ASTRONOMICAL APPLICABILITY OF COLLOIDAL QUANTUM DOT SHORT-WAVE INFRARED IMAGE SENSOR WITH SCALABLE PIXEL PITCH DOWN TO SUB-2 MICRON

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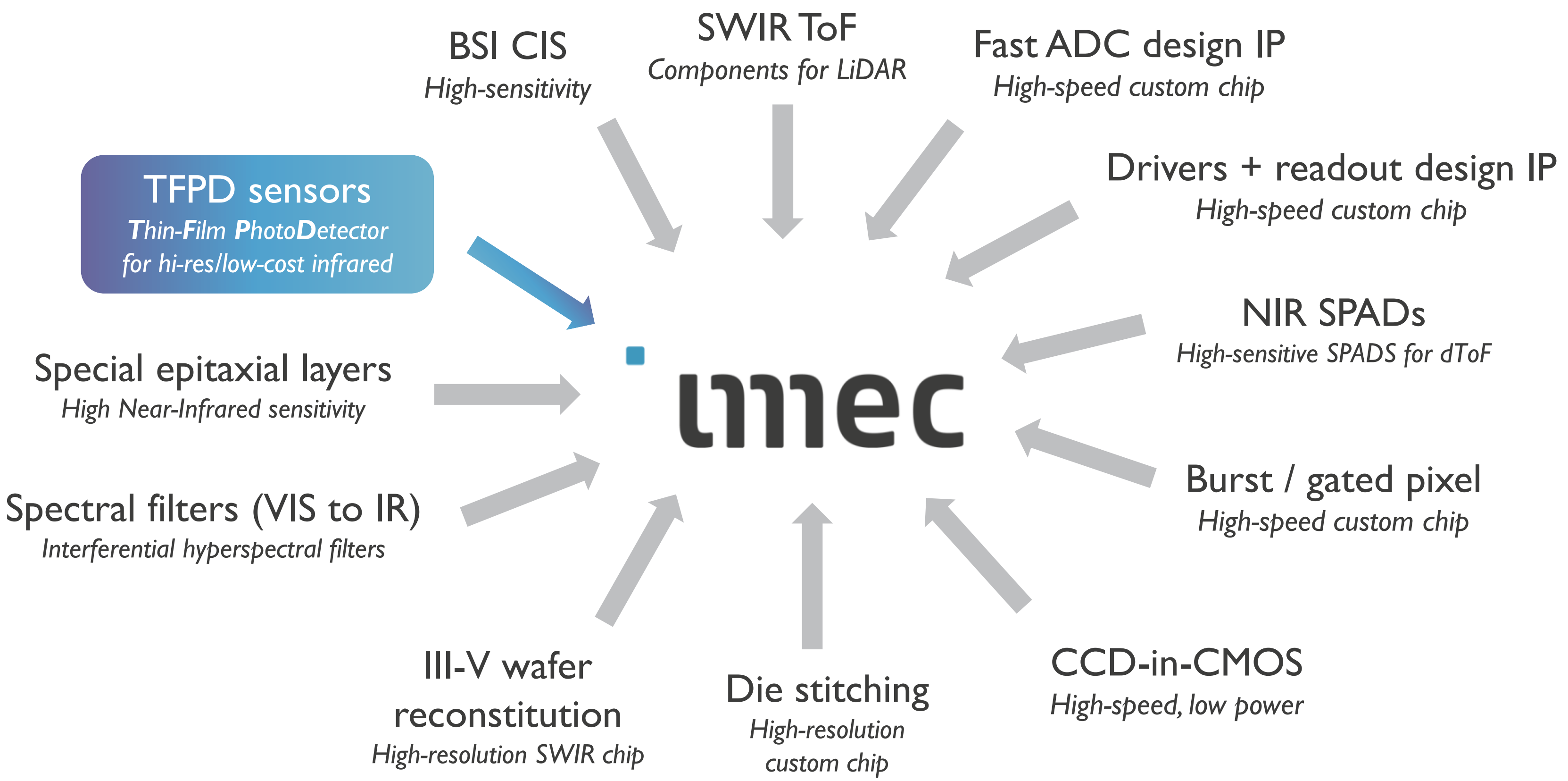
IMEC: INDEPENDENT R&D HUB

SEMICONDUCTOR SCALING AND NANOELECTRONICS
FOUNDED 1984
HQ IN LEUVEN, BELGIUM
4500 PEOPLE OF 97 NATIONALITIES
>600 PARTNERS
70% OF BUDGET FROM INDUSTRY

imec

IMEC IMAGING TECHNOLOGIES

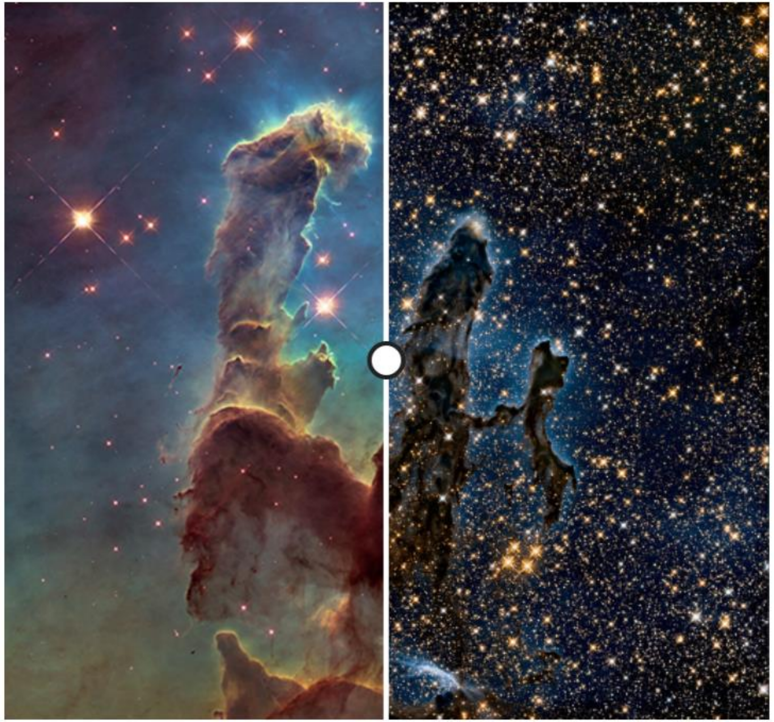
www.imec-int.com/infrared



ASTRONOMICAL INFRARED IMAGING

Drag button to views of the Eagle Nebula, 7,000 light years from Earth

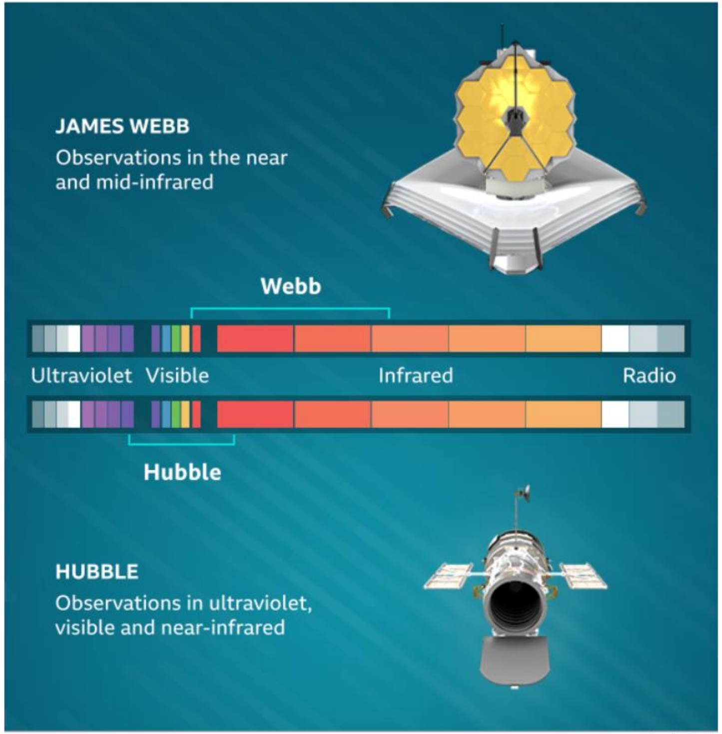
Image made with visible light **Image made with infrared**



Images: Nasa

BBC

Telescopes cover different parts of the electromagnetic spectrum



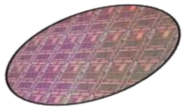
Source: Esa

BBC

TFPD (THIN-FILM PHOTODETECTOR) OPPORTUNITY

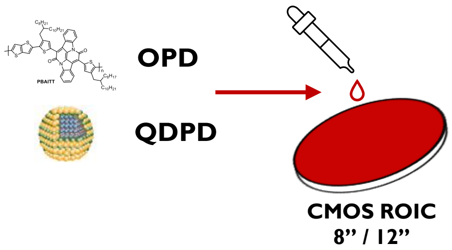
CIS
visible

- ✓ high maturity
- ✓ high throughput
  - >6B units/year!
  - substrate: 200-300 mm
- ✓ low cost
  - singe $ per camera
- x no SWIR EQE
  - 0% in SWIR
- ✓ small pixel pitch
  - SotA CIS 0.56 µm



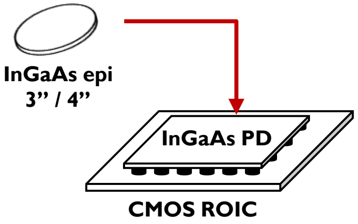
TFPD
Y-X-UV-Vis–IR

- » new technology
- » *potentially* high throughput
  - monolithic wafer-level flow
  - target substrate: 200/300 mm
- » *potentially* low cost
  - target: 10$ – 100$ (with volume)
- ✓ good SWIR EQE
  - ~60%
- ✓ small pixel pitch
  - <2 µm



III-V / II-VI / hybrid
IR

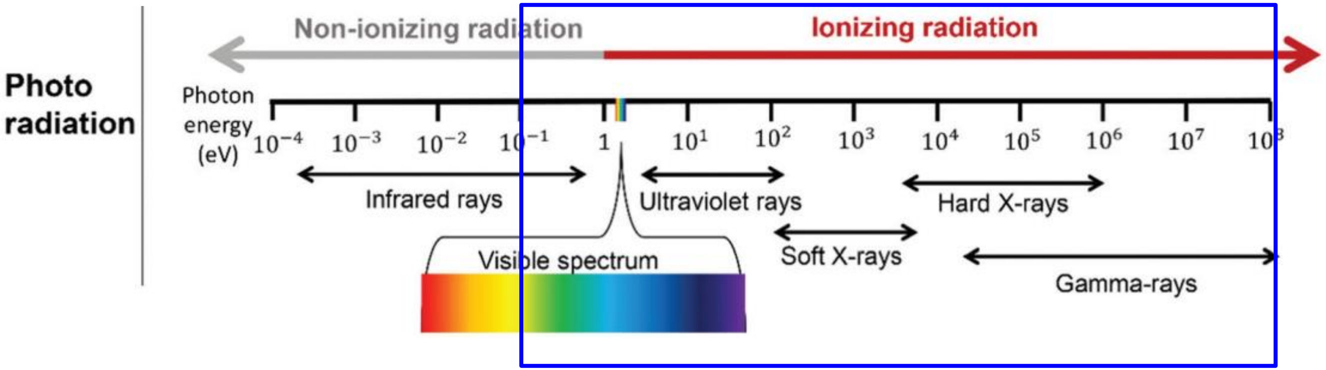
- ✓ high maturity
- x low throughput
  - ~10K units/year
  - substrate: 3-4 inch + flip-chip
- x high cost
  - several K$ per camera
- ✓ high SWIR EQE
  - 80-90%
- x large pixel pitch
  - SotA InGaAs 5 µm



QD ULTRA-SPECTRALITY

FROM γ-RAY TO LONG-WAVE INFRARED

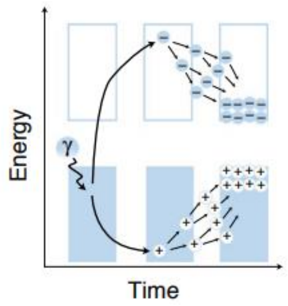
Radiation Spectrum



QDPD Detectable Photon Spectrum

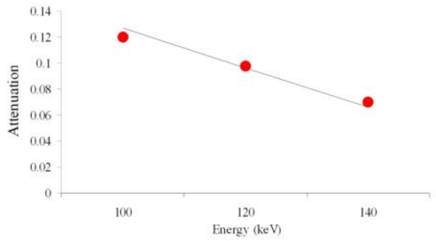
Mater. Adv., 2021, 2, 6744–6767

High energy photon to electrons



Nat. Photon. **16,** 14–26 (2022)

Thicker PD detects high-energy photons



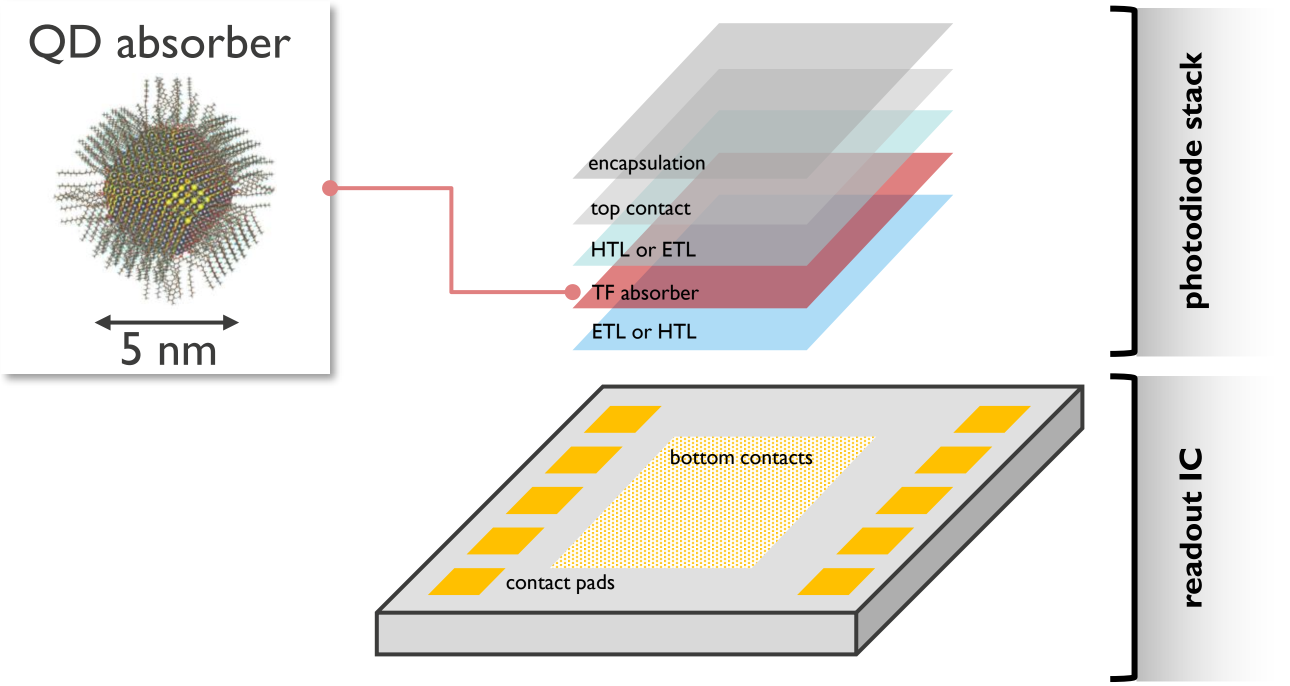
J. Park (Ed.) Photodiodes - World Activities in 2011

Ultra-spectrality can be realized by printing different thickness of QD for corresponding color unit pixel

PROCESS DEVELOPMENT

QUANTUM DOT IMAGE SENSOR

"MONOLITHIC HYBRID" INTEGRATION



→ customizable spectrum

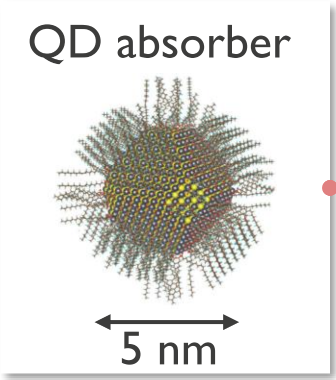
e.g. EQE peak at 1450 or 1550 nm

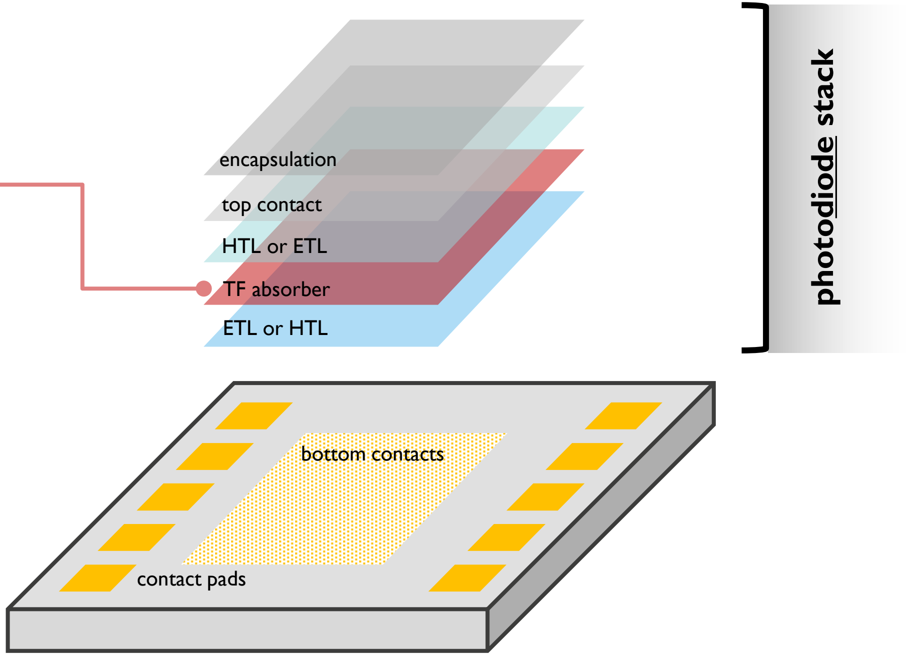
→ customizable readout

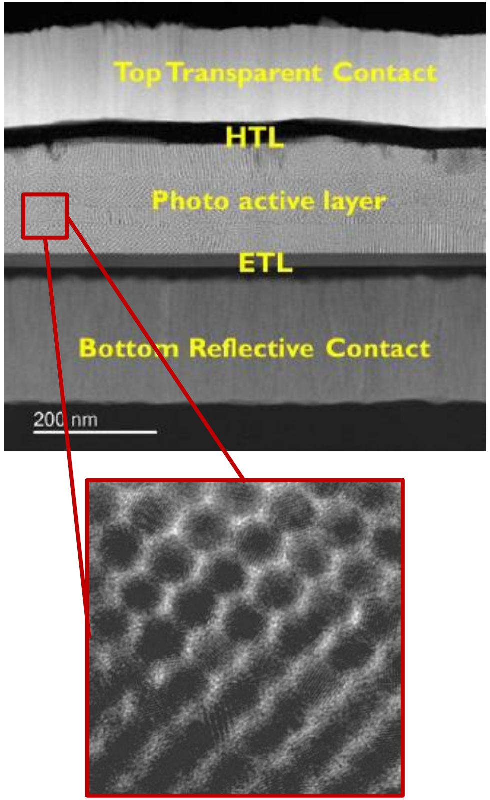
e.g. 2 μm pixel and 4K resolution

QUANTUM DOT PHOTODIODE

CAPTURING Λ > 1400 NM IN A 300 NM THICK FILM

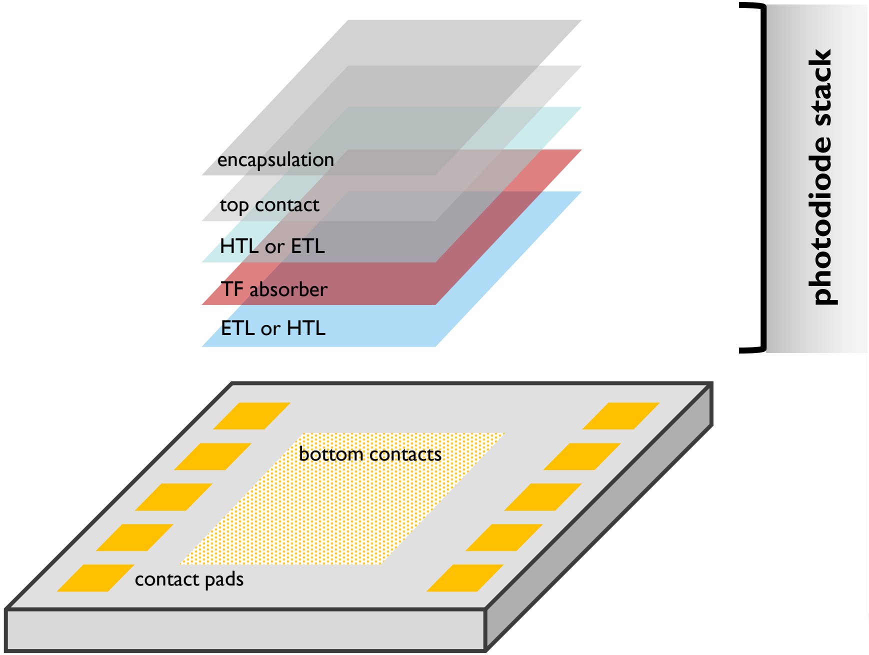


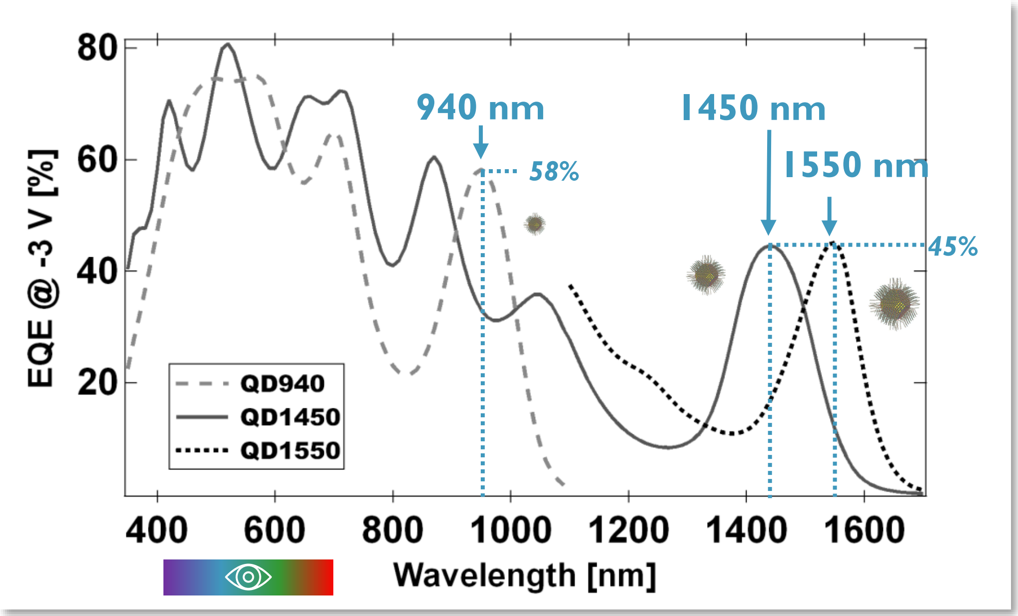




QD IMAGE SENSOR

SPECTRUM CAN BE CUSTOMIZED WITH TUNING OF THE STACK

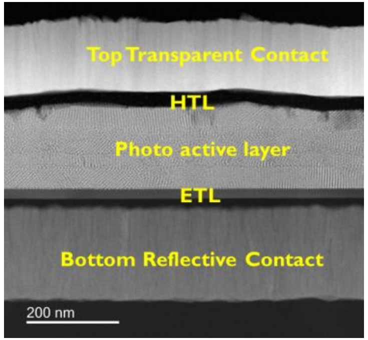




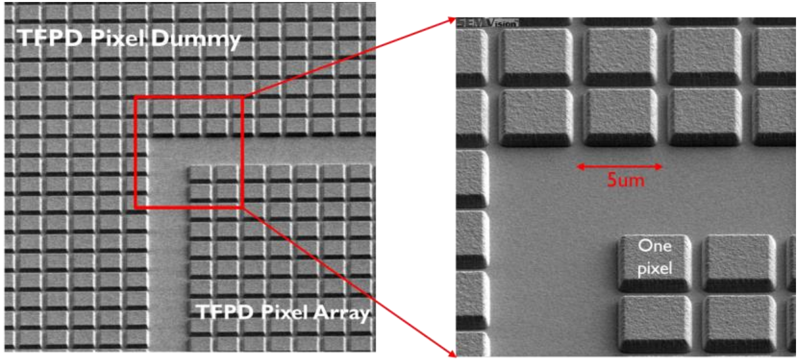
→ **eSWIR possible (and beyond!)**

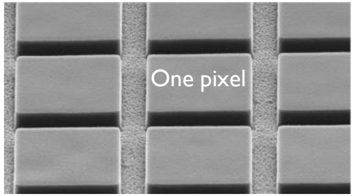
Pixelation - Wafer Level TFPD Stack Patterning

Post TFPD stack deposition



Post TFPD Pixelation Litho (DUV)





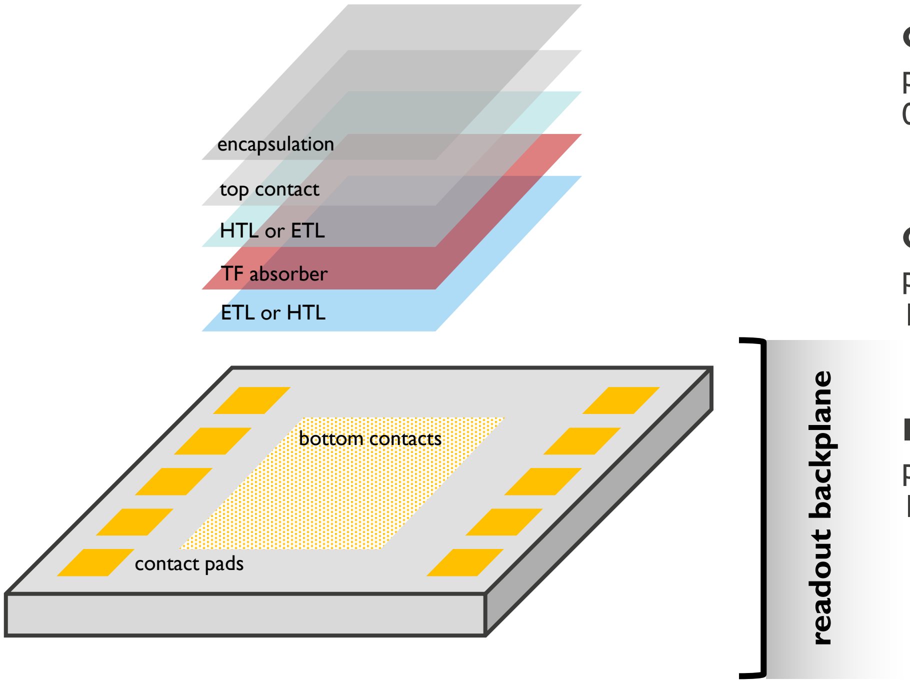
TFPD stack pixilation demonstrated at wafer level

*More details to be shared during VLSI 2022

2022 VLSI SYMPOSIUM

QD image sensor

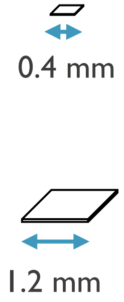
Readout can be customized for a certain form factor



Size of a VGA array
(640x480 px)

CIS monolithic
pixel pitch:
0.56 µm *(SotA)*

QD monolithic
pixel pitch:
1.82 µm *(imec SotA)*



Full-WF Single Chip:
Sensor Area 20, 000 mm^2,
6 Gigapixel (8 inch WF)

InGaAs flip-chip
pixel pitch:
15 µm *(SotA 5 µm)*

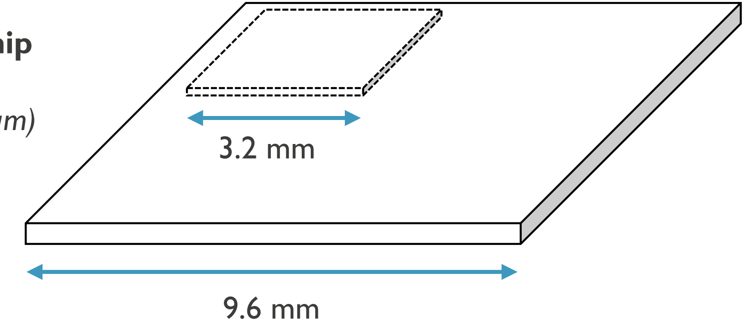
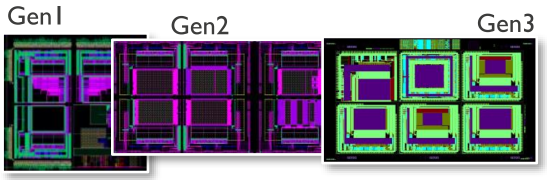


Image Sensor Design and Characterization

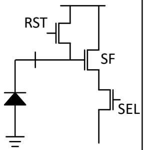
J. Lee et al., *IEDM* paper 16.5 (2020) DOI: 10.1109/IEDM13553.2020.9372018
V. Pejović et al., IEEE TED (2021) DOI: 10.1109/LED.2021.3093081

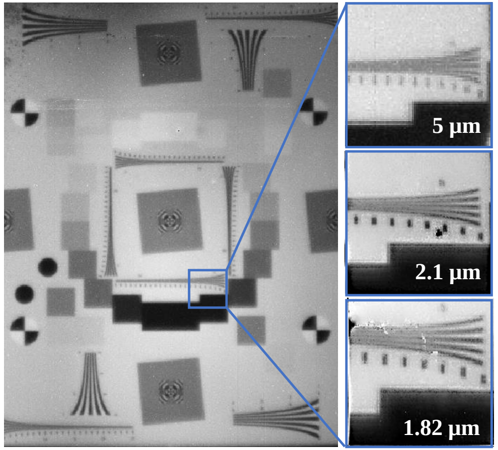
Customer ROIC designs

- Custom readouts and camera build



- Pixel architecture study for scaling

	3T	CTIA
Pixel Structure	PD + 3 transistors (RST, SEL, SF) 	PD + Amp. with feedback cap. + Buffer and switch
Pixel scaling	Good	Not good
Power consumption	Good	Not good (constant biasing for amp.)
PD bias	Variable → Linearity High voltage → Dark current	Stable Low voltage
Conversion gain	Good for scaled pixel size	Good for large pixel size
Read Noise (RN)	Good for scaled pixel size	Additional noise source (amplifier) Good for large pixel size



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	$\mu A/cm^2$
RN	33	12	25	e^-
PRNU	1.3	1.8	2.4	%
λ_{PEAK}	1400		1450	nm
EQE	13		40	%

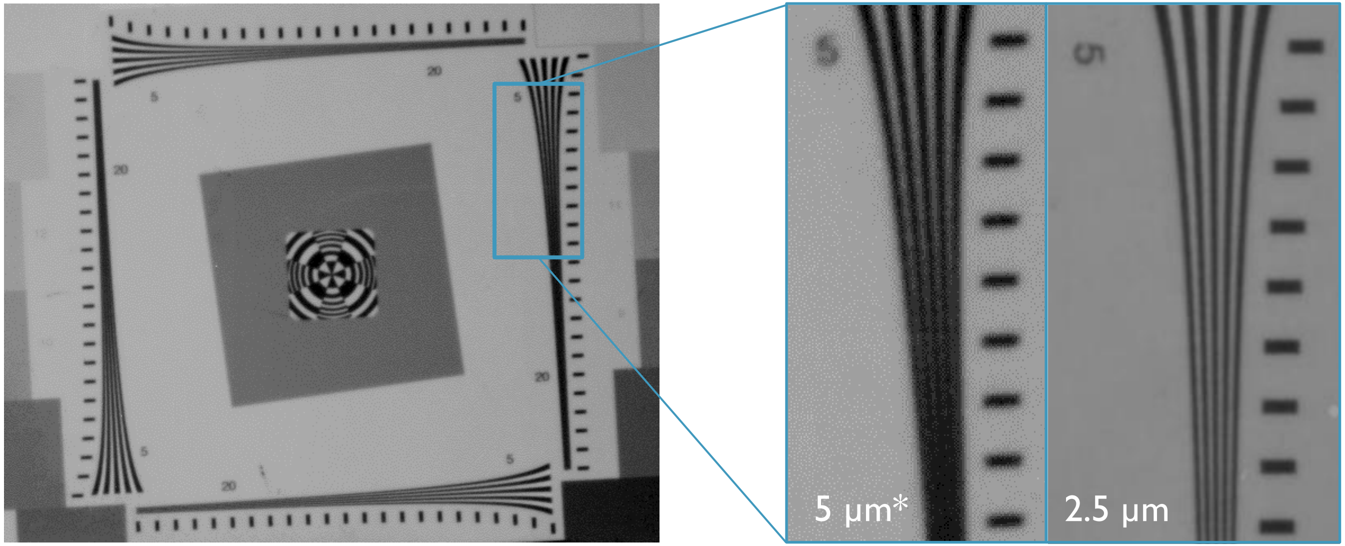
DR: dynamic range; **FWC:** full-well capacity; **J_D:** dark current density; **RN:** read noise; **PRNU:** photo-response non-uniformity; **λ_{PEAK}:** peak wavelength; **EQE:** external quantum efficiency

- **pixel < 2 µm**: enabler for compact (yet hi-res) sensors
- **pixel ≥ 5 µm**: good for low-light applications

High quality imaging in SWIR

Small pixel size → compact form factor + more details

Resolution chart image acquired with imec PbS QD1450 sensor



*SotA for InGaAs imagers

CubeSat

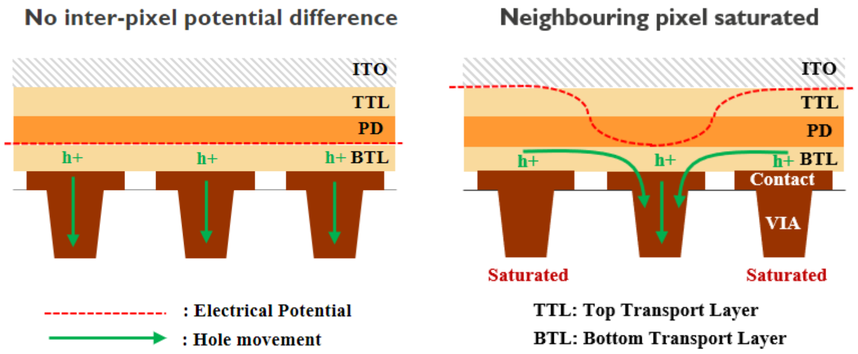
Credit: CSA

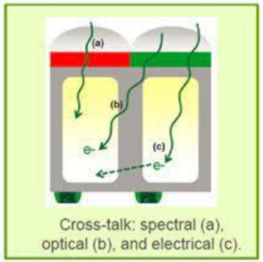
imec

TRANSPORT LAYER CONDUCTIVITY VS. BLOOMING

Less conductive (Less laterally mobile), Less Blooming

Blooming Characterization





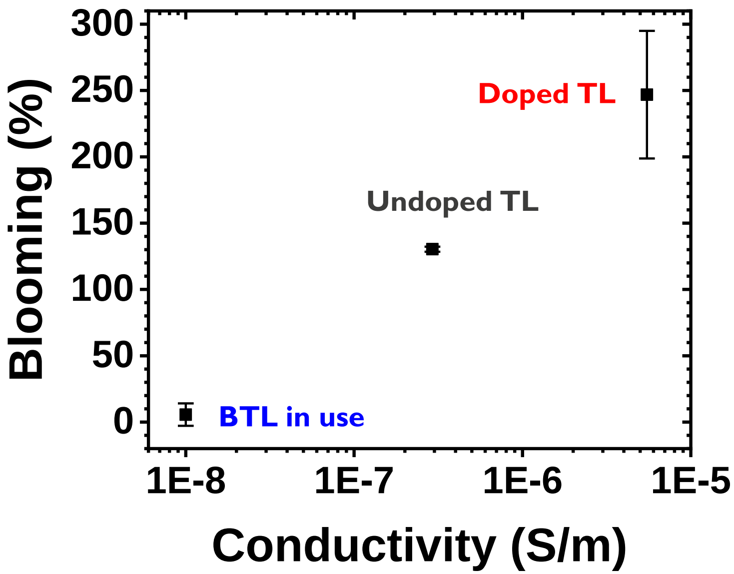
Cross-talk: spectral (a), optical (b), and electrical (c).

IEDM (2012): 24.2.1-24.2.4.

How to suppress X-talk of QD Imager

1. Spectral: Uniform QD size distribution
2. Optical: PD Full Pixelation
3. Electrical: Pixelation, Resistive TL

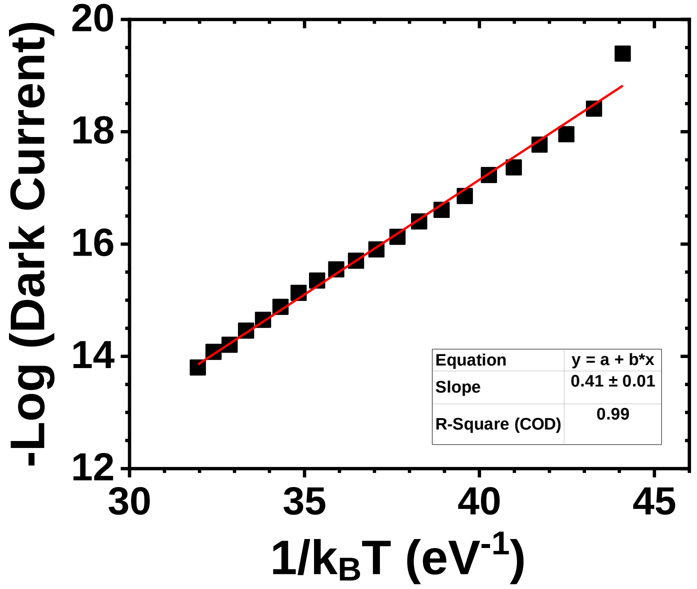
Blooming vs. Conductivity of TLs



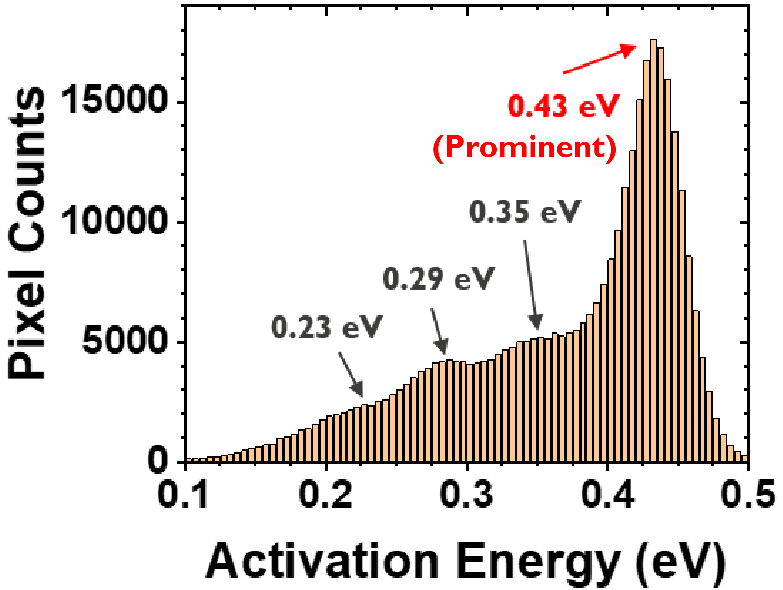
ACTIVATION ENERGY OF 0.41 EV FOUND

MULTIPLE PEAKS SEEN FROM 0.23 EV TO 0.43 EV (MID-BANDGAP ENERGY)

Arrhenius Plot



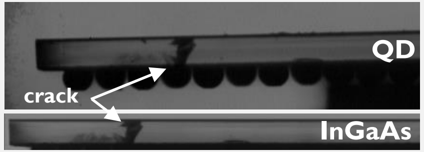
Activation Energy Histogram



TFPD image sensor validation

What have we tested?

Benchmarking
Validation of the imec camera against an off-the-shelf InGaAs

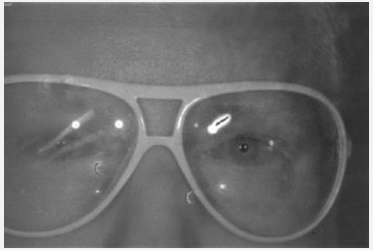


Package inspection (see-through)

QD imager (SWIR)

CIS webcam (VIS)

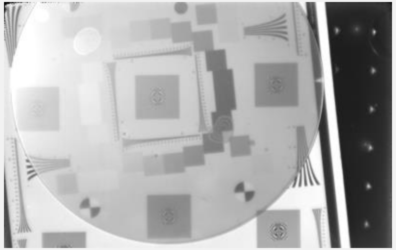
Security/surveillance (see through sunglasses)



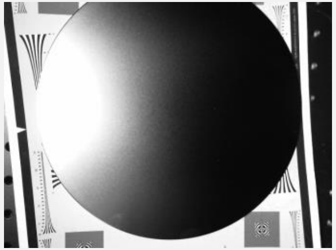
QD imager (SWIR)

CIS webcam (VIS)

Wafer inspection (detection of voids after bonding)



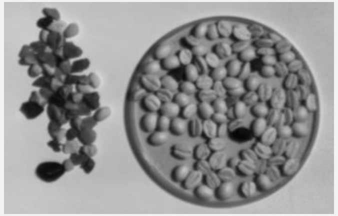
QD imager (SWIR)



CIS webcam (VIS)

Real-time Demo (Future Summits 2022)

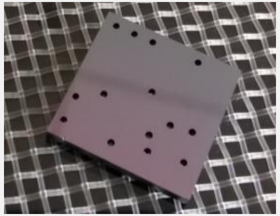
Food sorting (stones among coffee beans)



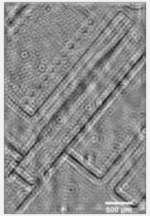
QD imager (SWIR)

CIS webcam (VIS)

Lens-free imaging (e.g. microscopy)



Si chip with channels



SWIR image

Where is the industry currently?

First products are already coming to market!

(and new players entering)

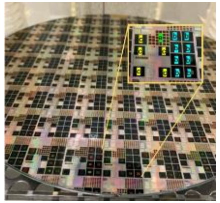
Emberion (Finland)
www.emberion.com

- Spectral range: up to 2000 nm
- Array size: 640 × 512 px
- Pixel pitch: 20 μm

SWIR Vision Systems (USA)
www.swirvisionsystems.com

- Spectral range: up to 2000 nm
- Array size: 1920 x 1080 px
- Pixel pitch: 15 μm

ST Microelectronics (France)
www.st.com



Pixel pitch: 1.62 μm
Wafer size: 300 mm

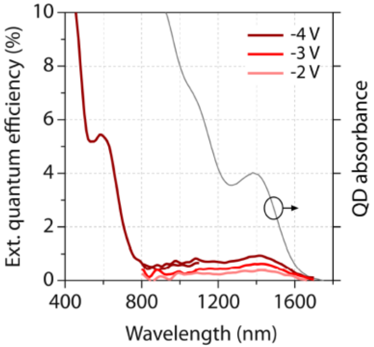
qurv (Spain)
www.qurv.tech

TFPD IMAGE SENSORS

R&D program at imec – technology building blocks

TRL

1st results on
SWIR InAs QDs

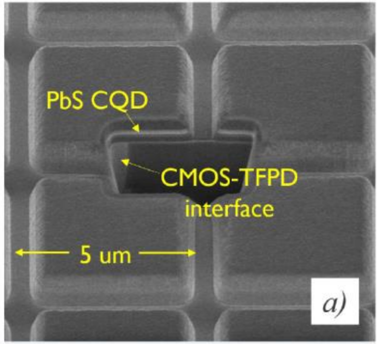


“what’s next?”

MRL

QD stack pixelation
on 200 mm wafers

2022 VLSI SYMPOSIUM

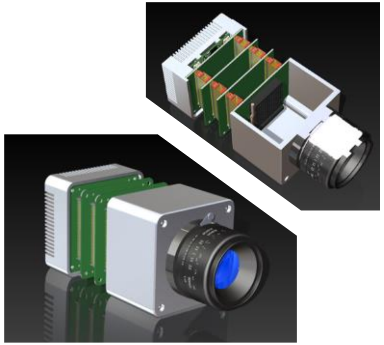


“how to manufacture?”

Validation

modular camera enabling
field testing at end users

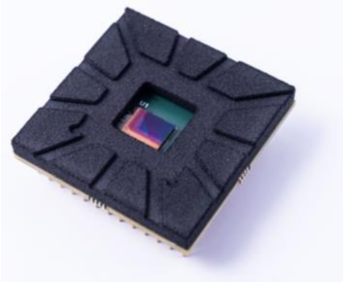
FUTURESUMMITS



“what are the specs?”

QD SENSORS FOR ASTRONOMICAL IR IMAGING

Highly Scalable IR Image Sensor



- Astronomical IR Image Sensor: Observing deeper and older universe
- QD Imager is enabling more scalable astronomical imaging
  - Large pixel number, WF-lv sensing area, High-resolution, Ultra-spectral imager
- Imec QD Imager has shown
  - QD Synthesis to PD stack development
  - Wafer-level process development
  - Imager design and deep-analysis
- Imec has been leading QD Imager innovation at the forefront.

IMEC QD IMAGE SENSOR TRACK RECORD

- **Press:**
  - *Promotional video: vimeo.com/653649418*
  - *IMVE magazine*, 18th Feb 2021, URL: bit.ly/3e4VUUr
  - *press release* (SWIR pixel pitch state-of-the-art: 1.82 μm), 9th Dec 2020, URL: bit.ly/3oypX9y
  - *imec magazine*, Oct 2019, URL: bit.ly/3vCeTfh
  - *press release* (SWIR pixel pitch state-of-the-art: 5 μm), 21st Oct 2019, URL: bit.ly/3aSHgh0
- **Publications:**
  - **J.H. Kim** et al. *IEEE Transactions on Electron Devices* (2022), DOI: 10.1109/TED.2022.3164997
  - **V. Pejović** et al. *IEEE Transactions on Electron Devices* (2021), DOI: 10.1109/TED.2021.3133191
  - **J.H. Kim** et al. *IISW 2021*, paper R40
  - **V. Pejović** et al. *IEEE Electron Device Letters* 42/8 (2021), DOI: 10.1109/LED.2021.3093081
  - **P.E. Malinowski** et al. *Proc. SPIE* 11765 (2021), DOI: 10.1117/12.2584144
  - **Y. Li** et al., *SEMI – CSTIC,* Symposium IV, Session V (2021)
  - **Z. Lin** et al., *Proc. SPIE* 11632 (2021), DOI: 10.1117/12.2578857
  - **J. Lee** et al., *IEDM 2020,* paper 16.5 (2020), DOI: 10.1109/IEDM13553.2020.9372018
  - **J. Lee** et al., *Proc. SPIE* 11407 (2020), DOI: 10.1117/12.2559949
  - **E. Georgitzikis** et al., *IEEE Sensors Journal* 20/13 (2020), DOI: 10.1109/JSEN.2019.2933741
  - **E. Georgitzikis** et al. *ACS Appl. Mater. Interfaces* 12/27 (2020), DOI: 10.1021/acsami.0c06781
  - **E. Georgitzikis** et al., *IISW2019,* paper R43 (2019)
  - **E. Georgitzikis** et al., *Adv. Funct. Mater.* 28 (2018), DOI: 10.1002/adfm.201804502
  - **E. Georgitzikis** et al., *IEEE Sensors* (2018)*, DOI: 10.1109/ICSENS.2018.8589515*
  - **P.E. Malinowski** et al. *Sensors* 17/2867 (2017), DOI:10.3390/s17122867

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