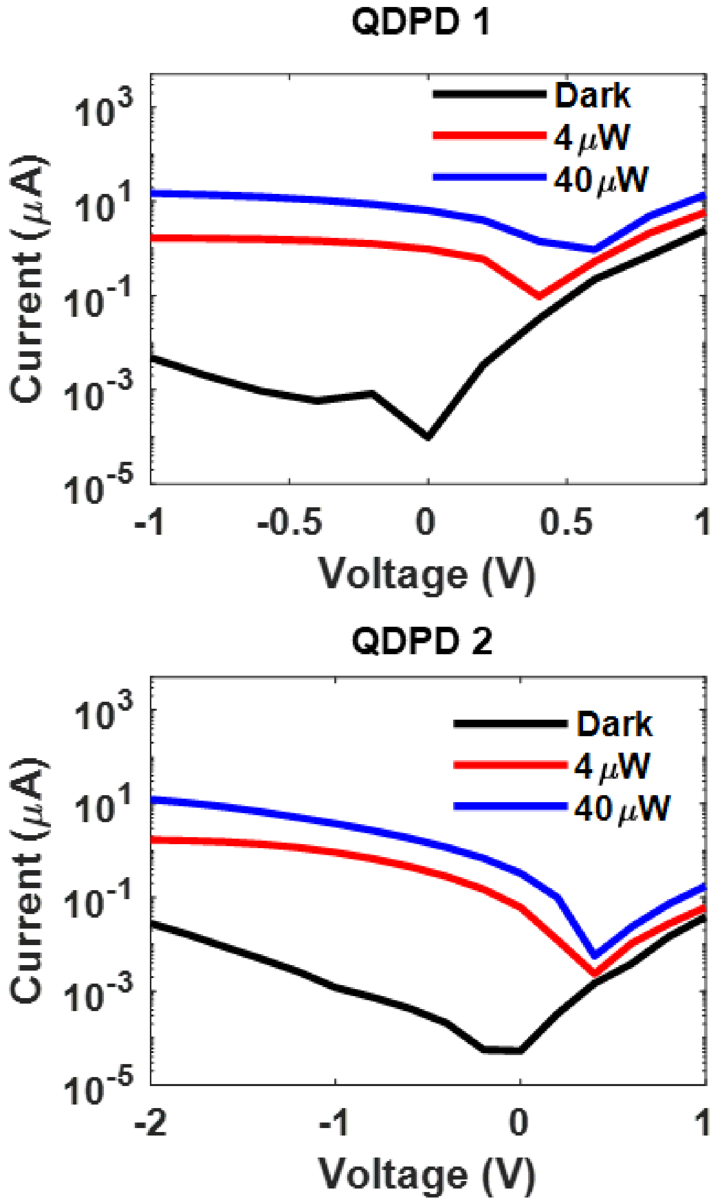
Spectrometer based on multi-color cascaded WG-QDPDs



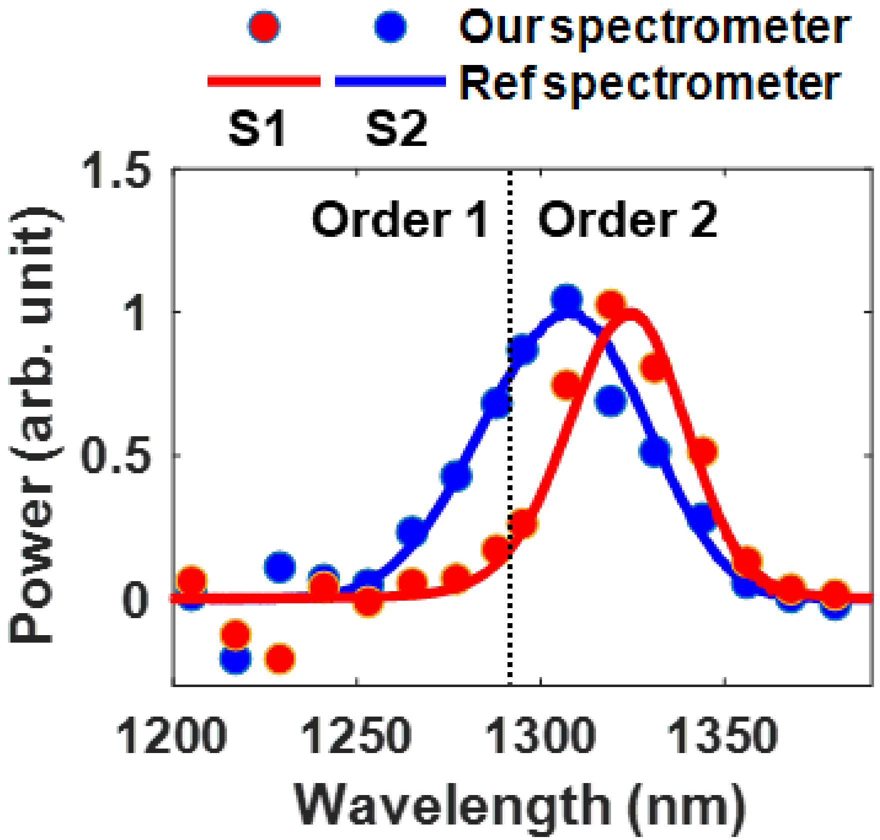


Planar concave grating
Metal-covered facets for large optical bandwidth

Spectrometer based on multi-color cascaded WG-QDPDs

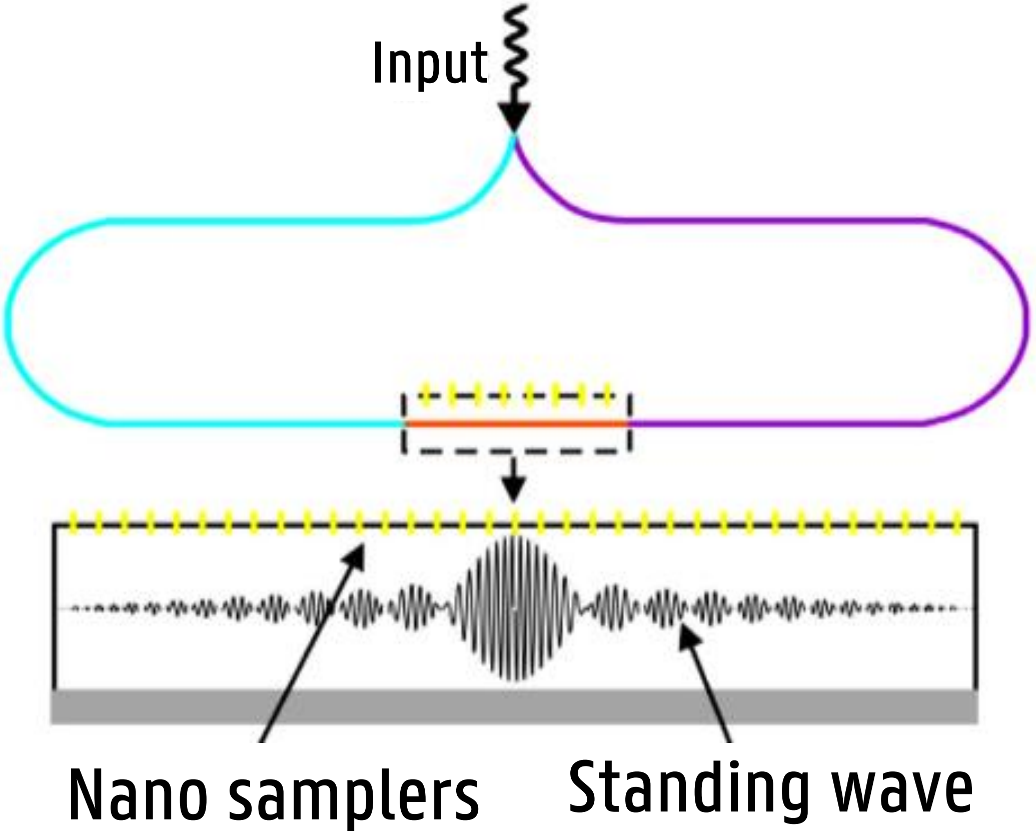


> 0.4A/W @ 10μW

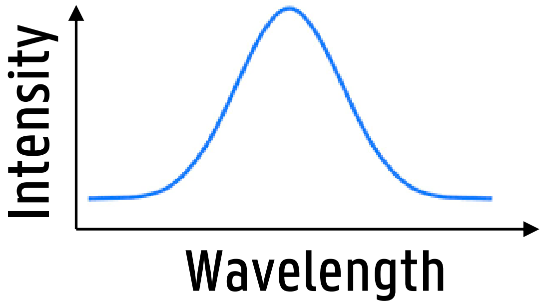


Sensing bandwidth
beyond single FSR

Stationary-wave Integrated Fourier Transform Spectrometer

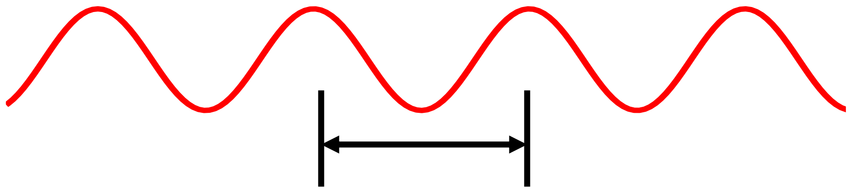


Fourier transform



L. Zhang, et al. Laser & Photonics Reviews, 2021.

SiN, wavelength 1.3 µm



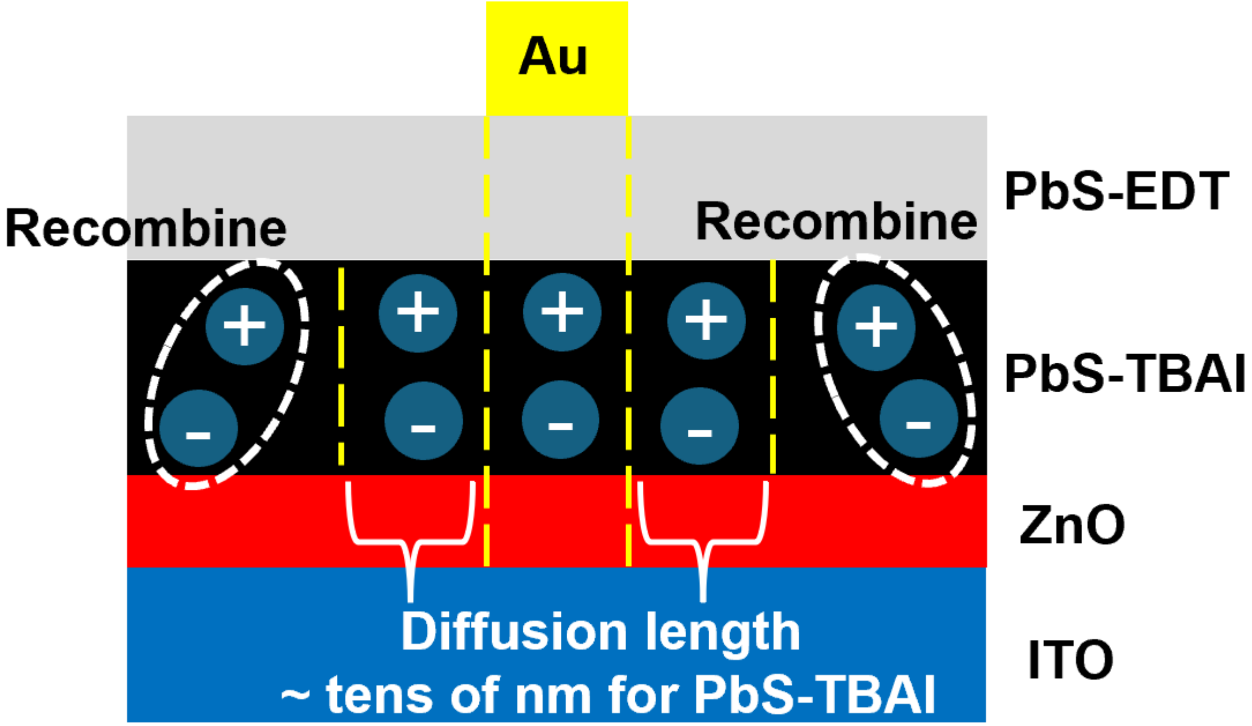
$$\frac{\lambda}{2n_{eff}} \approx 380 \text{ nm}$$

Nano-samplers challenging

Current approach:

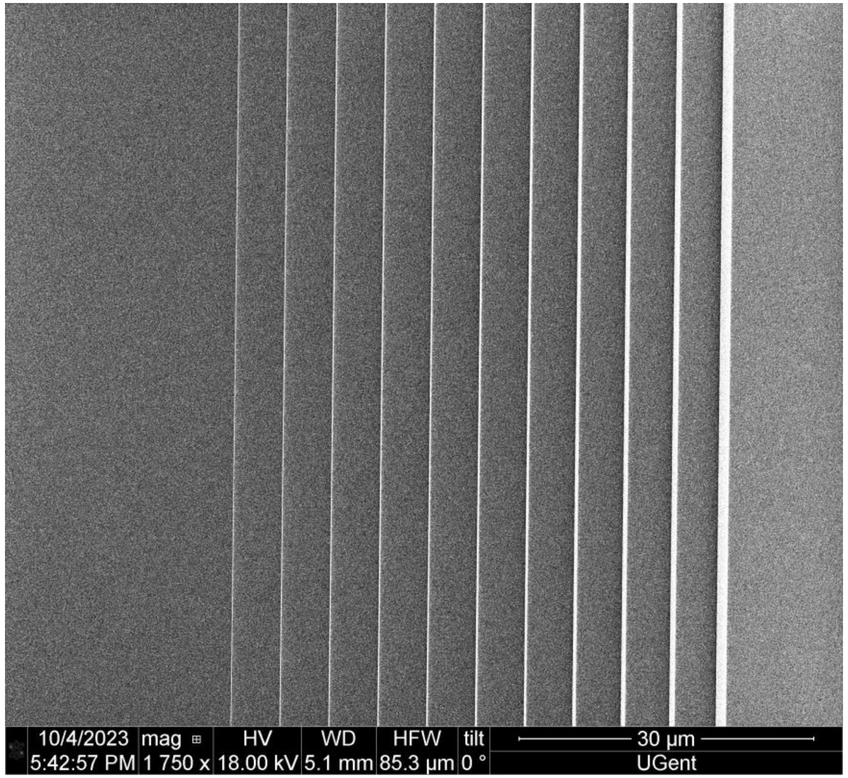
Nano scatters + camera

QDPD as Nano Samplers

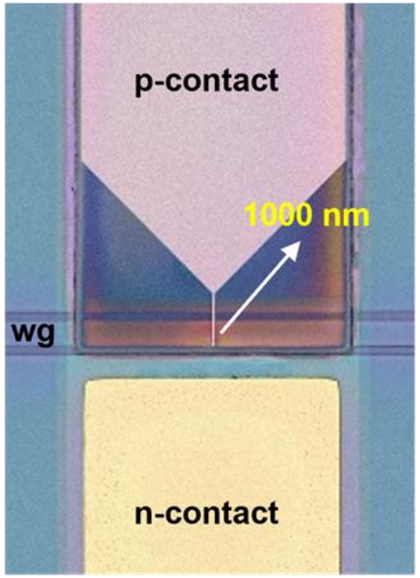


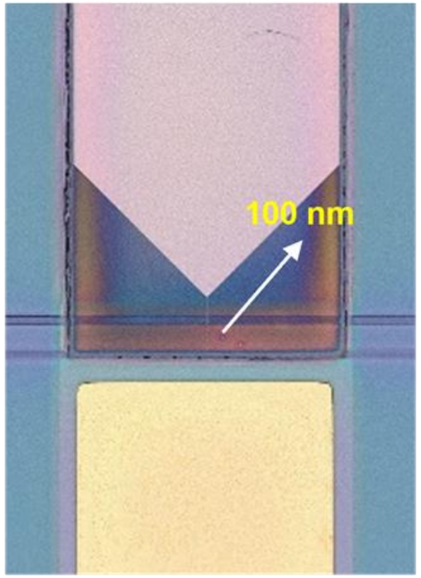
Small diffusion length
→ potential as nano detectors

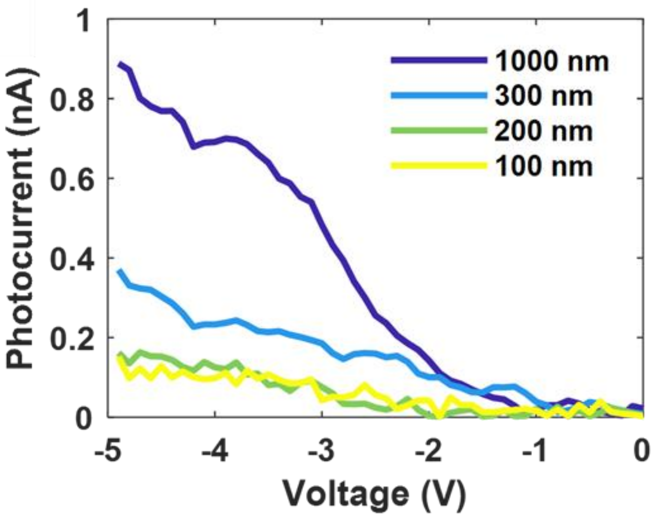
E-beam lithography + Liftoff
20 nm → 1 μm

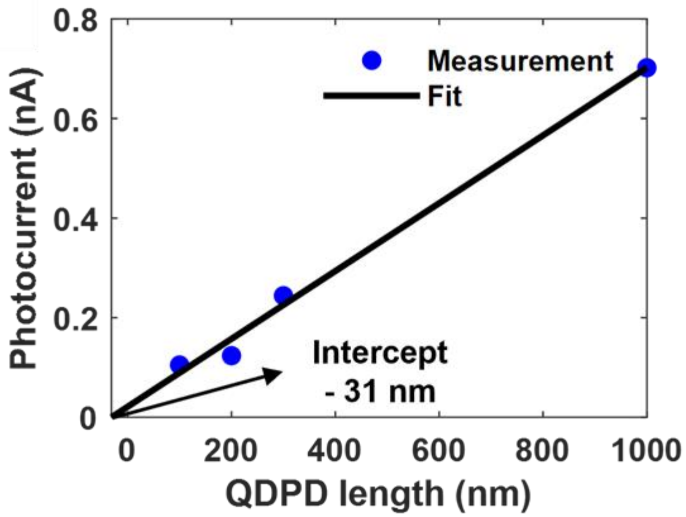


Performance of Nano QDPDs





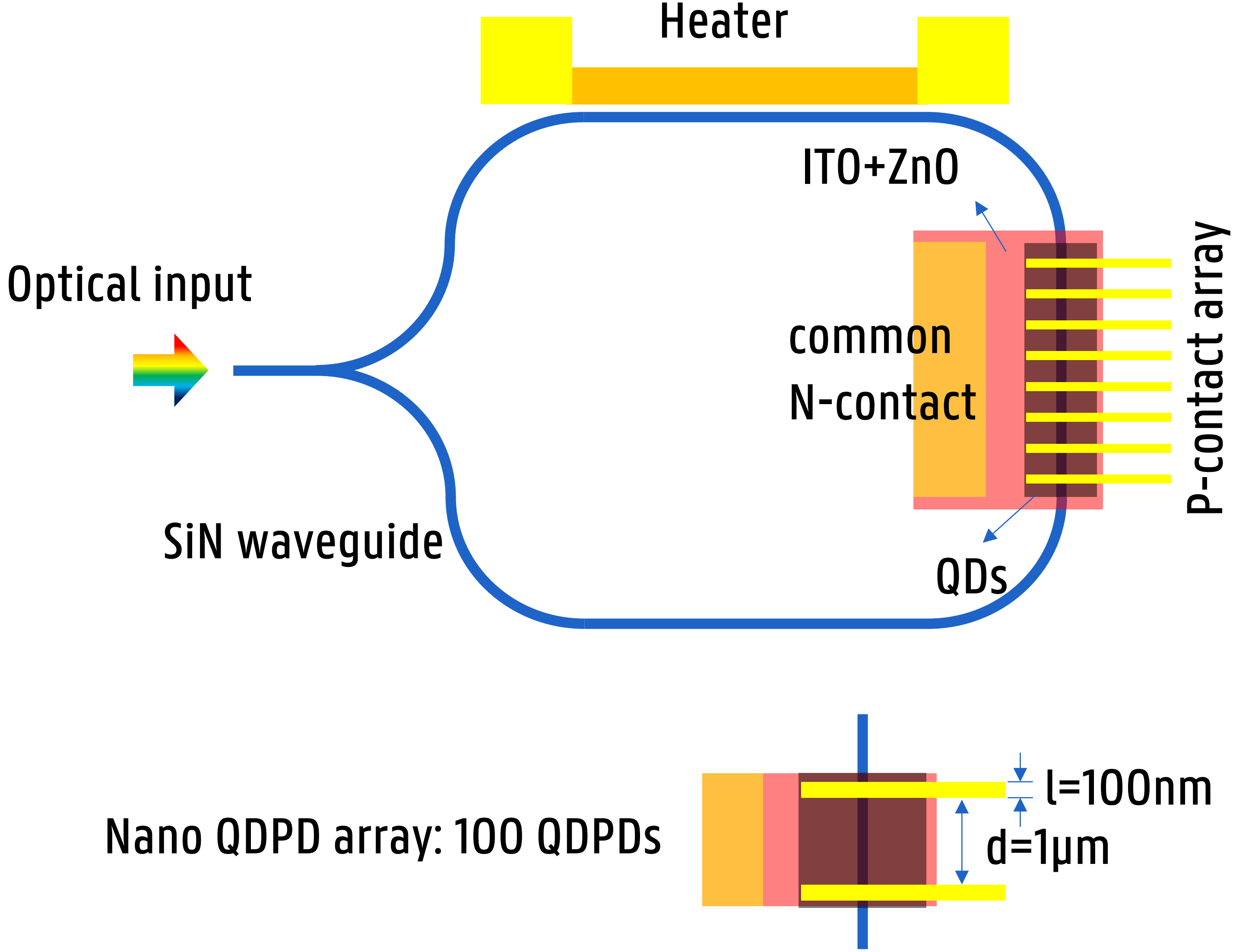




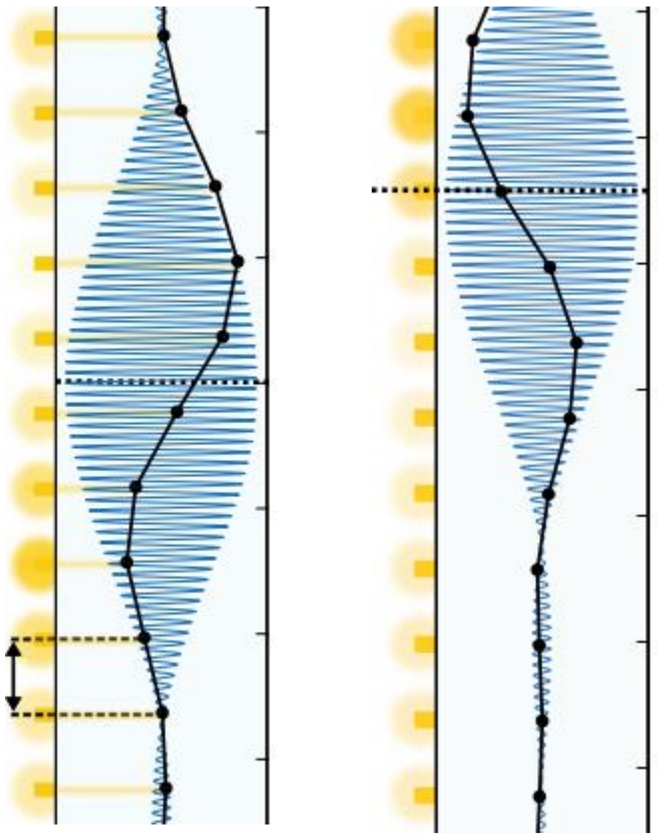
QDPD effective length
= p contact length + 31 nm

Feasible as nano-detector

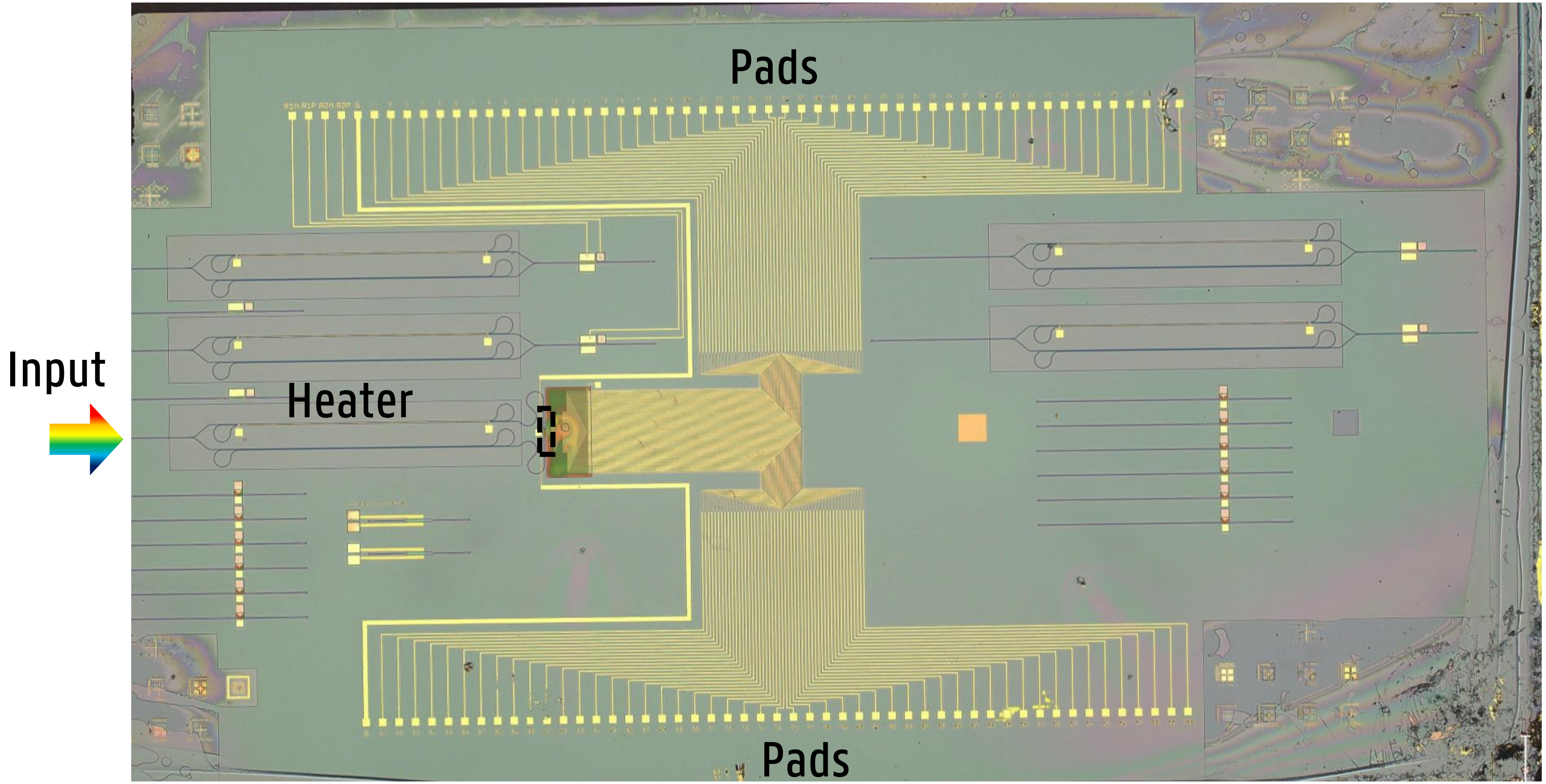
Stationary-wave Integrated Fourier Transform Spectrometer



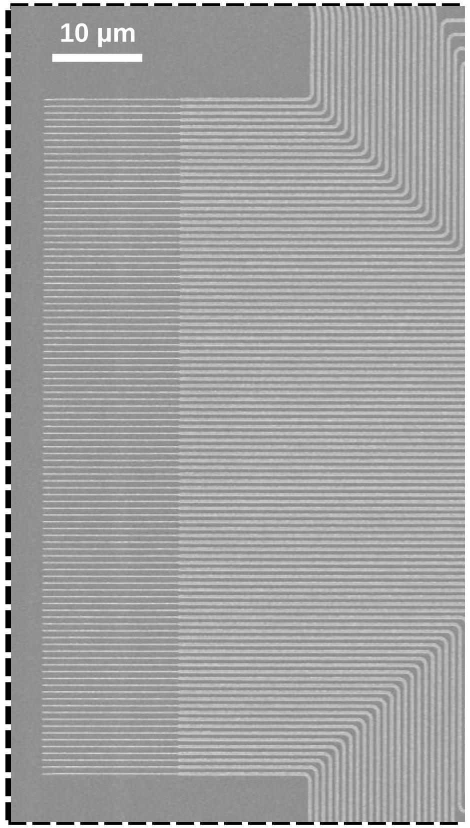
Heater ON



To Be Demonstrated



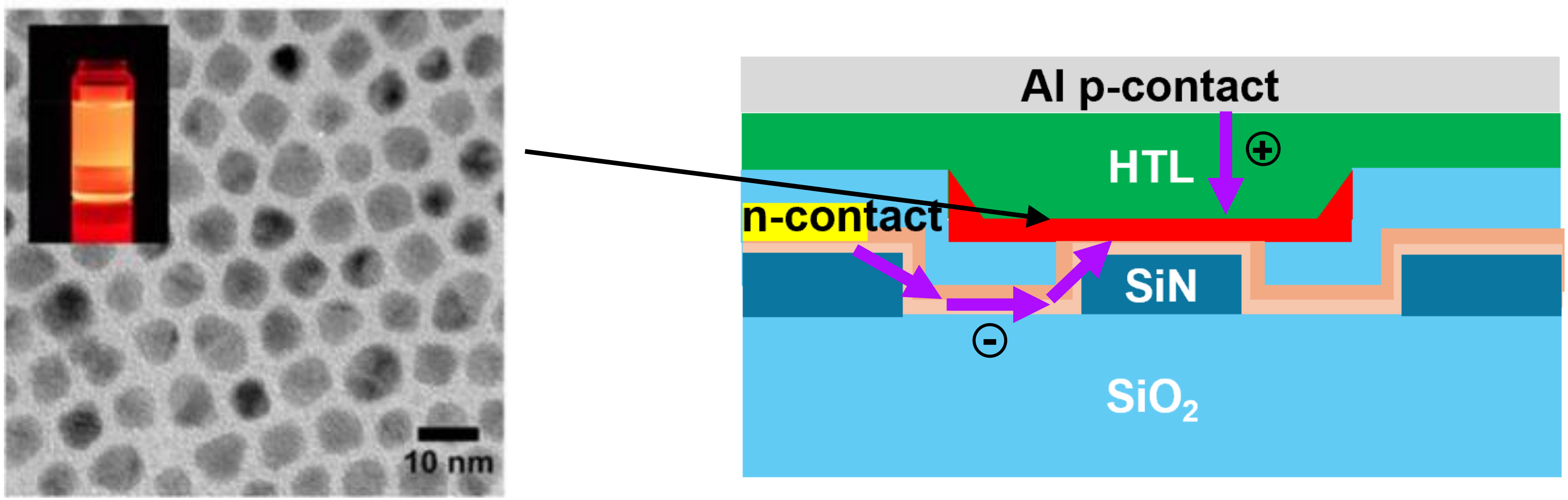
Nano QDPD array



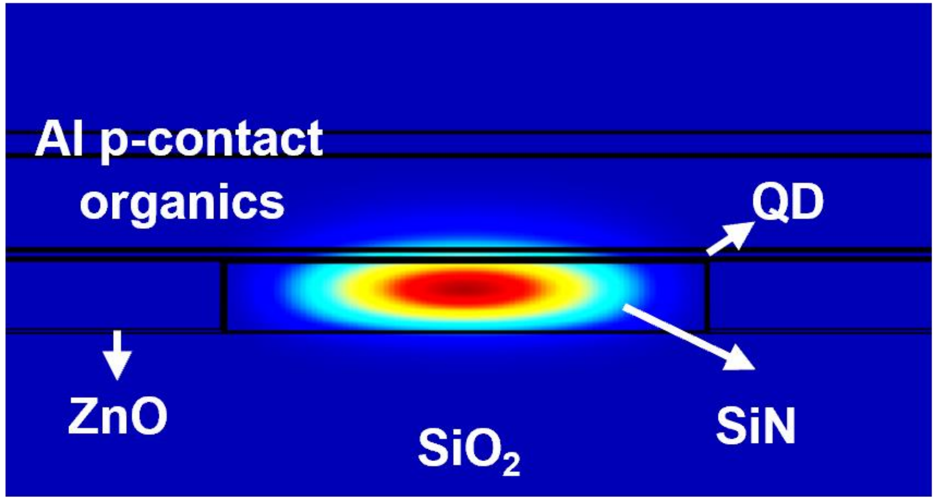
How about Light Emission on Chip?

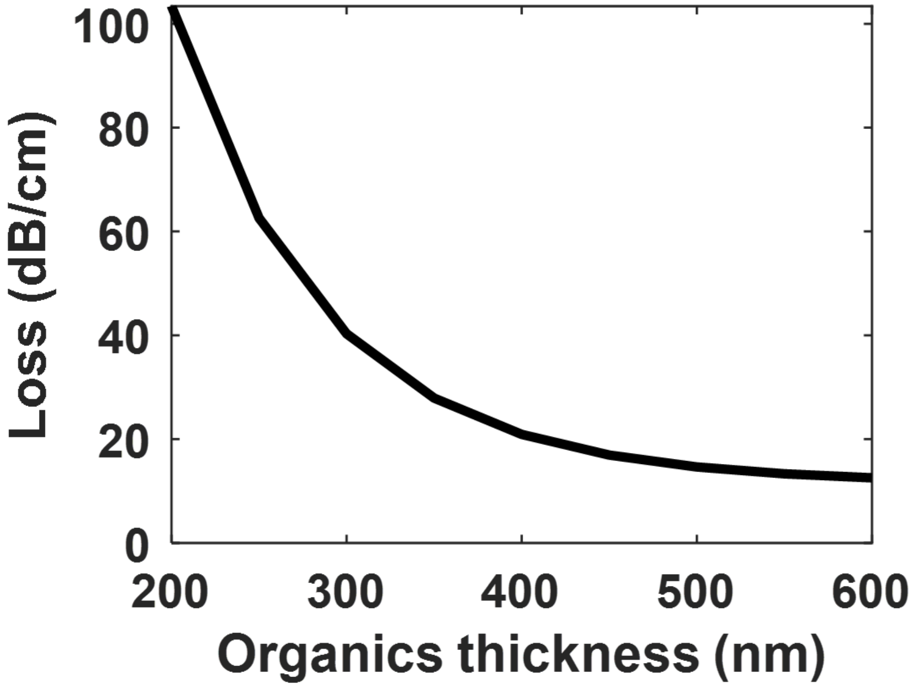
Integrated Electrically Driven QD Light Sources

CdSe/CdS core/shell QDs, emission 640 nm



Challenges to Achieve Gain

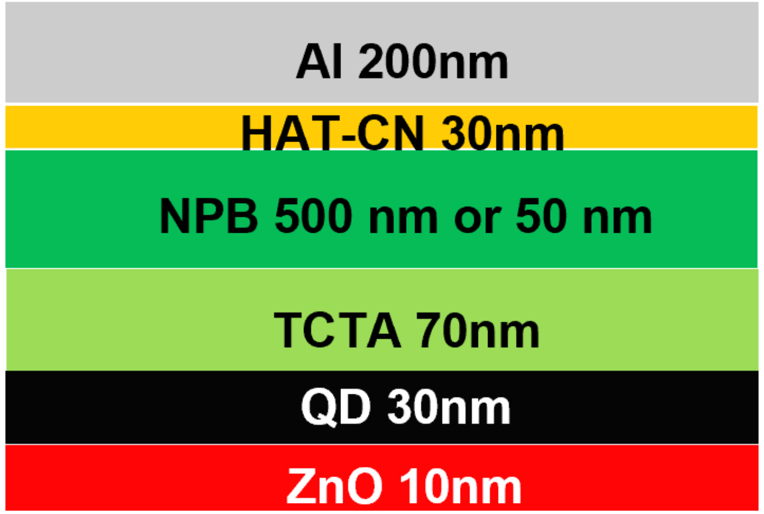


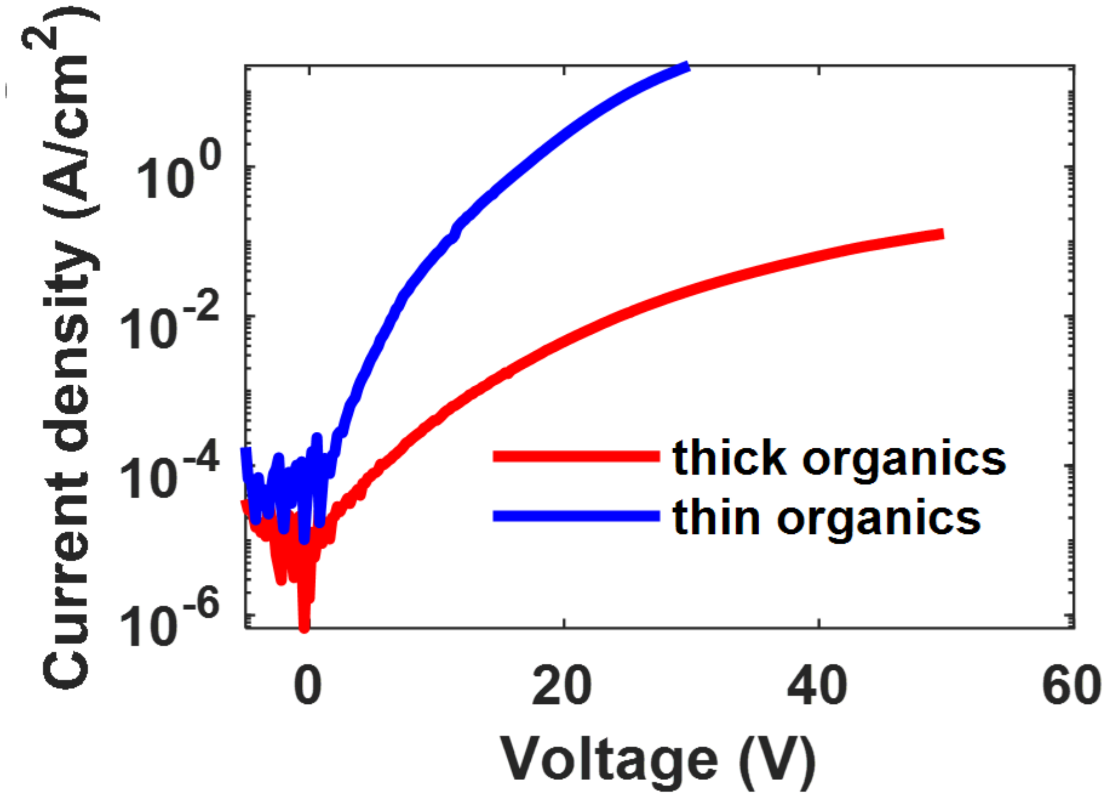


Low confinement factor in QD layer 4%
Low achievable modal gain 20cm^{-1} (87dB/cm)
Low optical loss for net gain

Thick HTL to reduce
p-contact absorption

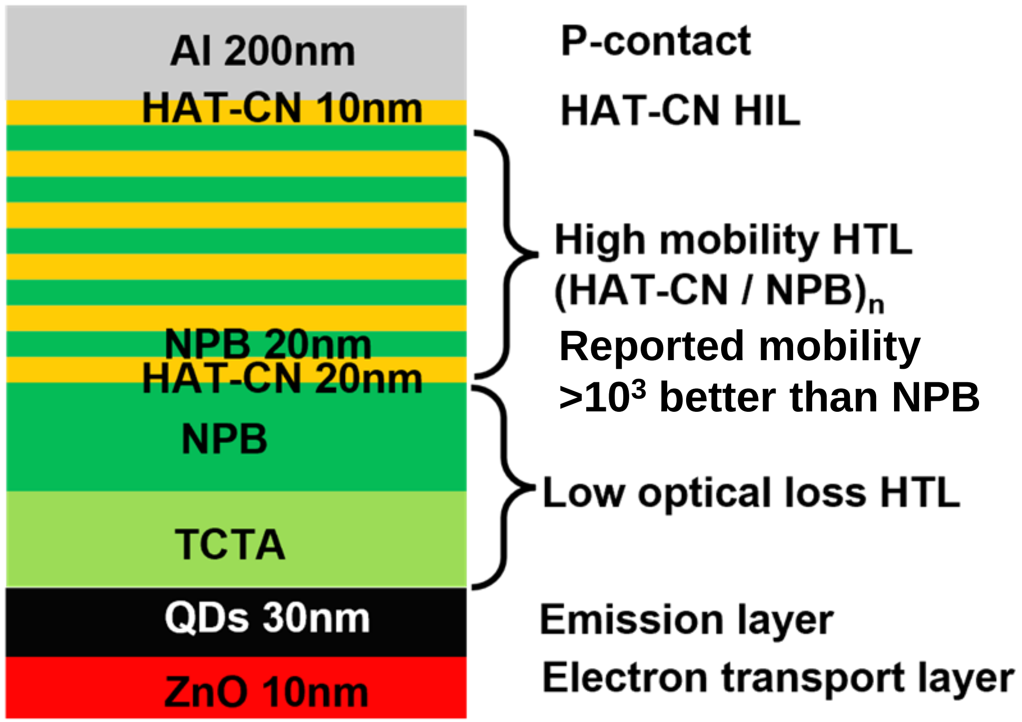
Challenges to Achieve Gain

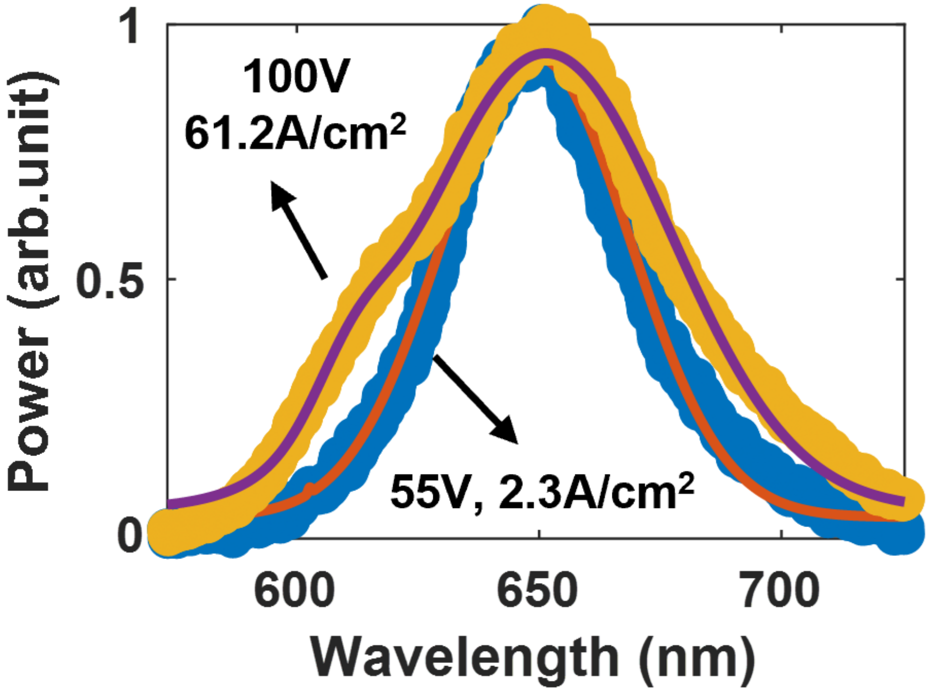




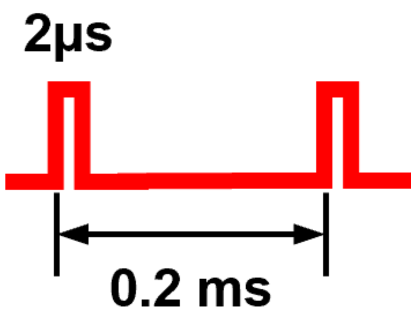
Thick HTL → Difficult hole injection

Where are we now?





Pulsed electrical pump



High state emission

No optical gain or ASE

Conclusion

Building blocks:

- Demonstrated 1.3 μm waveguide-coupled QDPD on SiN
- Demonstrated 2.1 μm waveguide-coupled QDPD on SOI
- Explored integration of electrically driven QD-based light sources on SiN waveguides
  more effort to balance hole injection and optical loss

Applications:

- Demonstrated classic spectrometer, planar concave grating + QDPD array
- Demonstrated novel spectrometer using two-color cascaded WG-QDPDs, decoupling spectral bandwidth and FSR
- Proposed integrated Fourier transform spectrometer using a QDPD array as nano-sampler
  effective length of nano QDPD ≈ p-contact length

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Thanks for your attention!