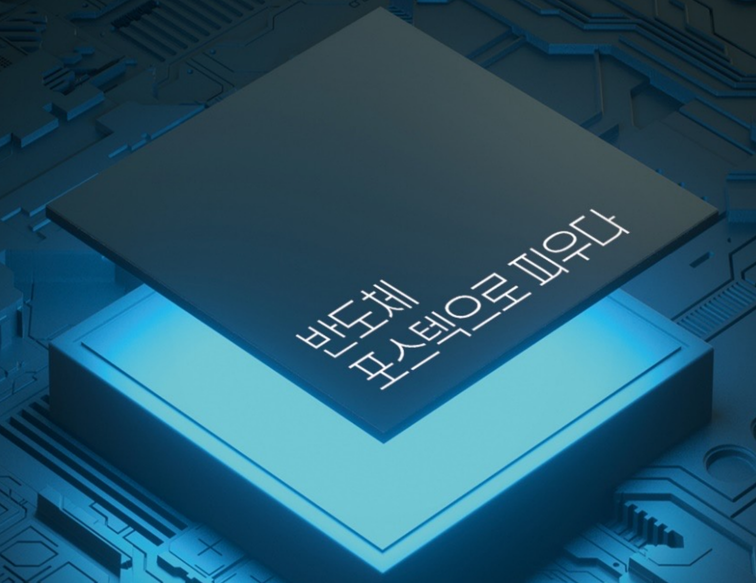
Image sensing technologies, challenges and vision



Prof Jiwon Lee

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POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY

반도체공학과
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Image Sensor

- Semiconductor device converting light to digital signal

https://news.samsung.com/

Photons

↓ Optics/device design

Electrons

↓ Device/analog design

Voltage Signal

↓ Mixed signal design

Digital number

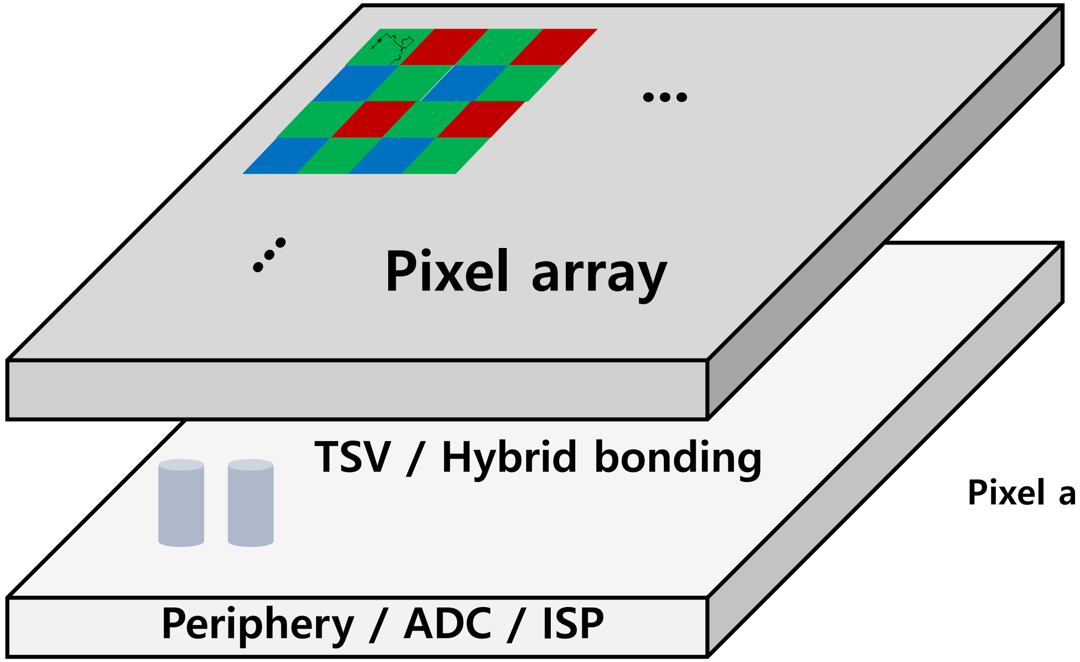
In millions parallel manner

Image Sensor and Pixel

Pixel: Picture element ➔ *Technology aware design*

Apple iPhone 13 Pro

- State of the art CIS for consumer application
: Back-side illumination, Stacked (TSV, hybrid-bonding)



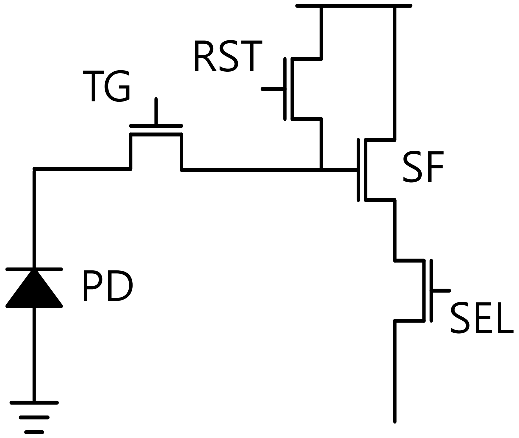
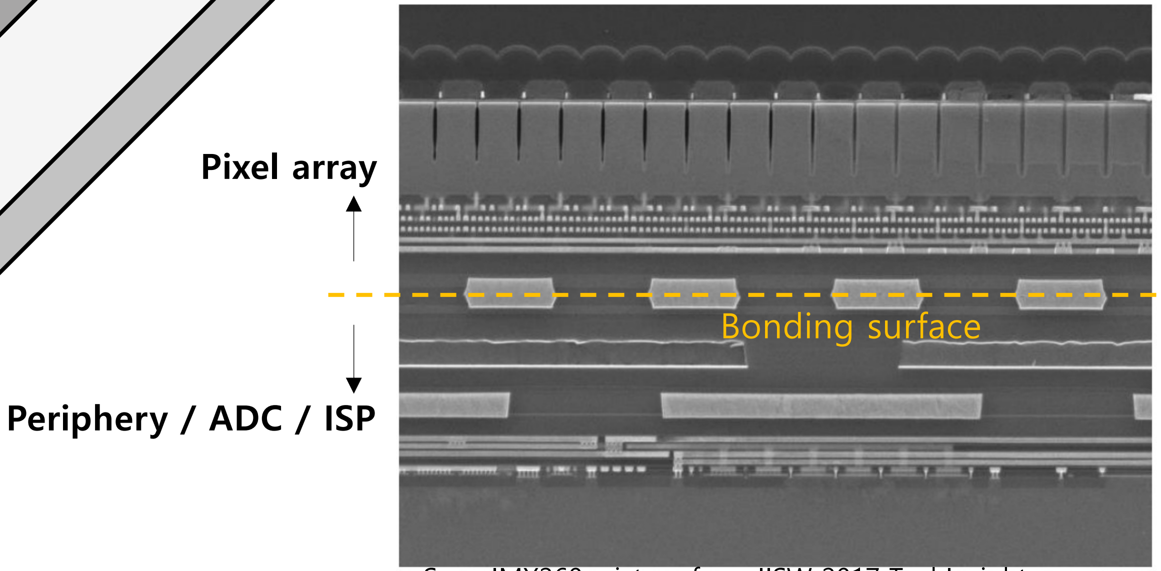


Image sensor pixel
1PD and 3-transistors
Transistors can be shared (2, 4, 8-shared)



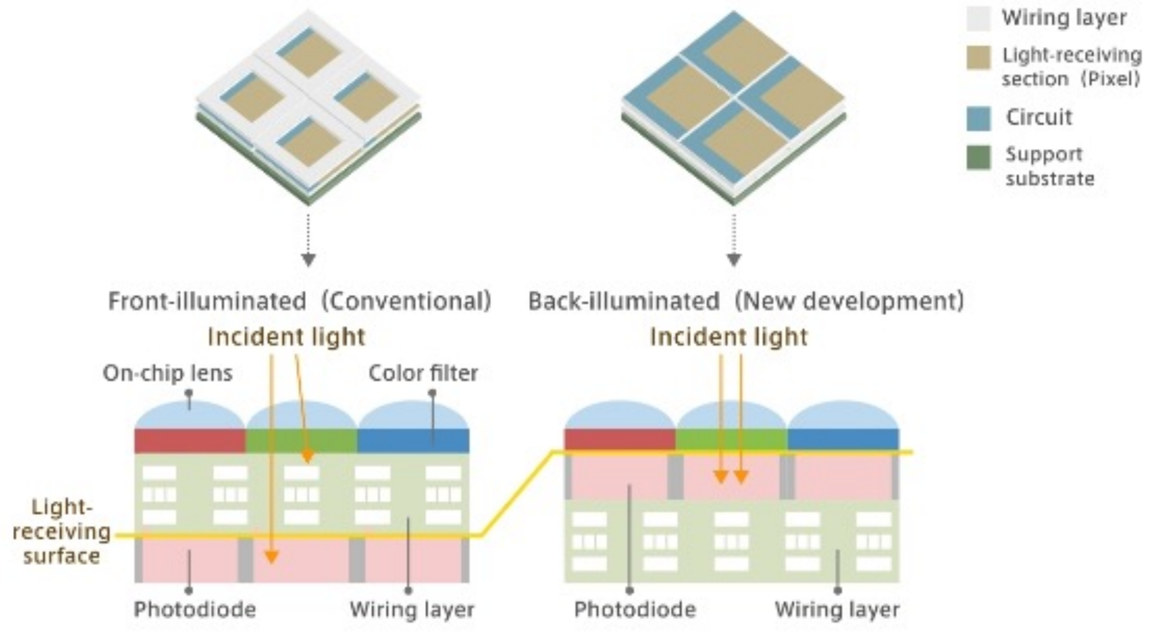
Sony IMX260, picture from IISW 2017 TechInsights

3D integration in CMOS Image sensor

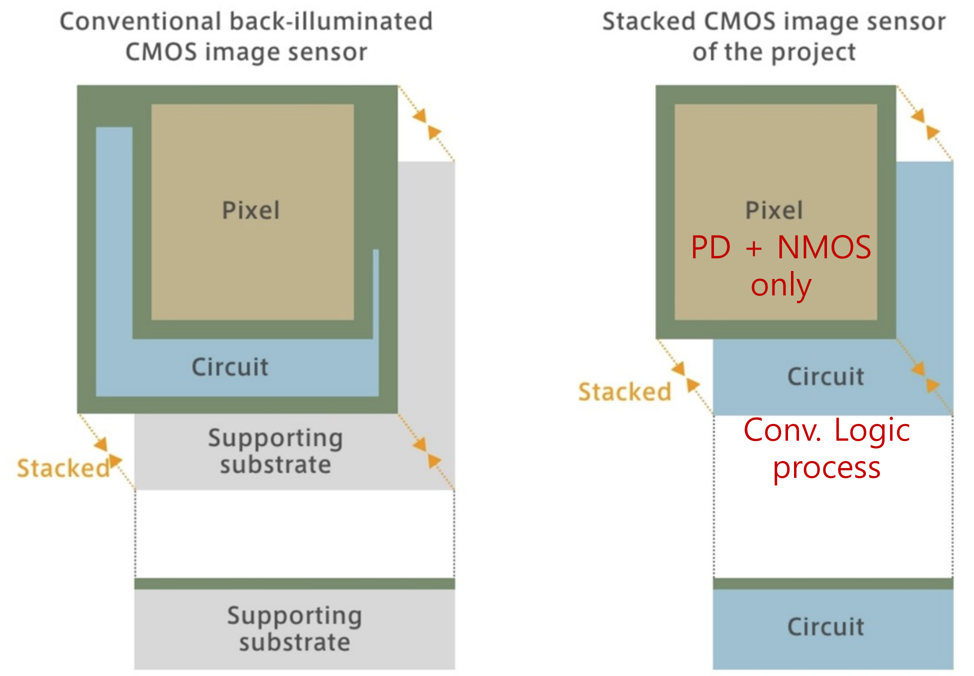
- 10-years since first commercialization

- Back side illumination for efficient photon collection

Front side illumination　　Back side illumination



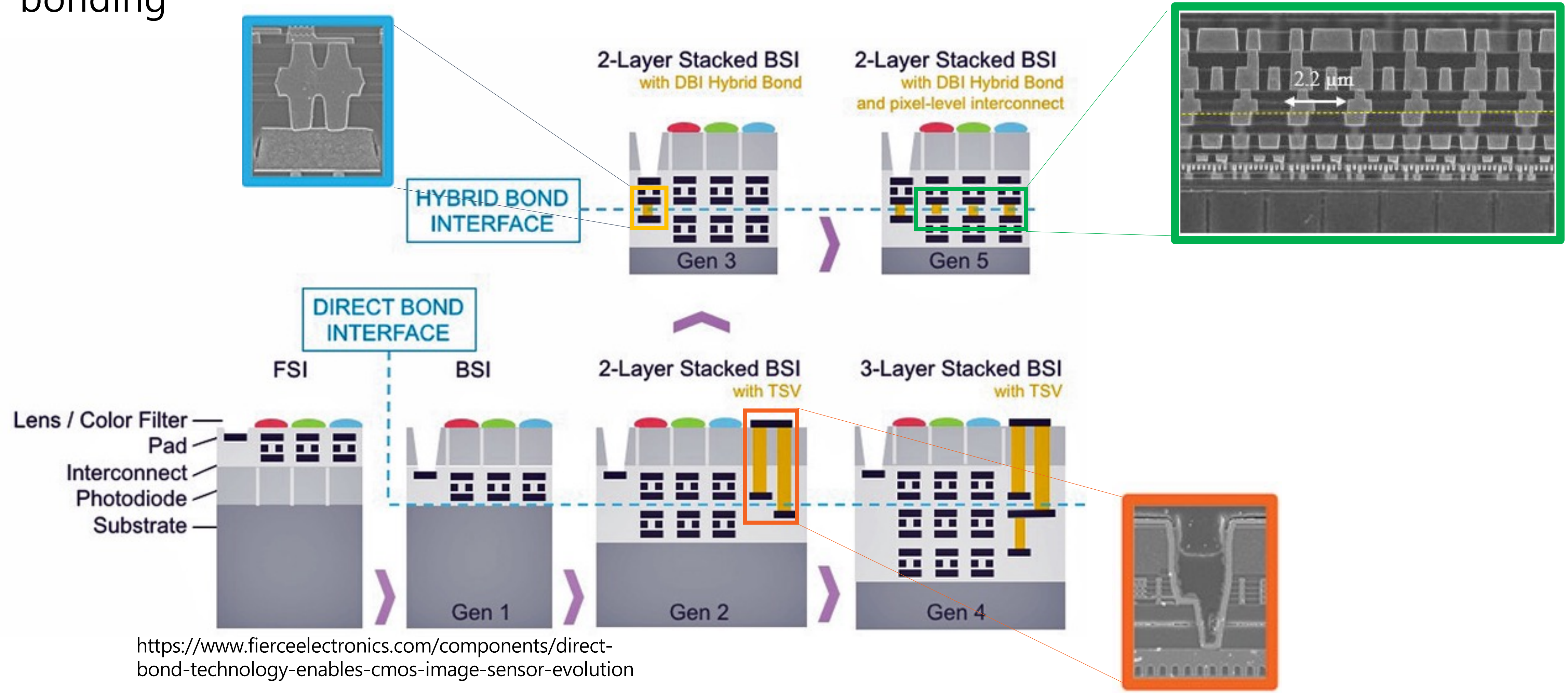
- Chip stacking for separate optimization
  - Pixel (Photodiode) vs. Readout circuit (tr)



*From Sony

Stacking technology

Chip stacking after processed then connected by **TSV** (Through Silicon Via) vs. **Cu-Cu Hybrid** bonding



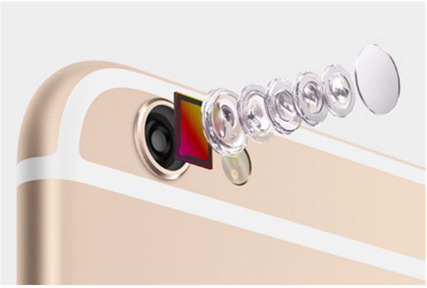
https://www.fierceelectronics.com/components/direct-bond-technology-enables-cmos-image-sensor-evolution

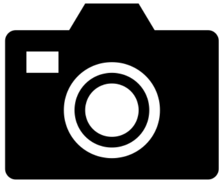
Paradigm shift in image sensing

- Heart of the camera

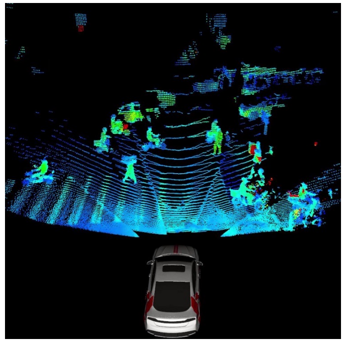
Photography

- Compact / DSLR / smartphone cameras



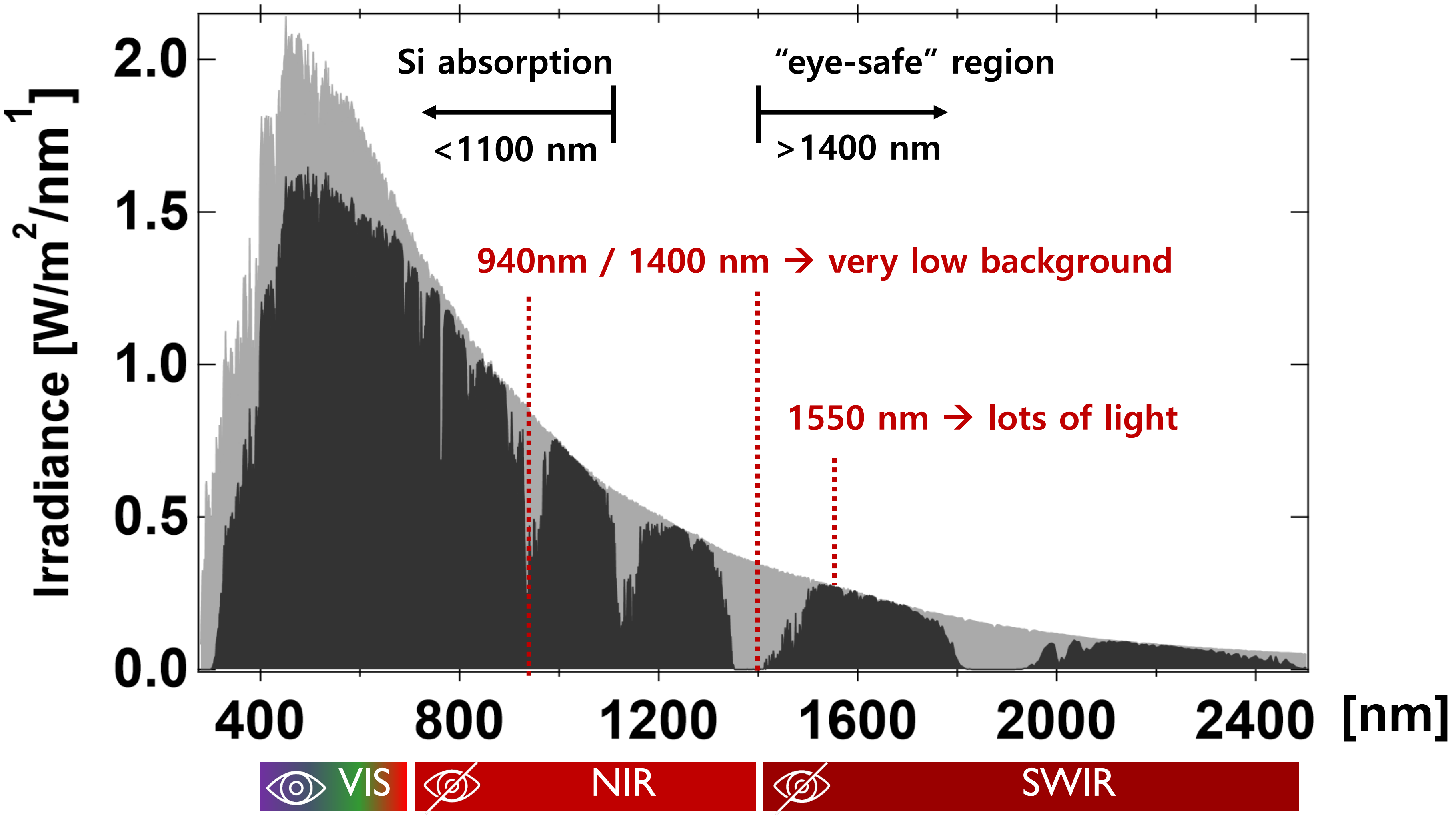



Face ID



from **picture taking**... ...to **information acquisition**

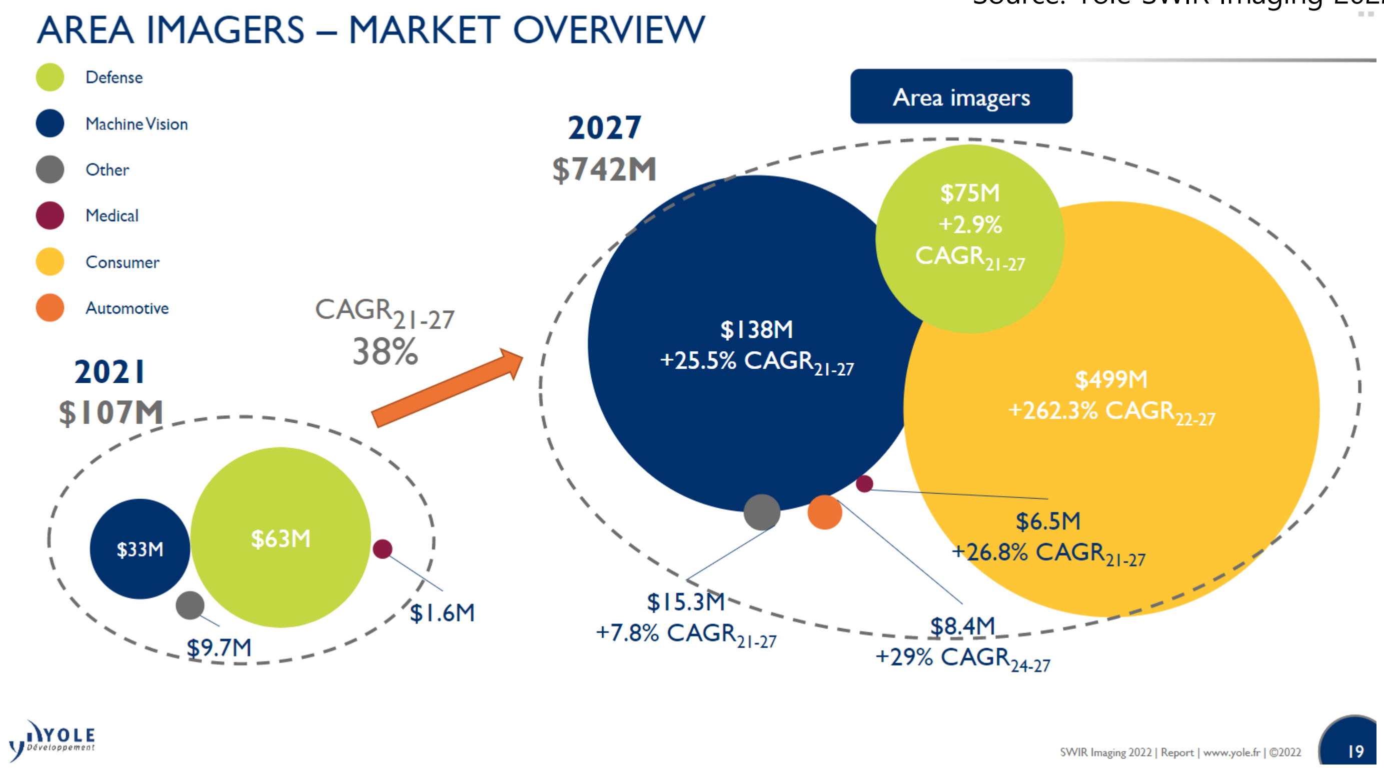
Infrared: NIR / SWIR

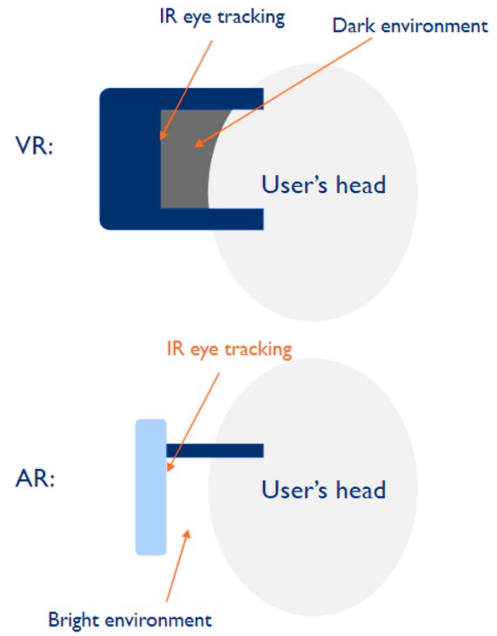


SWIR Market Opportunity

- Emerging SWIR Market
  - Machine Vision / Consumer

*Source: Yole SWIR Imaging 2022





From Yole, 'SWIR report' 2022

Iphone 14 Pro

Airpod3 & Pro

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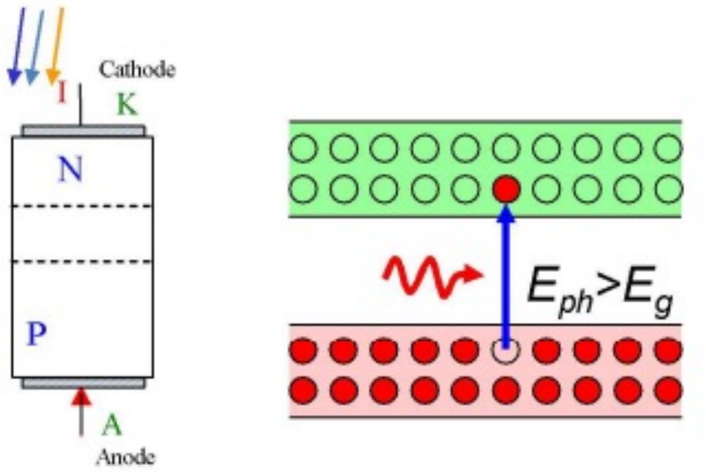
PIXEL LAB

How to address imaging from UV to LWIR

- Use either Photodetector (mostly photodiode) or Thermal detector
  - Use a semiconductor material to convert incident photons to electrical charges

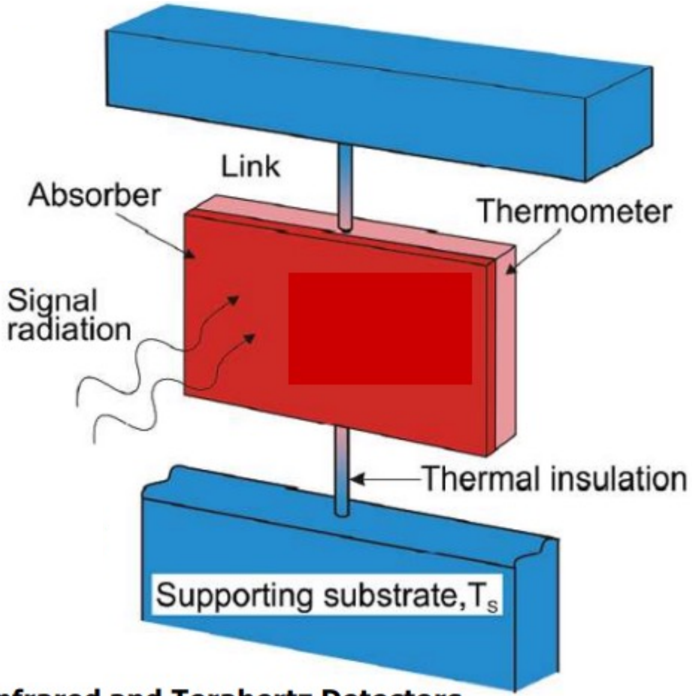
$$\frac{hC}{\lambda} > E_g \Rightarrow \frac{1.24}{E_g} = \lambda_c \text{ Cut-off wavelength}$$

  - Silicon (Eg =1.12eV), λ_c μm, Near Infrared (NIR)



Photodetector

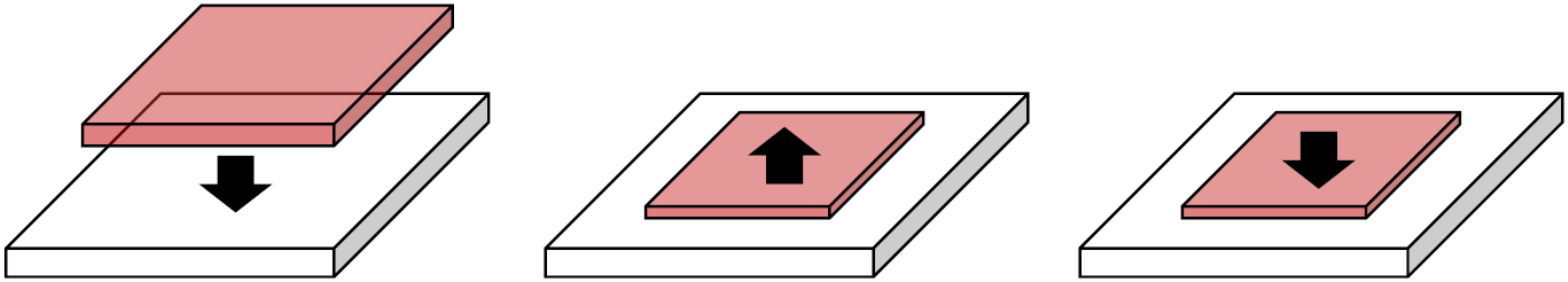
Thermal detector



Infrared and Terahertz Detectors, A. Rogalski, CRC Press (2019)

How to extend wavelength

Choose the (non-Si) absorber and get it on the readout

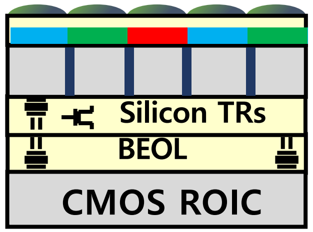


bond	**grow**	**deposit**
↓	↓	↓
InGaAs HgCdTe ...	Ge / SiGe InGaAs ...	quantum dot (QD) organic (OPD) perovskite (PePD) ...

QD (Quantum Dot) image sensor

Si CIS
visible

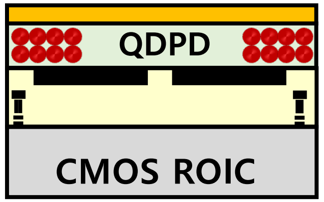
- ✓ high maturity
- ✓ high throughput / monolithic
  - >6B units/year!
- ✓ low cost
  - single $ per camera
- x no SWIR EQE
  - Si transparent above 1 µm
- ✓ small pixel pitch / high resolution
  - SotA CIS 0.56 µm



SotA CIS x5 pixels

QD TFPD
visible – NIR – SWIR - eSWIR

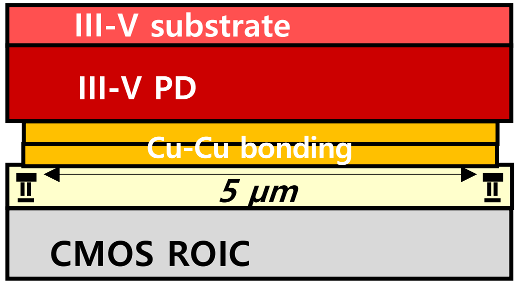
- » maturing technology
- ✓ high throughput / monolithic
  - wafer-level process in preparation
- » low cost
  - target: 10$ – 100$
- ✓ good SWIR EQE
  - spectrum tunable per application
- ✓ small pixel pitch / high resolution
  - imec SotA ≤ 2 µm



SotA QD x2 pixels

InGaAs, HgCdTe
short-wave infrared

- ✓ high maturity
- x low throughput / hybrid
  - ~10K units/year
- x high cost
  - several K$ per camera
- ✓ high SWIR EQE
- x large pixel pitch / low resolution
  - SotA InGaAs ≥ 5 µm

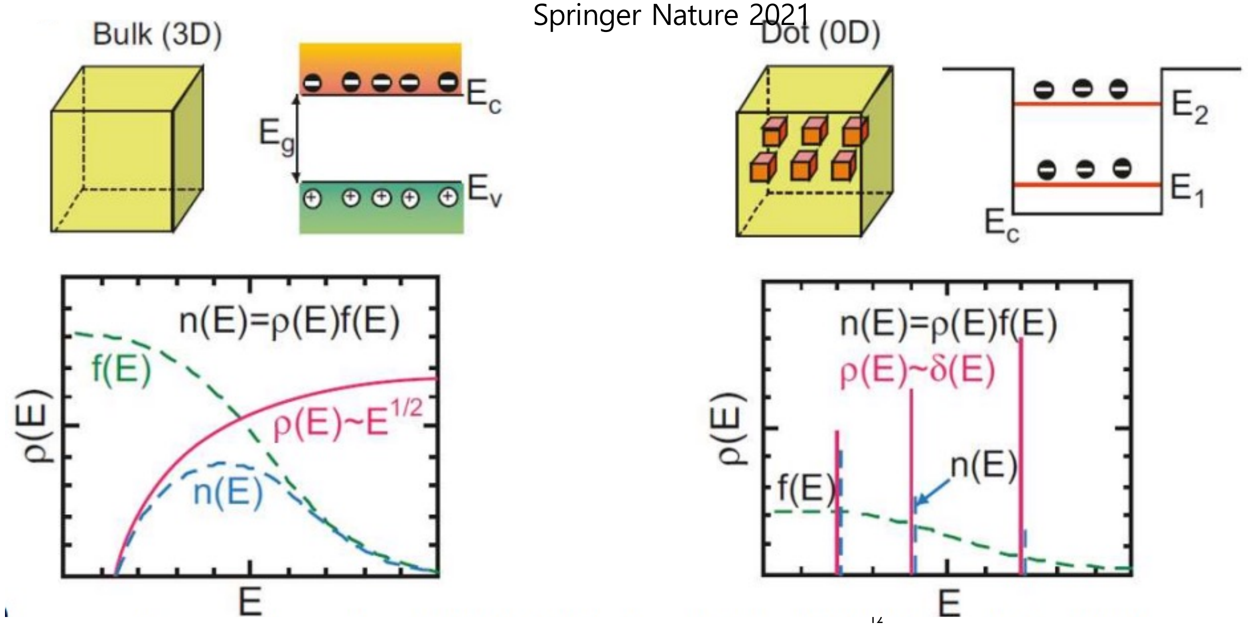


SotA InGaAs (Sony)

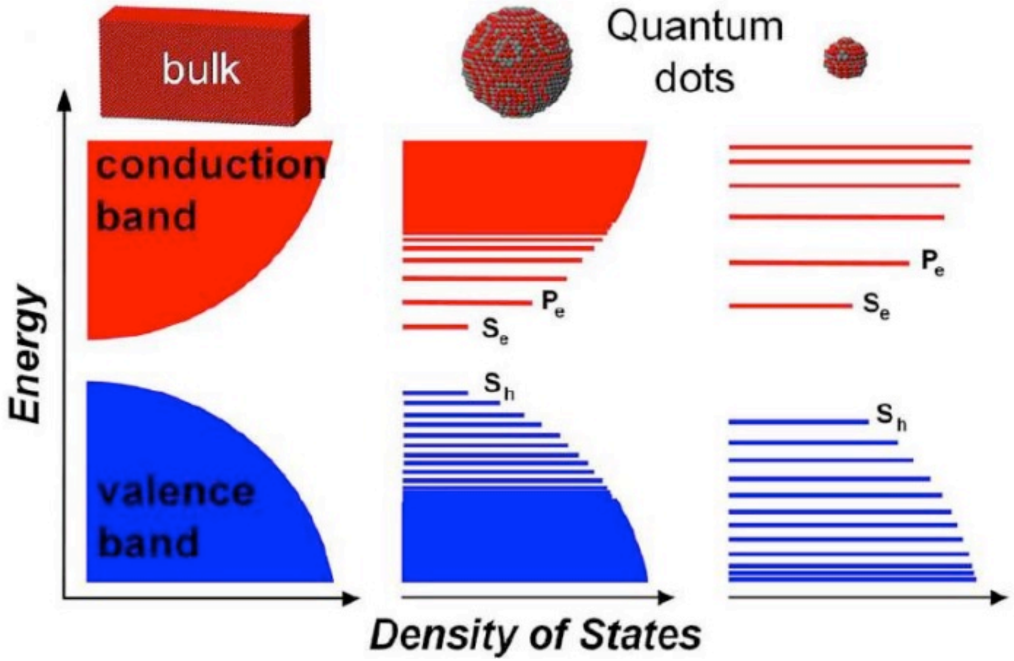
Quantum Confinement Effect

- QD feature discrete states whose energy depend on QD size (and shape)

Progress in quantum dots Photodetectors, A. Rogalski, Springer Nature 2021



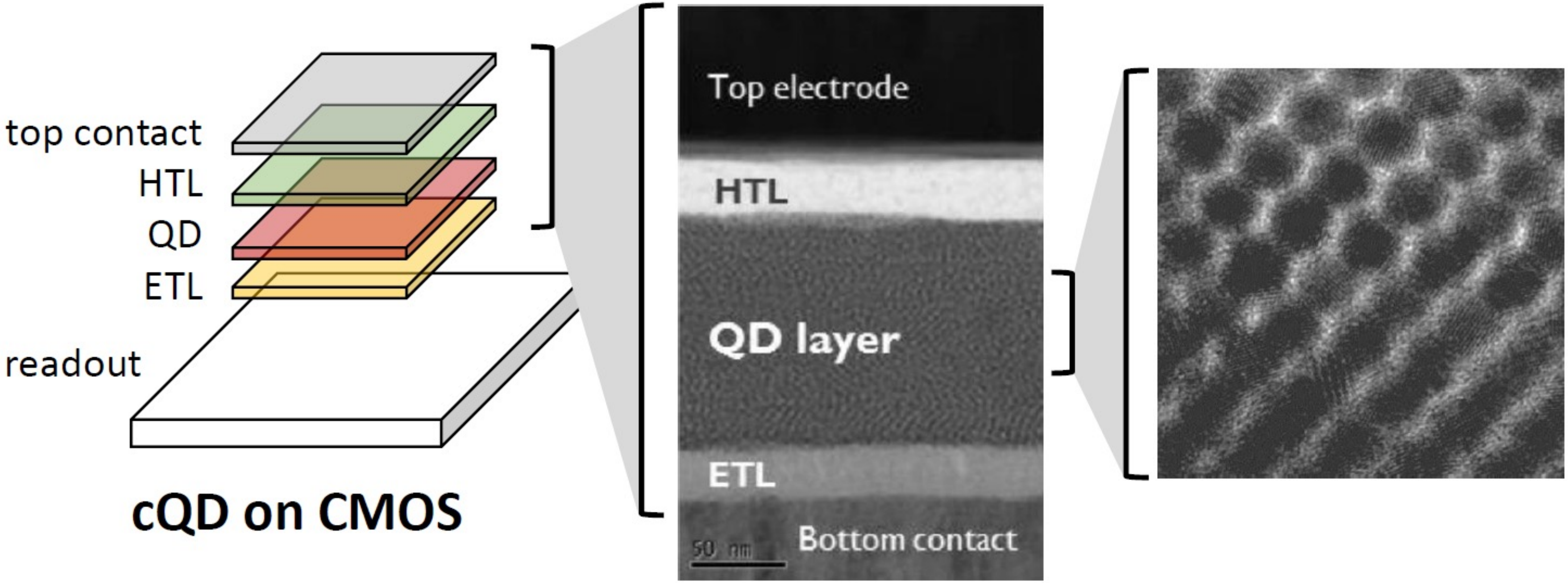
ρ(E) density of states
f(E) Fermi dirac distribution



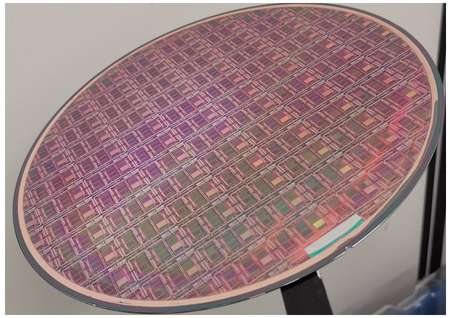
Building devices from colloidal quantum dots C. R. Kagan & al., Science, Issue 6302 2016

QD image sensor

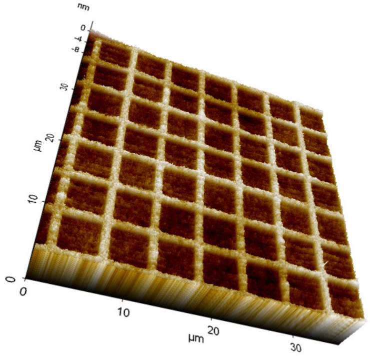
Monolithic integration of QDPD on Silicon ROIC



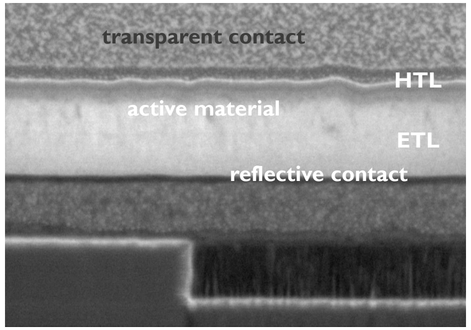
From QDPD to Image sensor – Monolithic integration on Si ROICs



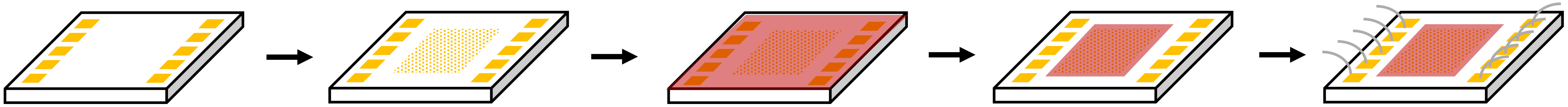
ROIC chips on 200 mm wafer



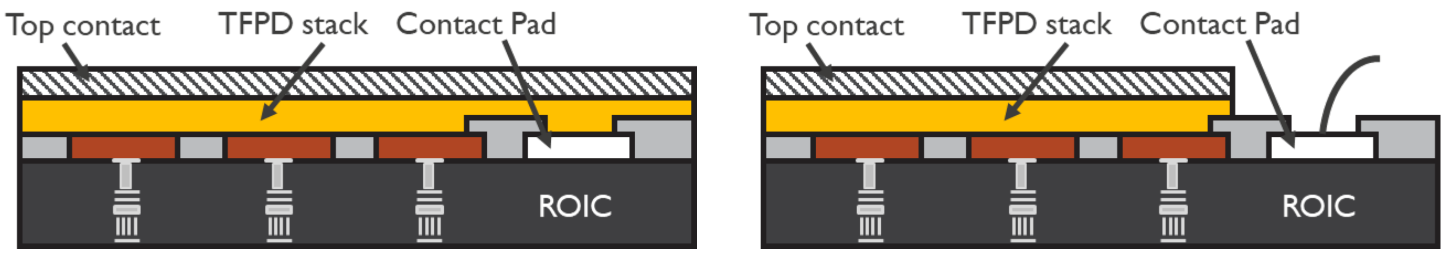
planarized contacts (<10 nm)



TFPD stack on flat ROIC



ROIC with contact pads → ROIC with planarized contacts → stack deposition (spin-coating or PVD) → stack patterning (pad access) → Packaging and testin g



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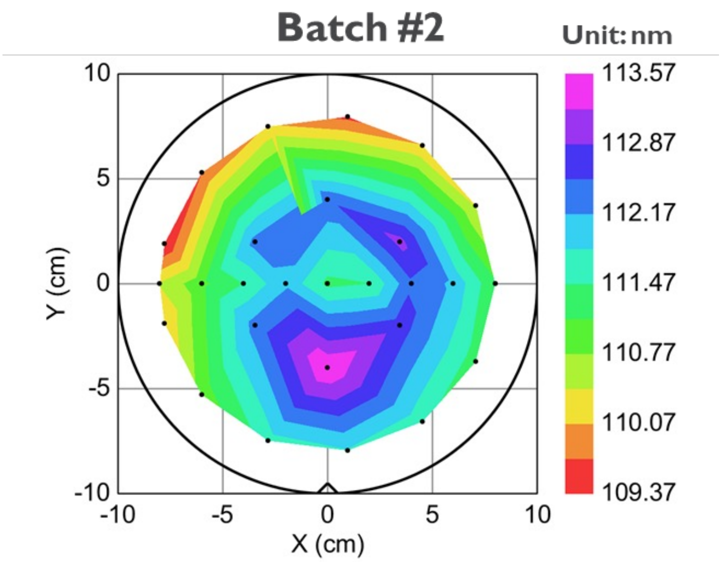
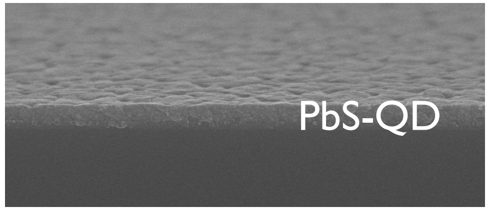
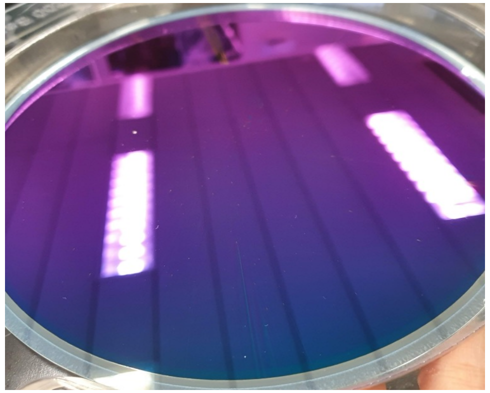
Pixelation - Wafer Level TFPD Stack Patterning

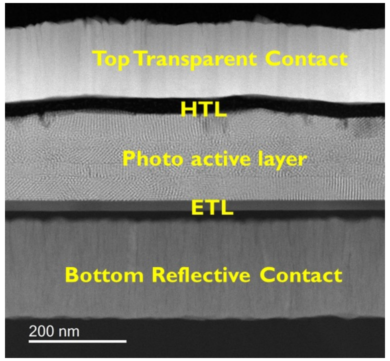
Wafer level TFPD stack deposition

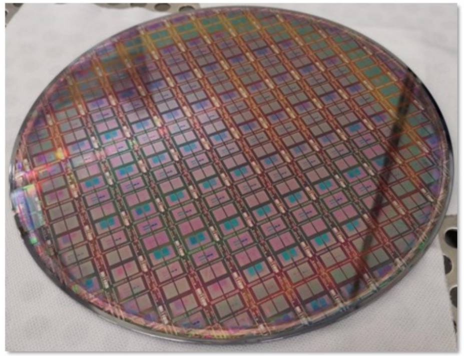


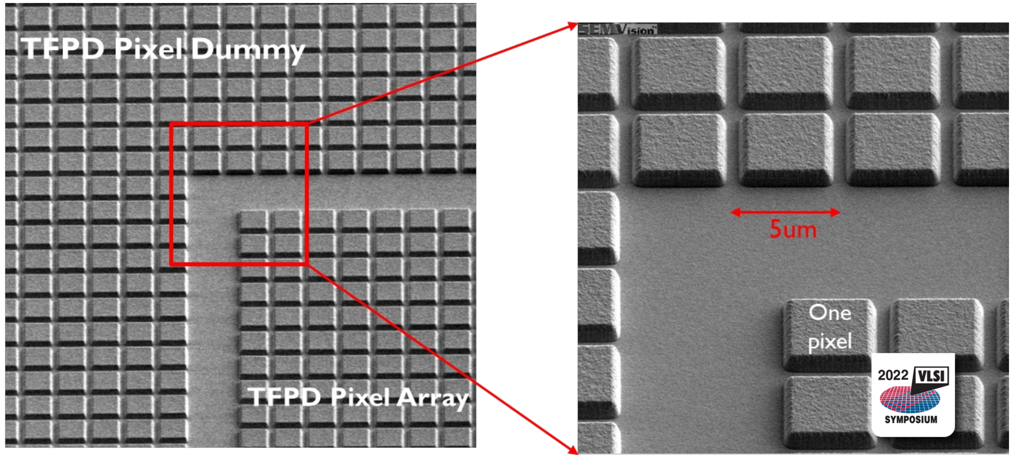




Post TFPD Pixelation Litho (DUV)





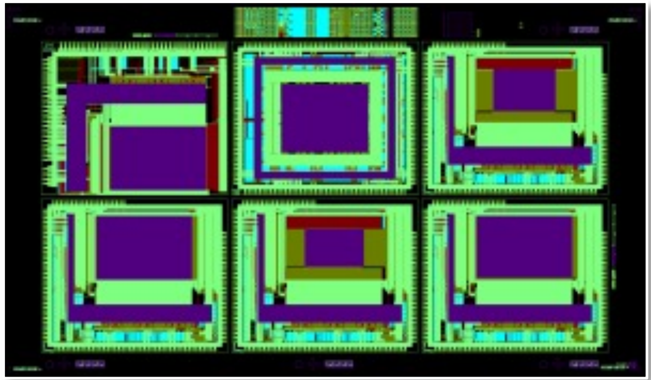


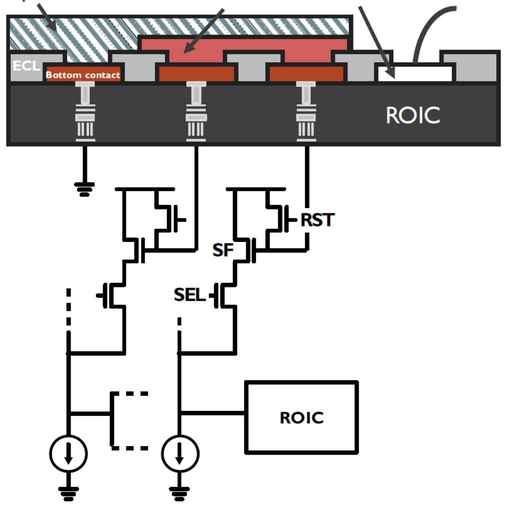
*Yunlong Li, Jiwon Lee et. al., VLSI 2022

TFPD stack pixilation demonstrated at wafer level

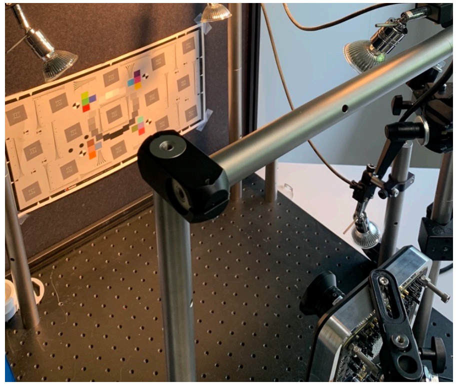
QD SWIR Image sensor design and camera build

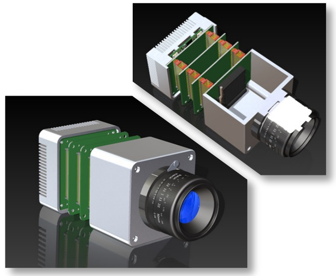
ROIC Design

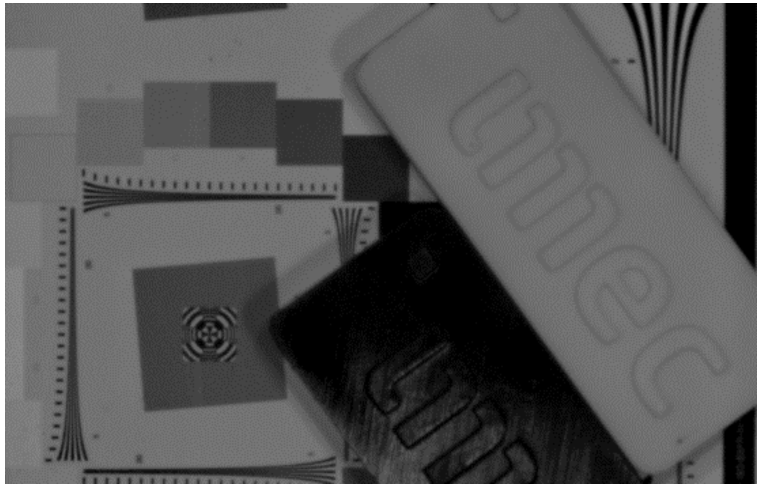




Camera build

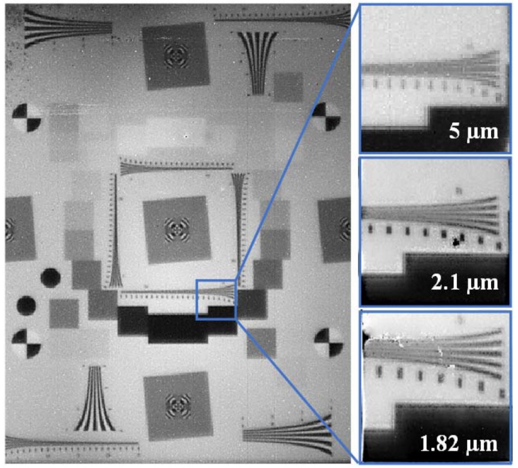






Demonstration

IEDM 2020: J.Lee et al. 0.1109/IEDM13553.2020.9372018



Camera characterization

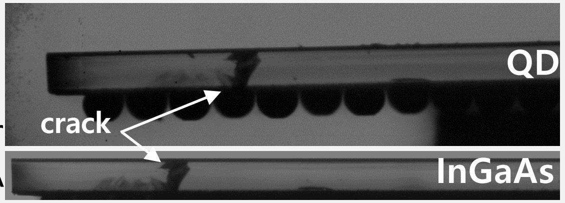
Parameter	gen1 [2020]		gen2 [2021]	Unit
Pixel pitch	5	1.82	5	µm
Resolution	768x512	128x128	768x512	px
DR	84	63	82	dB
FWC	470	16.8	325	Ke$^-$
J_D	0.3	0.2	3.3	µA/cm^2
RN	33	12	25	e$^-$
PRNU	1.3	1.8	2.4	%
λ_{PEAK}	1400		1450	nm
EQE	13		40	%

DR: dynamic range; **FWC:** full-well capacity; **J_D:** dark current density; **RN:** read noise; **PRNU:** photo-response non-uniformity; **λ_{PEAK}:** peak wavelength; **EQE:** external quantum efficiency

Imager Demonstration

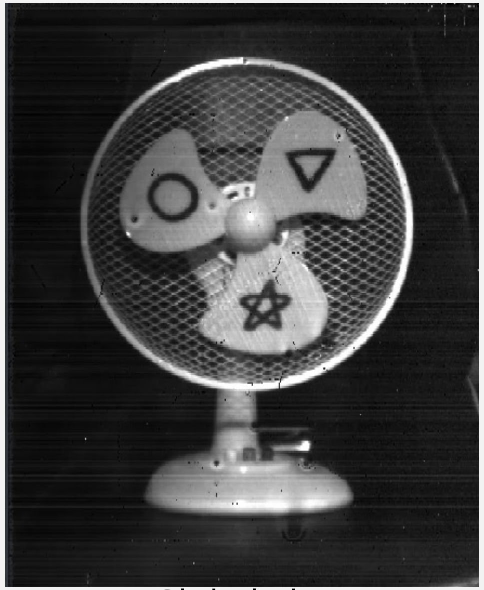
What have we tested?

Benchmarking
Validation of the imec camer
gainst an off-the-shelf InGaA



Global shutter operation

Rolling shutter



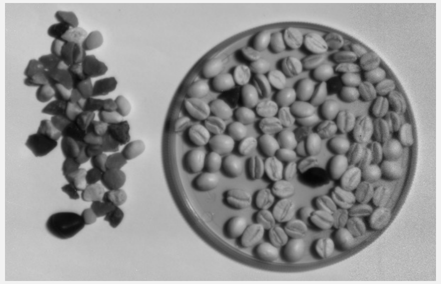
Global shutter

Security/surveillance (see through sunglass
es)

QD imager (SWIR)

CIS webcam (VIS
)

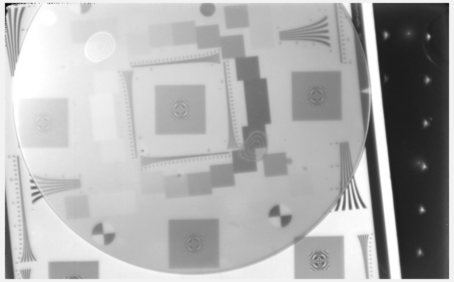
Food sorting (stones among coffee beans)



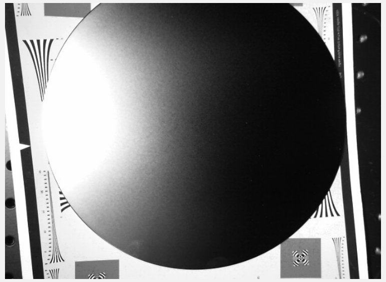
QD imager (SWIR)

CIS webcam (VIS)

Wafer inspection (detection of voids after bonding)



QD imager (SWIR)



CIS webcam (VIS)

Package inspection (see-through)

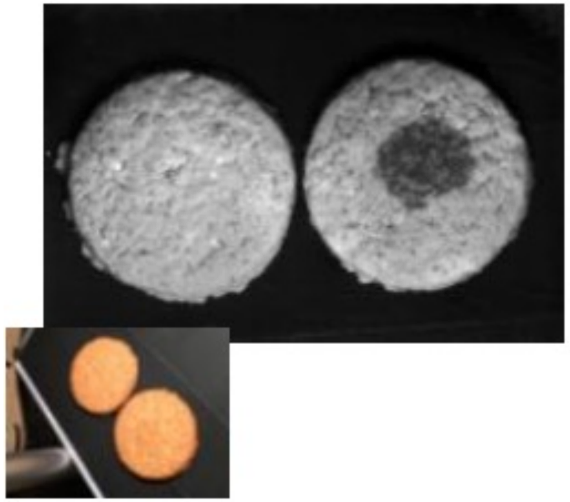
QD imager (SWIR)

CIS webcam (VIS)

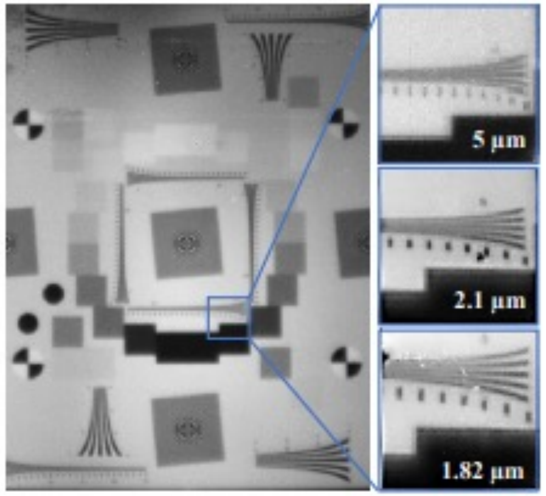
Work in Progress - Improving Image Quality

2018
The first QDPD image

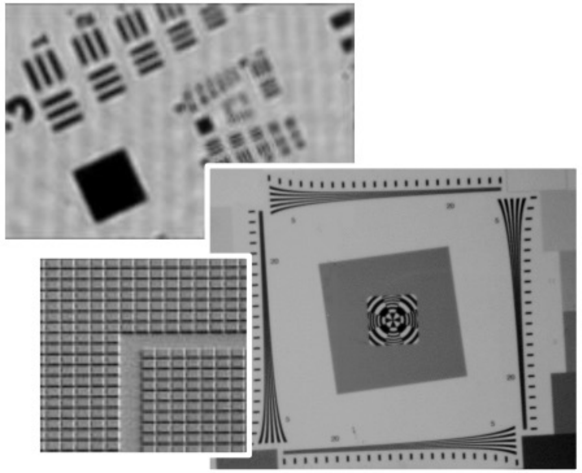
2019
5µm SWIR imager (VGA)



2020
Smallest pitch SWIR (1.82µm)



2021
EQE>40%, wafer level pixelation

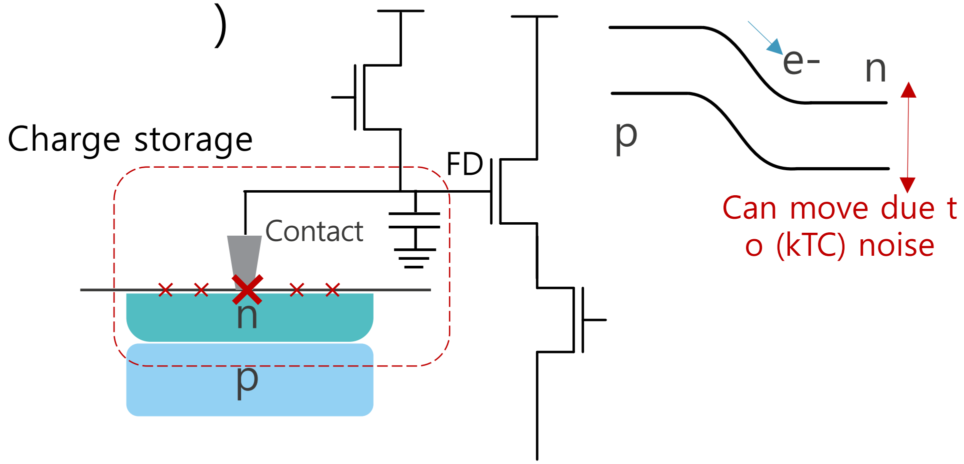


What next?

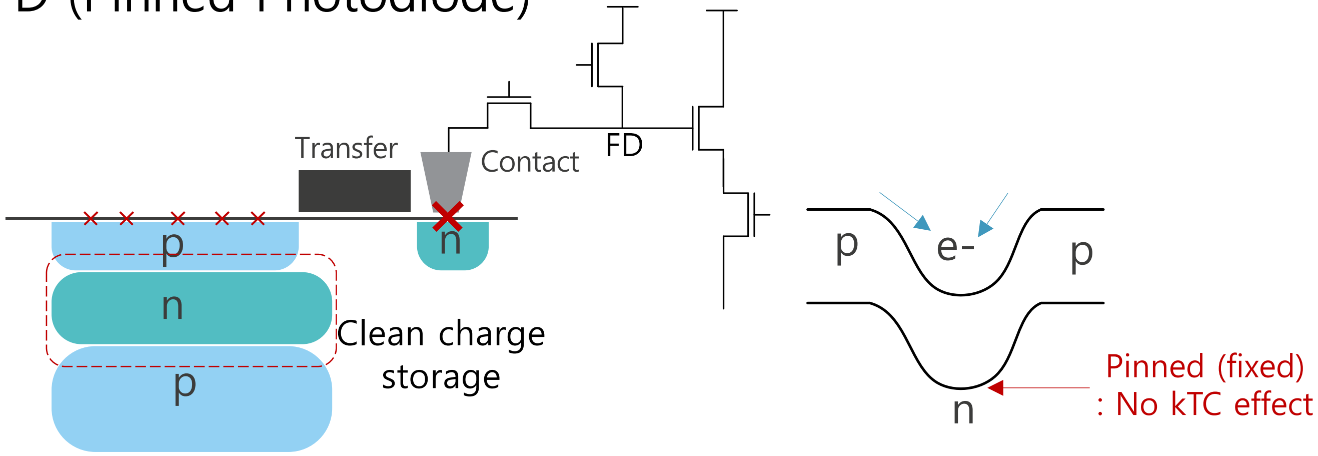
➔ ***<u>Noise reduction for SNR improvement</u>***

Today Main Mainstream Silicon Image Sensor

- PD (Photodiode
)



- PPD (Pinned Photodiode)



Requirements: Separation of PD from FD (e-to-V conversion node)

Reset Level Pinning ➔ no-KTC noise

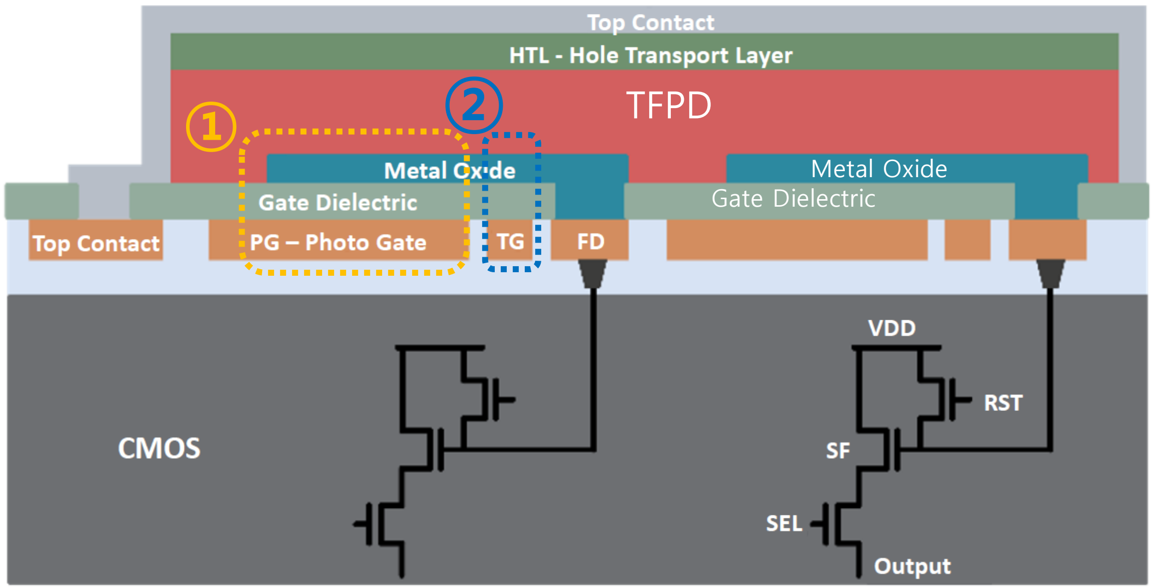
"Further refinement and widespread adoption of the PPD in CMOS image sensors occurred in the early 2000's and helped CMOS APS achieve imaging performance on par with, or exceeding, CCDs."

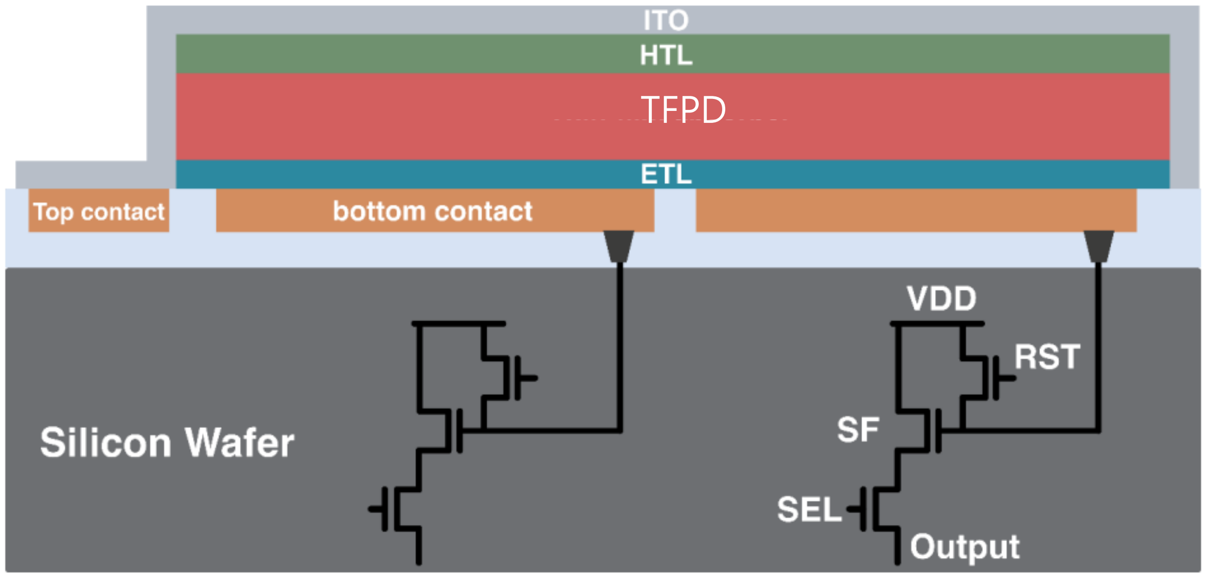
- by Eric R. Fossum from 'A review of the pinned photodiode for CCD and CMOS image sensors' 2014

- **Non-Silicon PPD hasn't been demonstrated yet.**

The First Thin-film PPD (Pinned Photodiode)

- Co-integration of TFT and Thin-film PD on Si-ROIC
  - **Photogage (PG)**: MOS + TFPD ➔ To fix PD reset potential
  - **Transfer Gate (TG)**: To separate PD from e-to-V conversion node (FD)



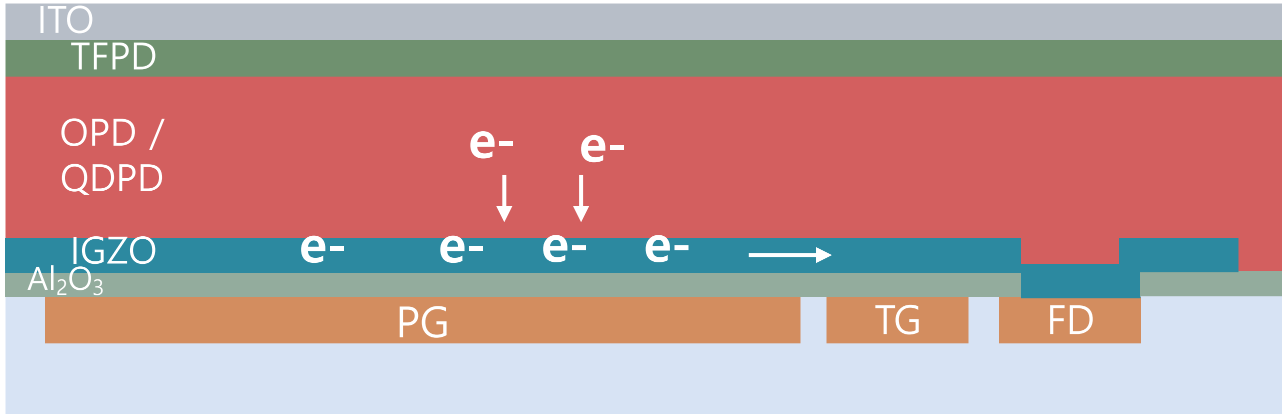


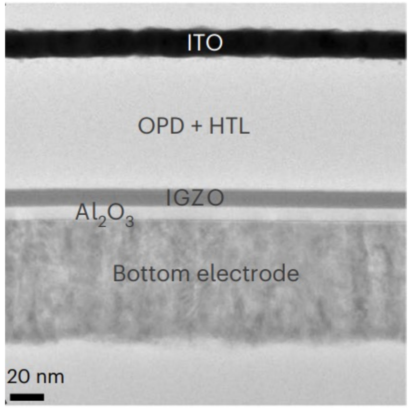
nature electronics

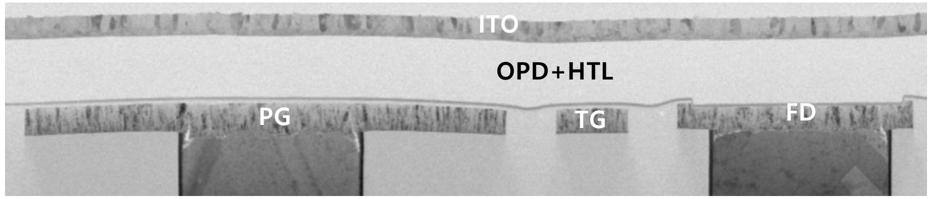
J.Lee et. al., Nature electronics 2023 (https://doi.org/10.1038/s41928-023-01016-9)

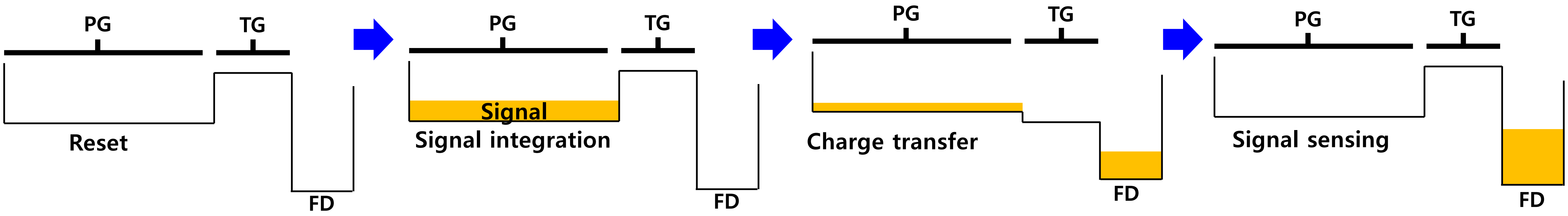
Operation: TF-PPD

- Photo-generated charges move to IGZO and integrated
- Charge transfer when TG open



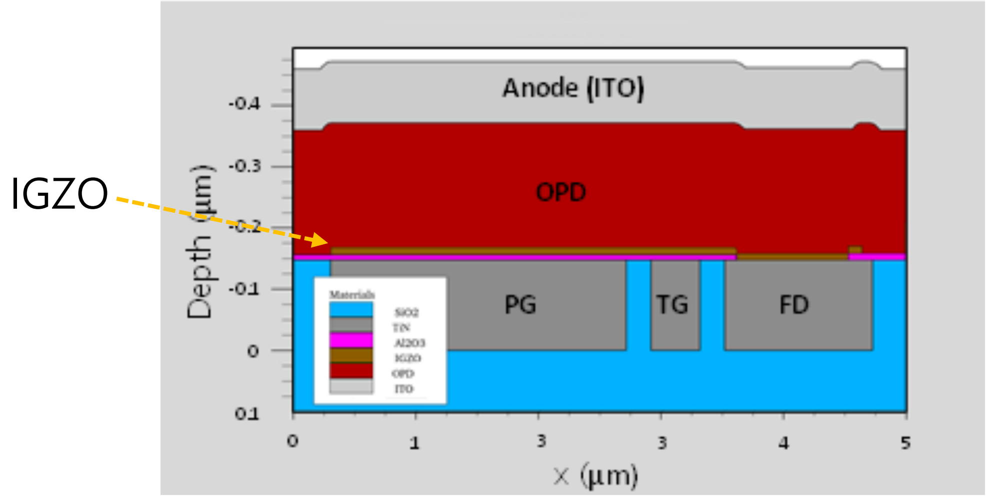




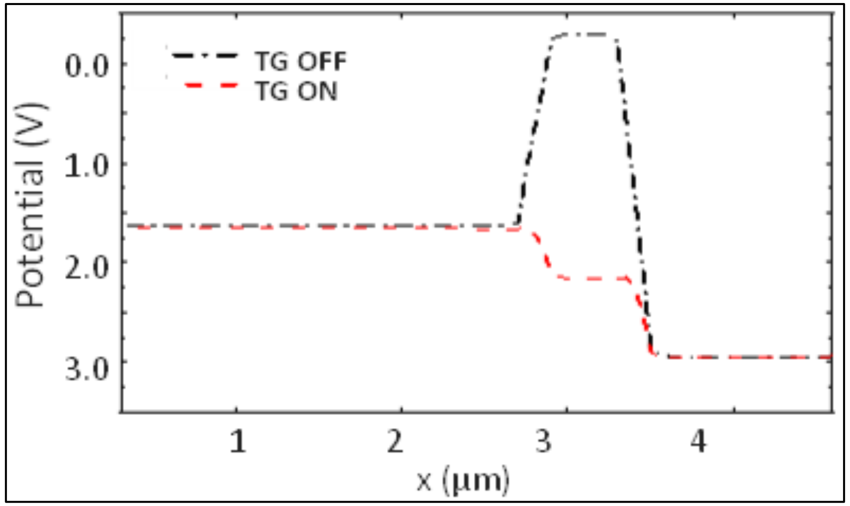


TCAD Simulation

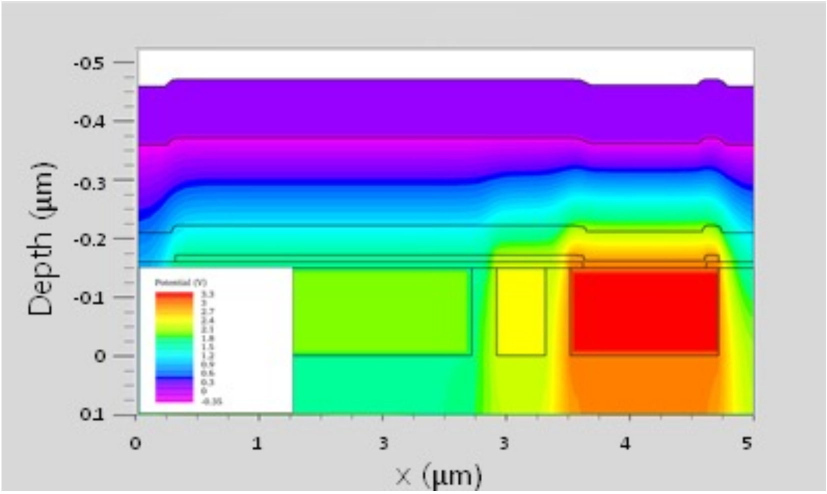
5µm Pixel structure (SILVACO)



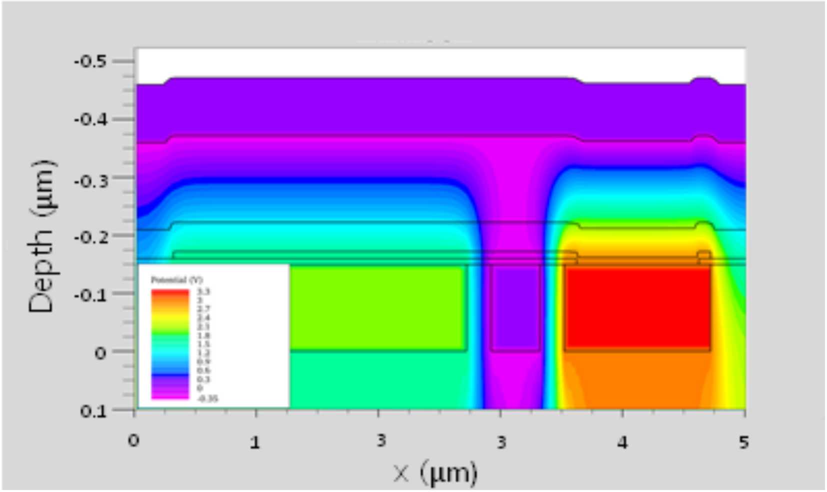
Horizontal potential profile through IGZO



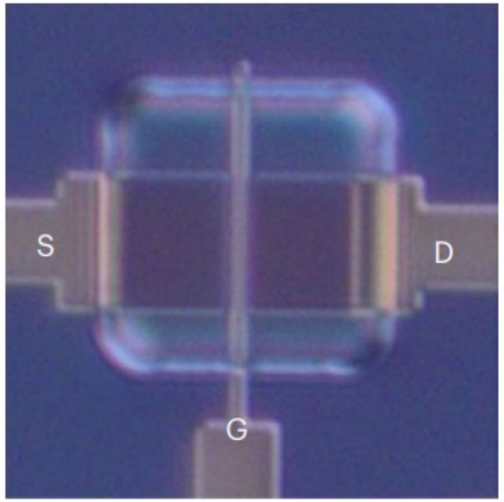
TG on

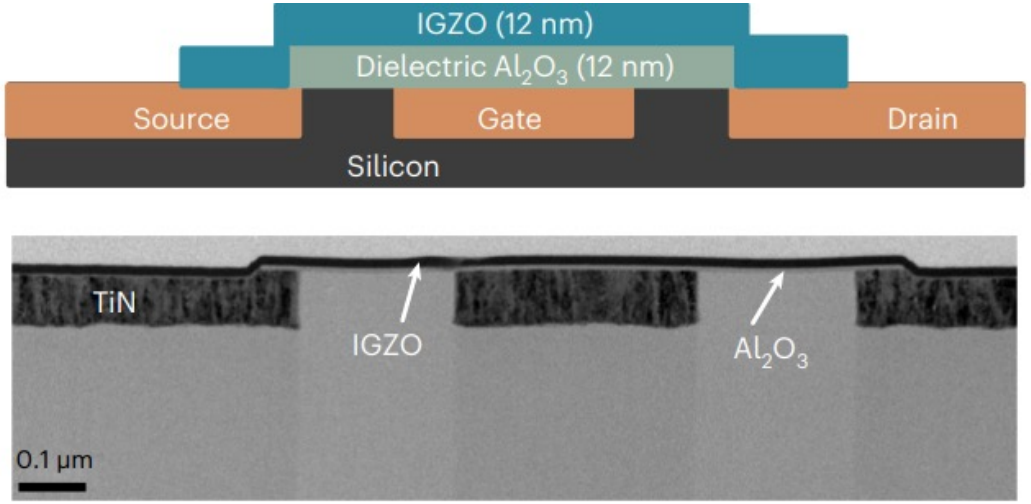


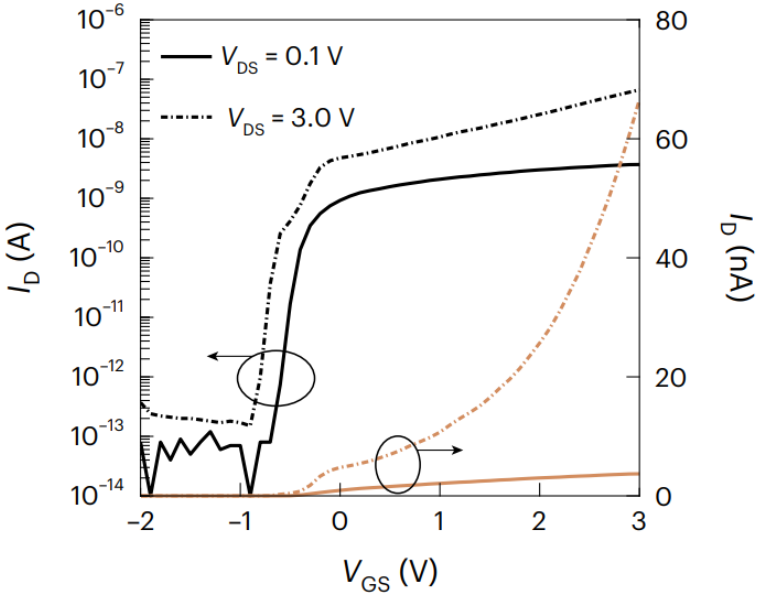
TG off



- To directly integrate TFPD on top
  - Vth = -0.5V, SS=90mV/dec



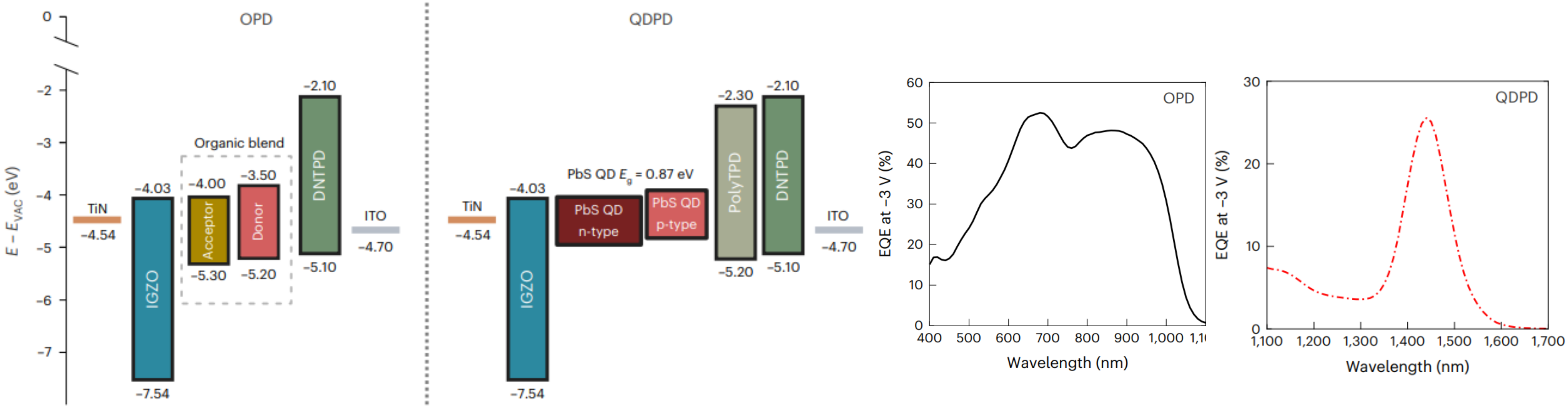




Photodiode Stack

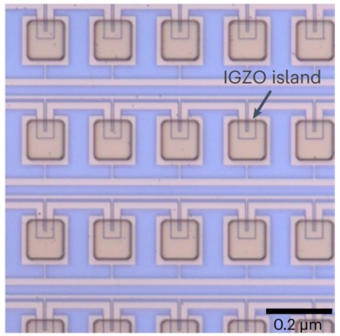
OPD and QDPD example of TF-PPD

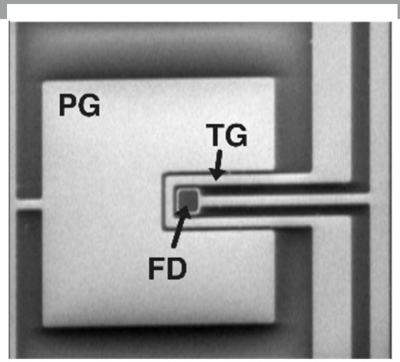
- OPD: about 40% EQE at 1,000nm
- QDPD: 26% EQE at 1,450nm

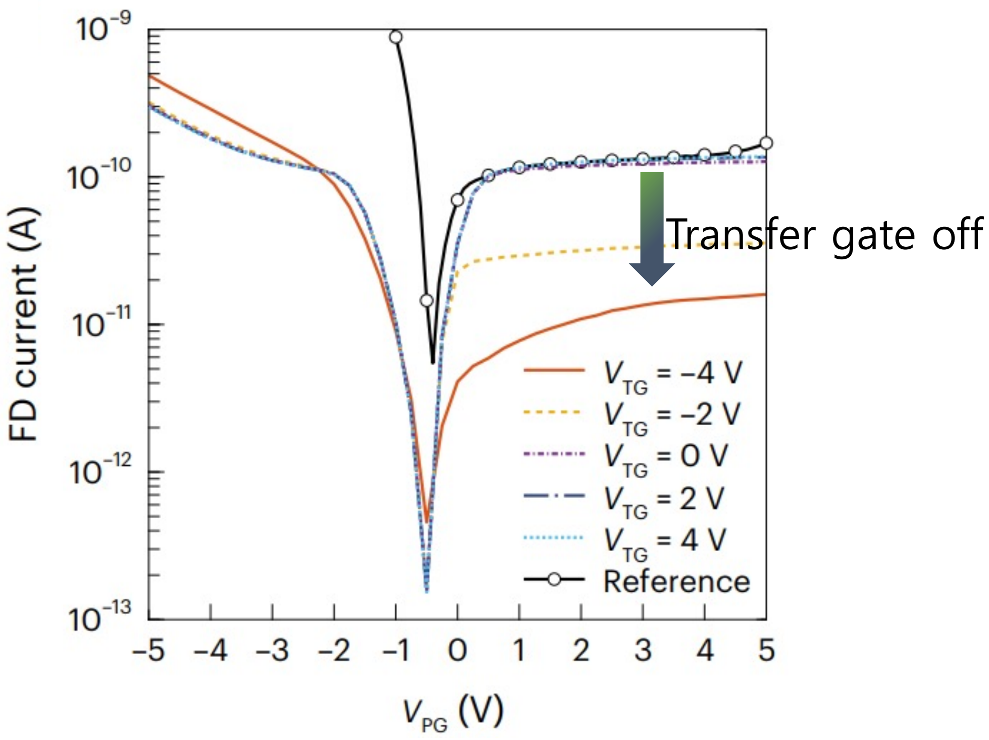


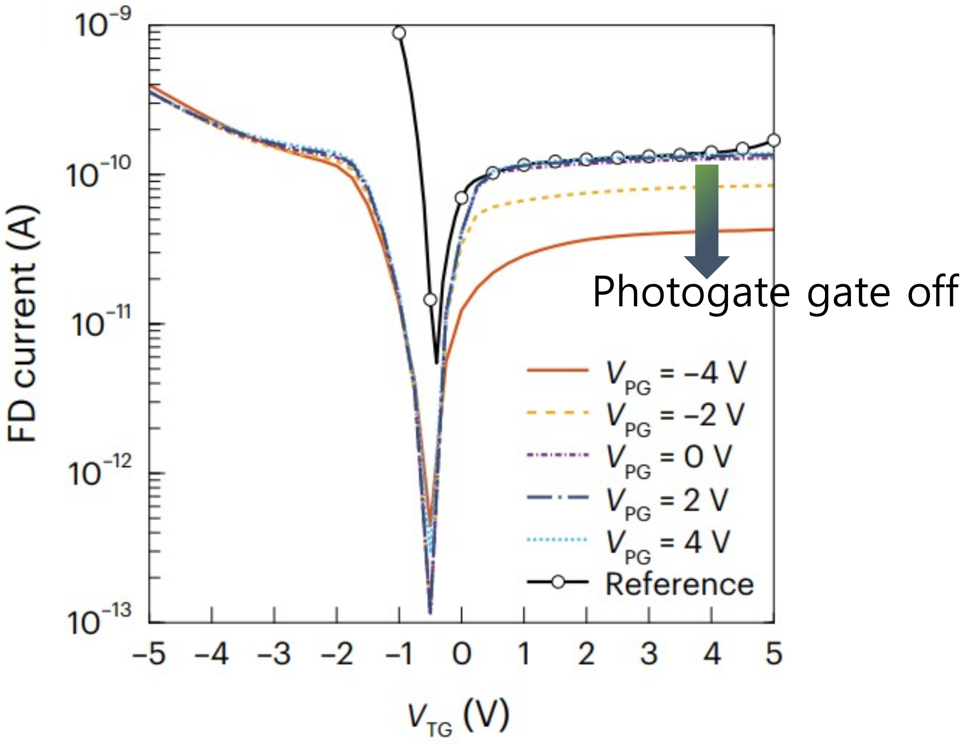
Photogate and Transfer gate operation

- Operation:
  - PD potential modulation by Photogate
  - Charge accumulation and transfer by Transfer Gate





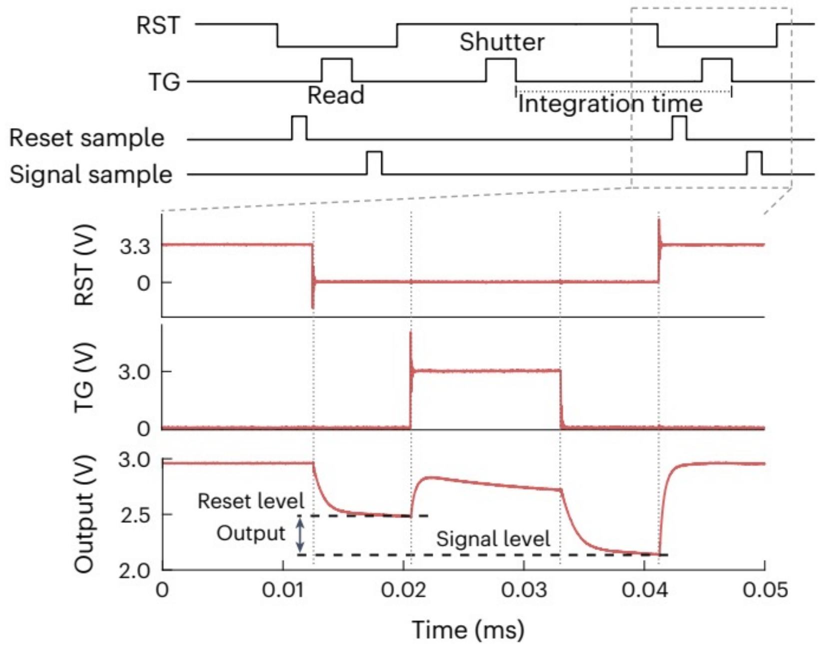




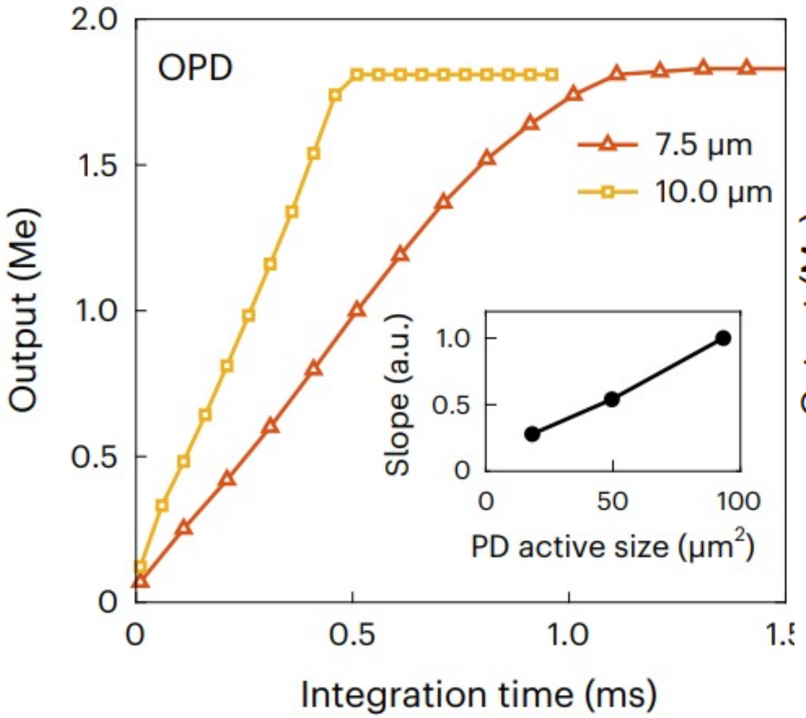
Charge integration and transfer

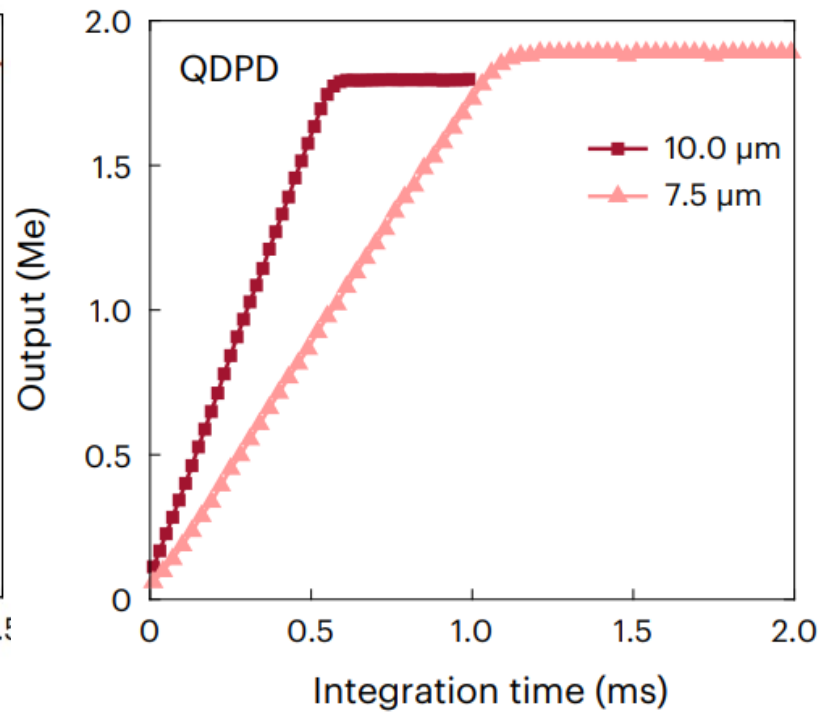
- Charge transfer operation, linear operation

Operation timing diagram



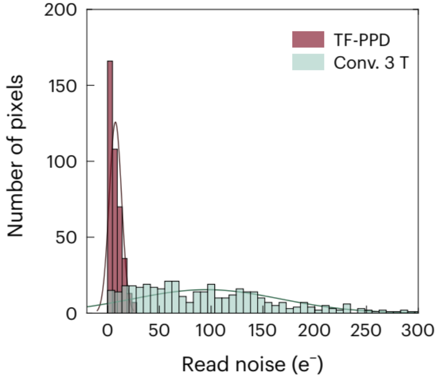
Output vs. integration time

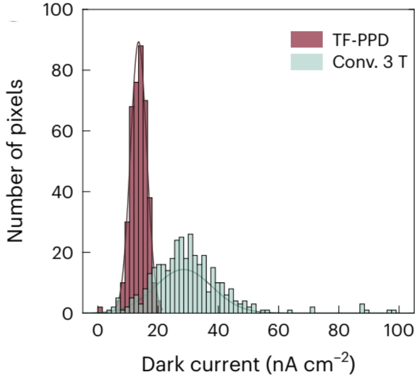




TF-PPD Demonstration (W/ OPD)

- Better image quality with reduced noise

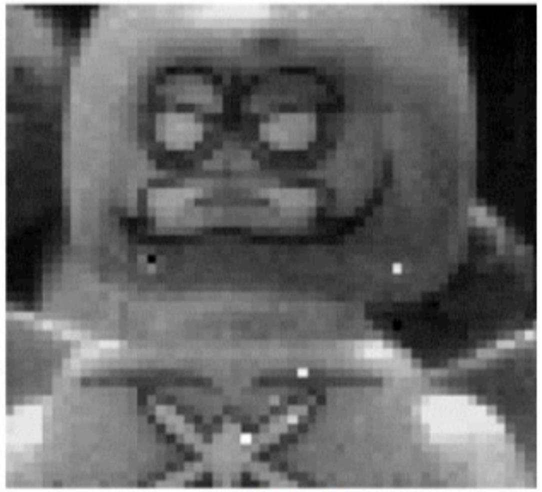




Reference

Conv. 3T

TF-PPD



acquired under the same conditions

Summary

- State-of-the-art Silicon Image Sensors to approach the theoretical limits of classical photography
- Shortwave infrared (SWIR) is becoming important for efficient information sensing.
- Quantum dot photodiode offer a cost-effective solution for high-resolution SWIR image sensors.
- The first TF-PPD has been demonstrated:
    - Low noise, low dark current, high conversion gain

반도체공학과

POSTECH