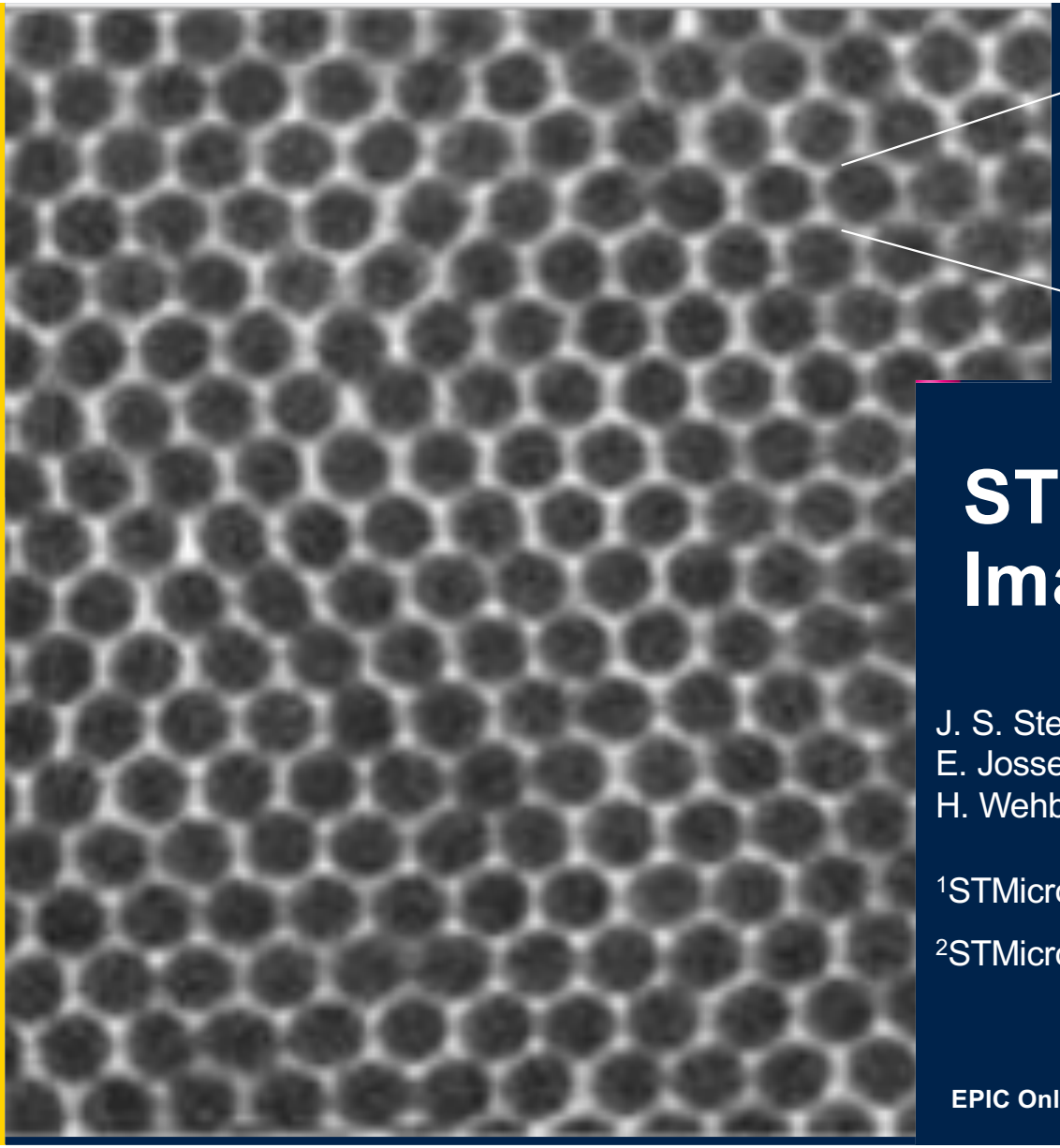

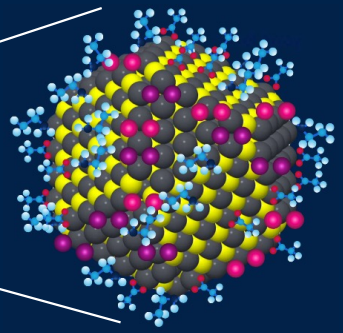

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ST Colloidal Quantum Dot Image Sensor Technology

J. S. Steckel[1], J. Arnaud[1], A. G. Pattantyus-Abraham[2], A. Singh[2], E. Josse[1], M. Bidaud[1], M. Sarmiento[2], A. Arnaud[1], E. Mazaleyrat[1], H. Wehbe-Alause[1], K. Rochereau[1]

[1]STMicroelectronics, France

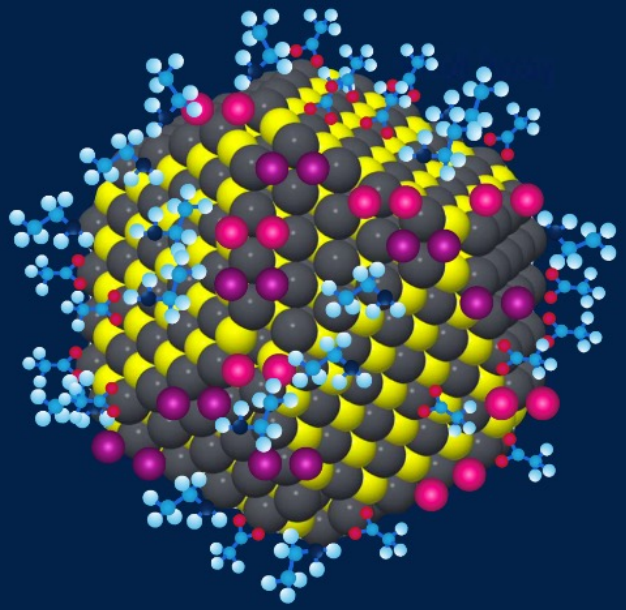
[2]STMicroelectronics, CA, USA

EPIC Online Technology Meeting on Quantum Metrology and Quantum Sensors

Agenda

1. ST QuantumFilm technology
2. Image sensing beyond silicon
3. SWIR imaging capabilities with ST QF image sensors
4. Summary & conclusion

1 – ST QuantumFilm technology



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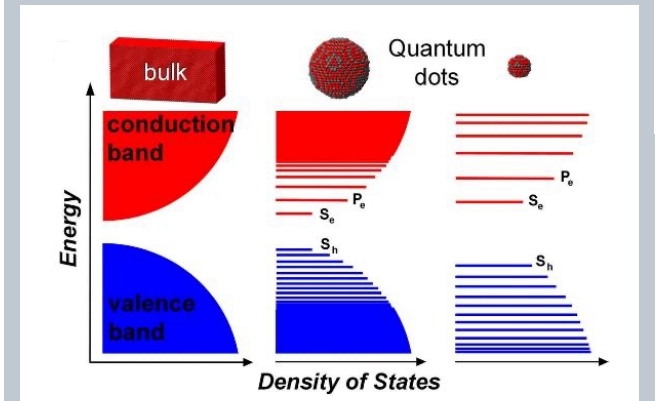
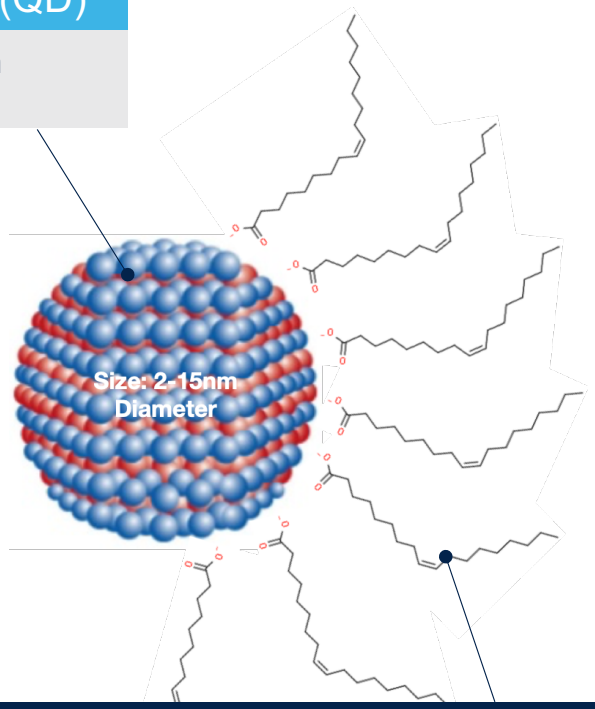
Colloidal Quantum Dot Technology
Solution-Based Semiconductors

Semiconductor nanocrystal: Quantum Dot (QD)

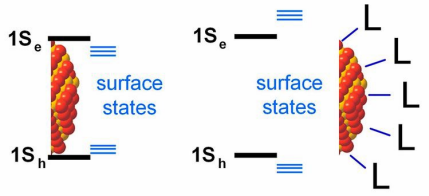
Size, shape, and composition determine the absorption wavelength of the first excitonic peak

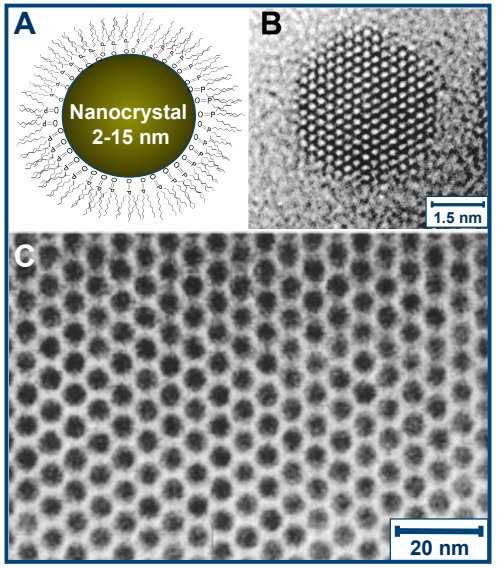
Quantum confinement





Trap states





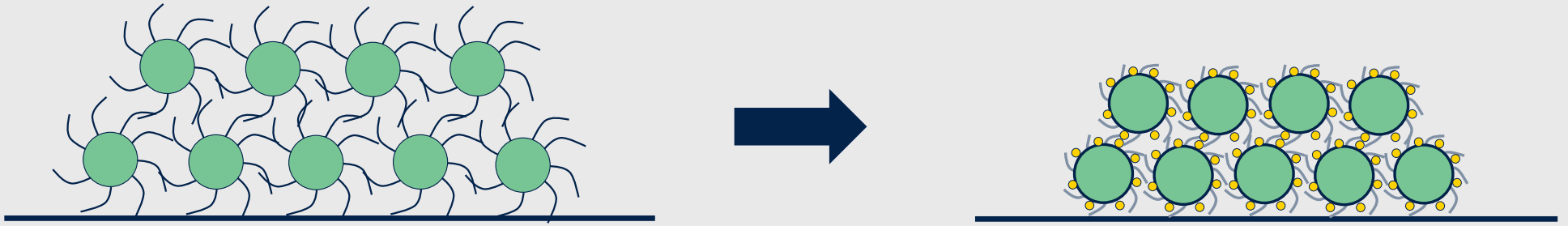
Ligands

- Surface bound molecules that passivate and protect the QD surface
- Tune the doping level and stabilize solid QD films
- Impart colloidal stability in solution

From colloidal QDs in solution to solid QuantumFilms

QuantumFilms (QF) fabrication

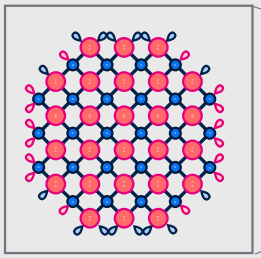
QuantumFilms are thin, solid-state films made of **colloidal QDs** embedded in a matrix of **ligands**



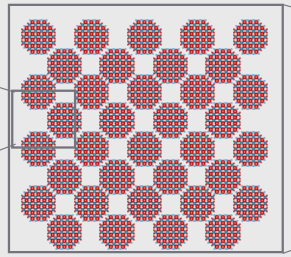
Colloidal QDs dispersed in solution are dispensed on wafer by spin-coating

Proprietary processing enables the creation of highly dense QD films with improved charge transport and passivated trap states

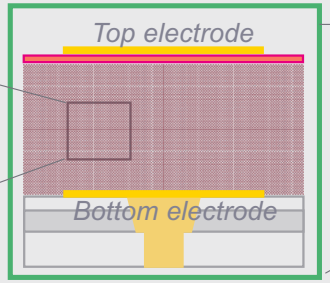
From colloidal QDs in solution to photodiode devices



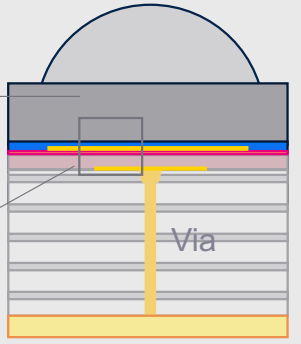
Single
PbS QD



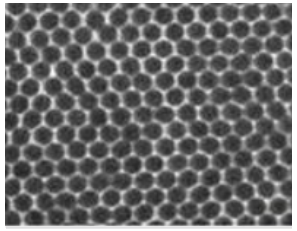
Thin QD film with
ligand matrix



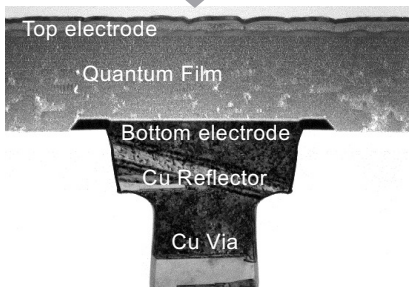
QF photodiode
cross section

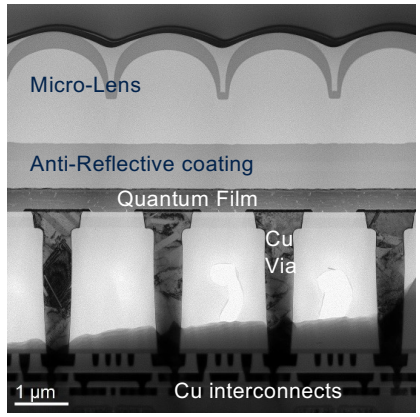


Photodiode array on 65 nm
High density analog & digital
silicon ROIC

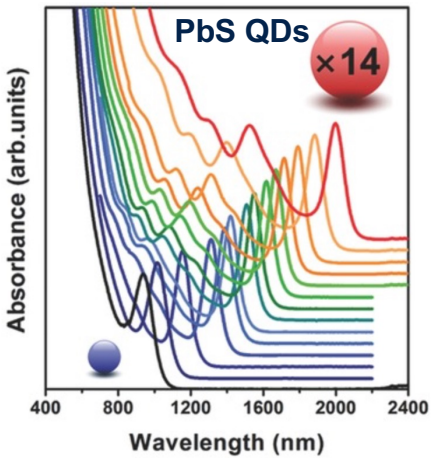


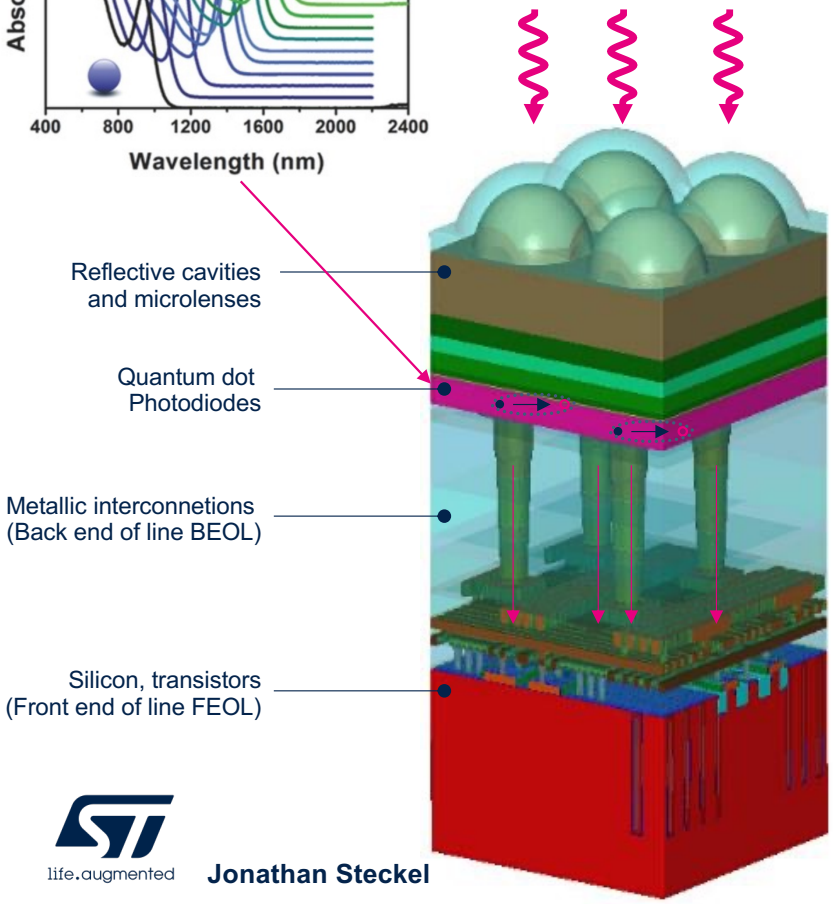
Solid Quantum Film (QF)





QuantumFilm technology integration at ST





QuantumFilm for Photodetection

- Tunability of peak response: UV-Vis-NIR-SWIR-MWIR
- Highly-absorbant materials due to quantum confinement inside nanoparticles
- Enables thin layer for reduced cross-talk and improved resolution
- Low-cost technology:
  - Chemically-synthesized QDs, spin-coated layers, CMOS compatible at 300mm wafer scale

Above IC integration

- 100% fill-factor photodiode
- Enables shrink of complex global shutter pixel
- 1.62-2.2µm pixel pitch demonstrated at 300mm wafer scale

High quantum efficiency in the SWIR

- QE @ first excitonic peak > 60% (940-1400nm)
- Large spectral response from UV, Vis, NIR, to full SWIR

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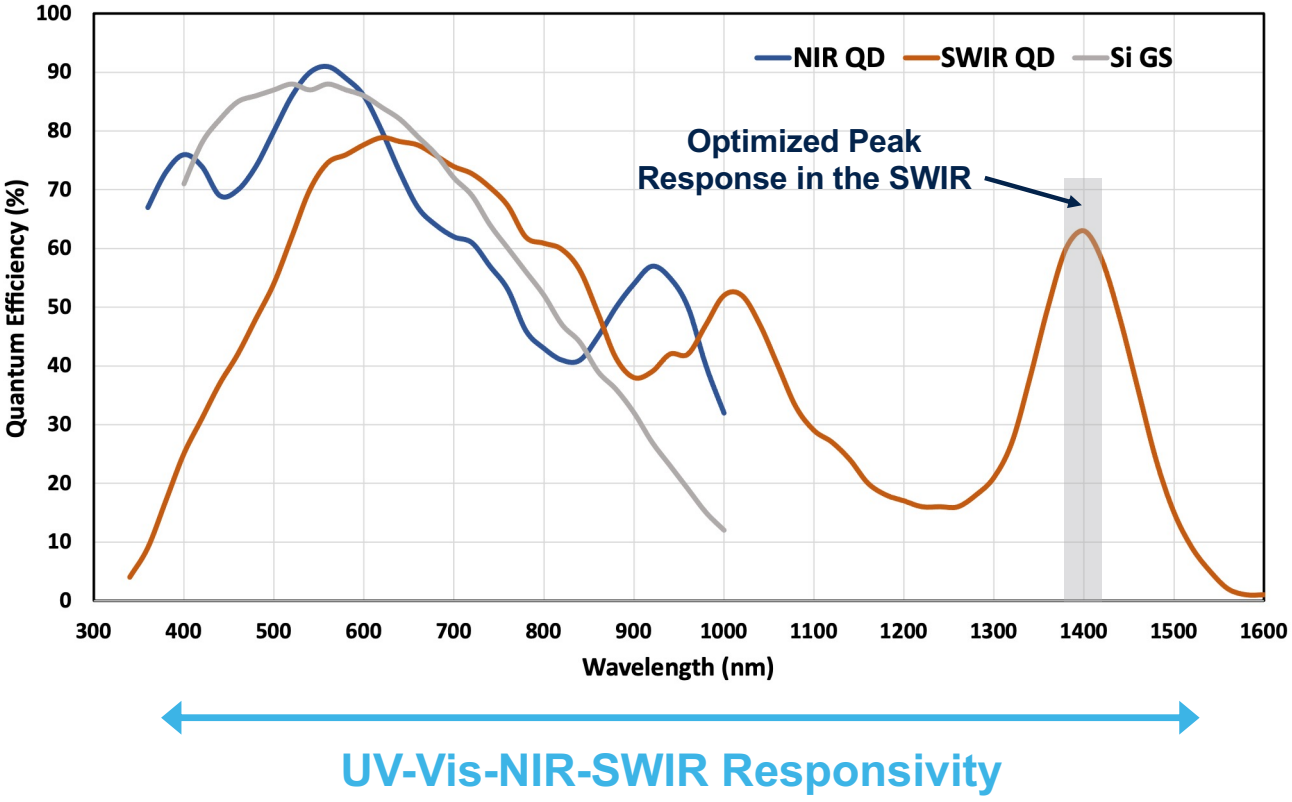
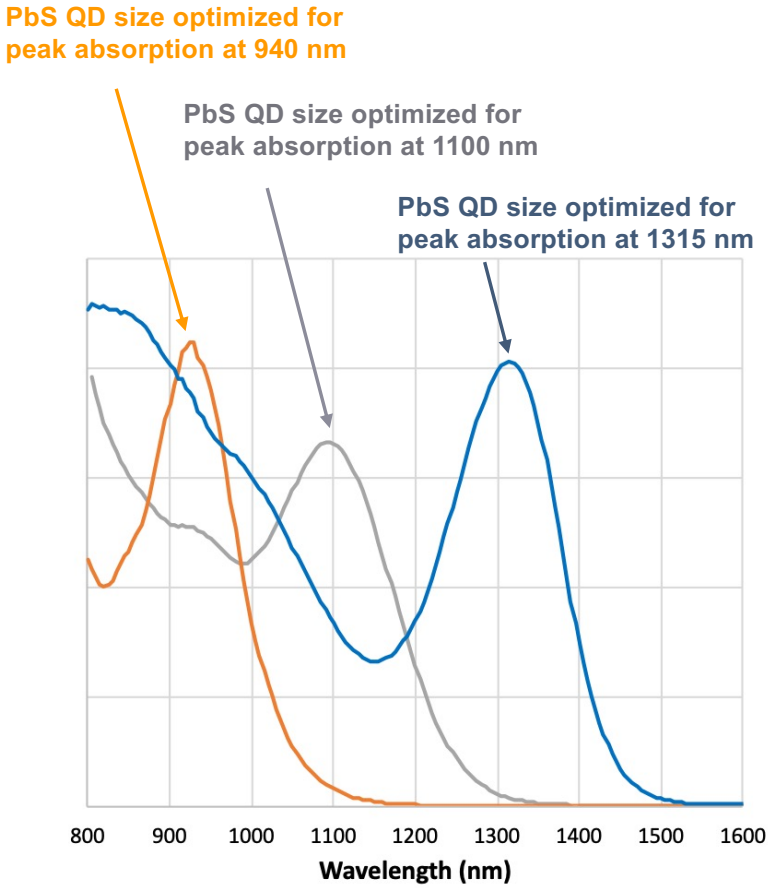
Jonathan Steckel

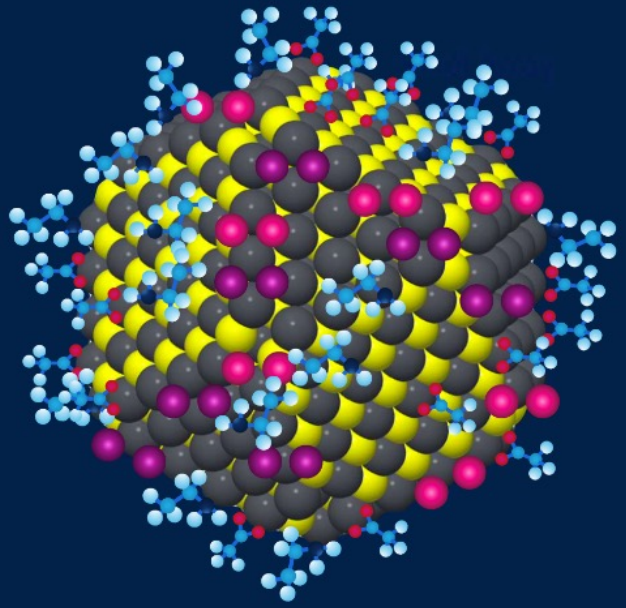
Tunability of the spectral response using QD technology



UV-Vis-NIR-SWIR Responsivity



2 – Image sensing beyond silicon



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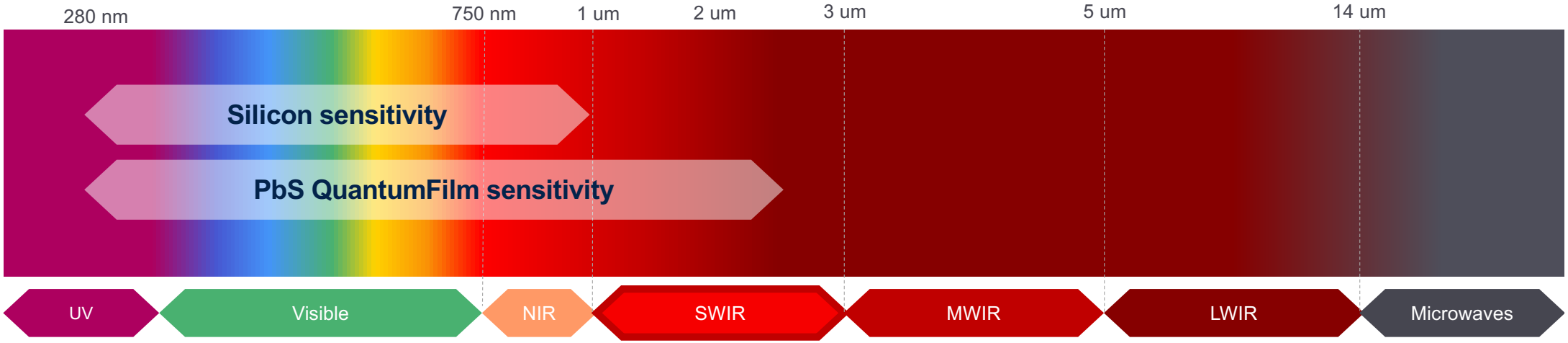
Short-Wave Infrared (SWIR) sensing



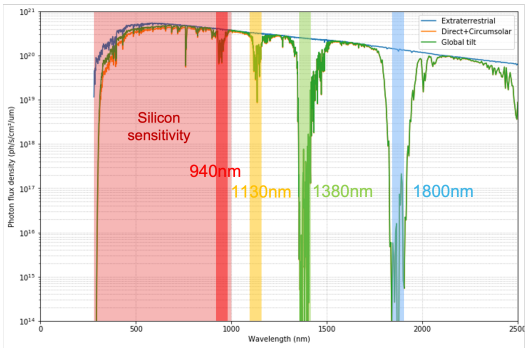
- Short-wave infrared (SWIR) refers to wavelengths of light from **1000 nm to 3000 nm** (1 µm to 3 µm)
- Silicon has no sensitivity beyond 1000 nm
- ST QuantumFilm technology allows access to new types of imaging capabilities and markets that are impossible using visible light

SWIR image sensing value proposition for large markets

Human body imaging

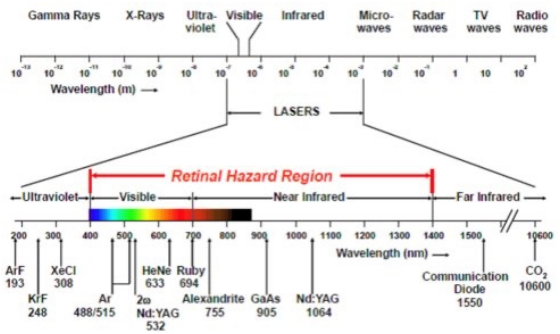
Human skin, hair, and eyes appear the same for all people and are highly distinguishable from non-human materials

Resilience to ambient light



Can image in **solar blind regions** removing sun ambient noise and glare for **better sensitivity/SNR**

Eye Safety

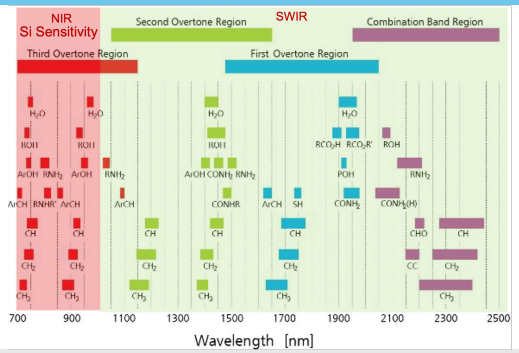


>10X safer for the eye providing higher brightness illumination and **better SNR**

Enhanced vision

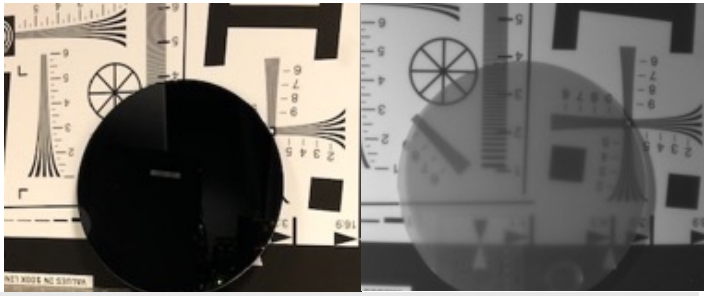
SWIR light is scattered less by particles suspended in air (**higher penetration coefficient**) making it possible to **see through fog, smoke, rain, snow**, etc.

Hyperspectral imaging



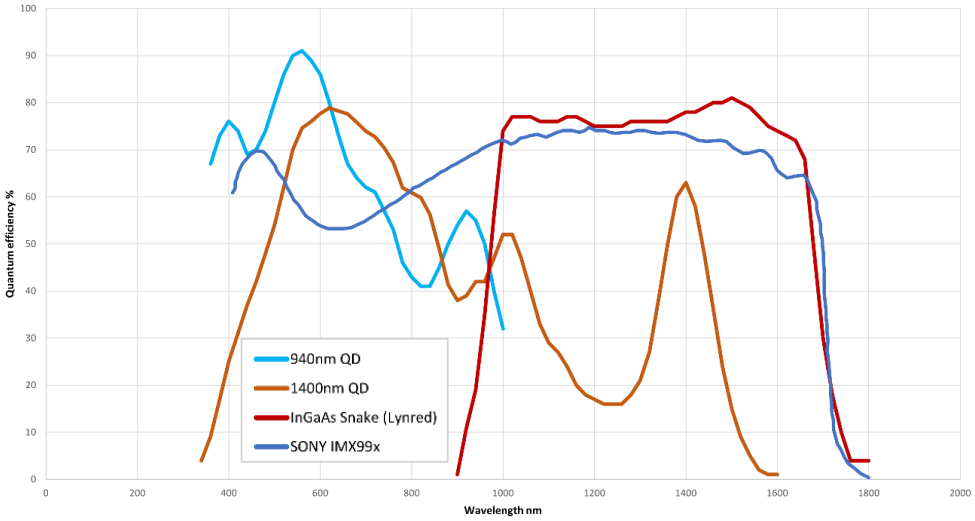
SWIR imaging enables hyperspectral imaging

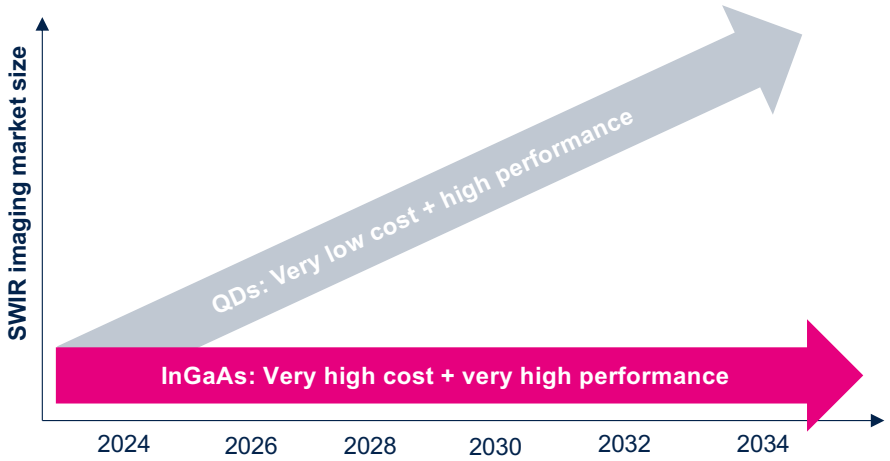
Imaging through Silicon



Silicon is transparent to SWIR light enabling SWIR imaging through Si based devices

QD vs. InGaAs image sensors





SWIR InGaAs image sensors

Large barriers for InGaAs mass market adoption

- Expensive materials
- Expensive processing: Die-to-die fabrication
- Wafer bonding process = Limitations on array size, pixel size, and sensor resolution
- Very expensive sensors

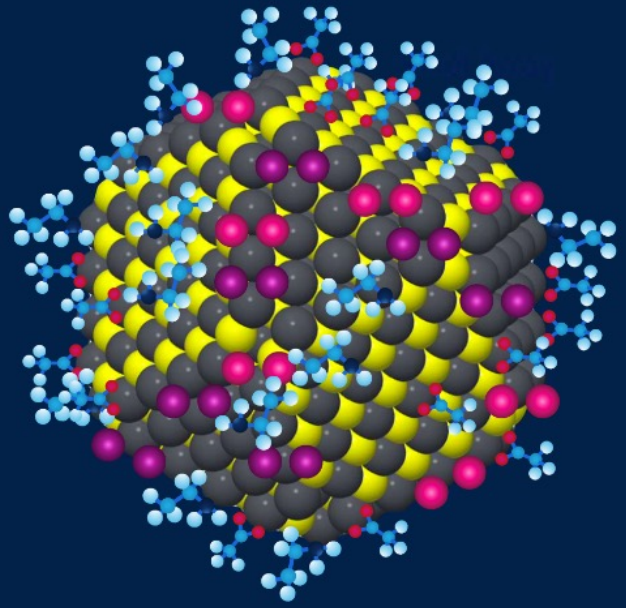
InGaAs image sensors will remain strong in niche markets where cost is less of a driver

- Space, defense, science, high-end performance applications
  - High speed, high efficiency, very stable

SWIR QD image sensors

- **QD image sensors will drive large SWIR imaging market** growth by enabling new sensing applications to emerge for large-volume consumer electronics use-cases
- Driven by **orders of magnitude lower price at mass market scale combined with high performance**

3 – SWIR imaging capabilities with ST QF image sensors



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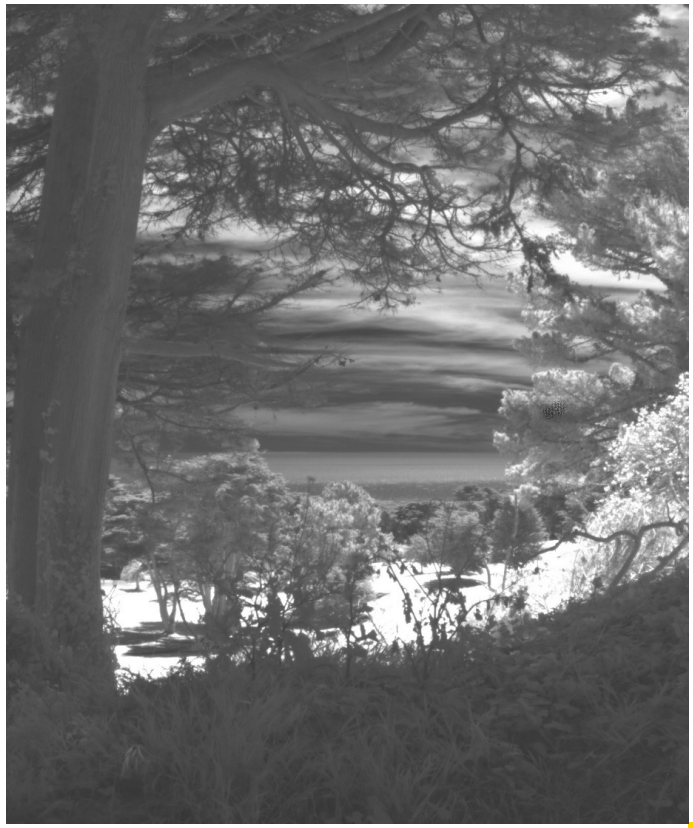
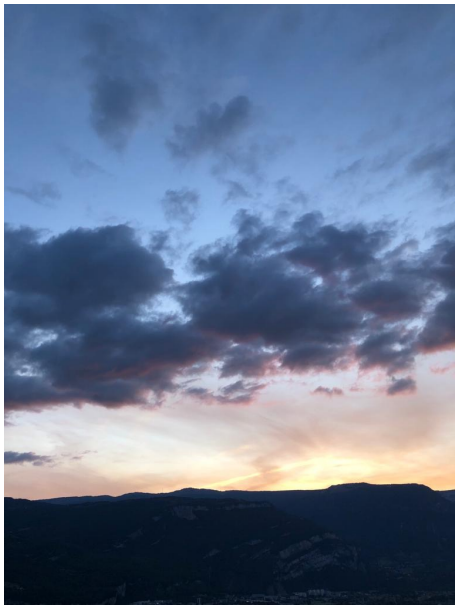
Creating new art: SWIR photography

SWIR mixed scene photography: Sky, sea, forest



QF1400

Illumination: Daylight – Sunny day @3PM



RGB image taken by smartphone

QF1400

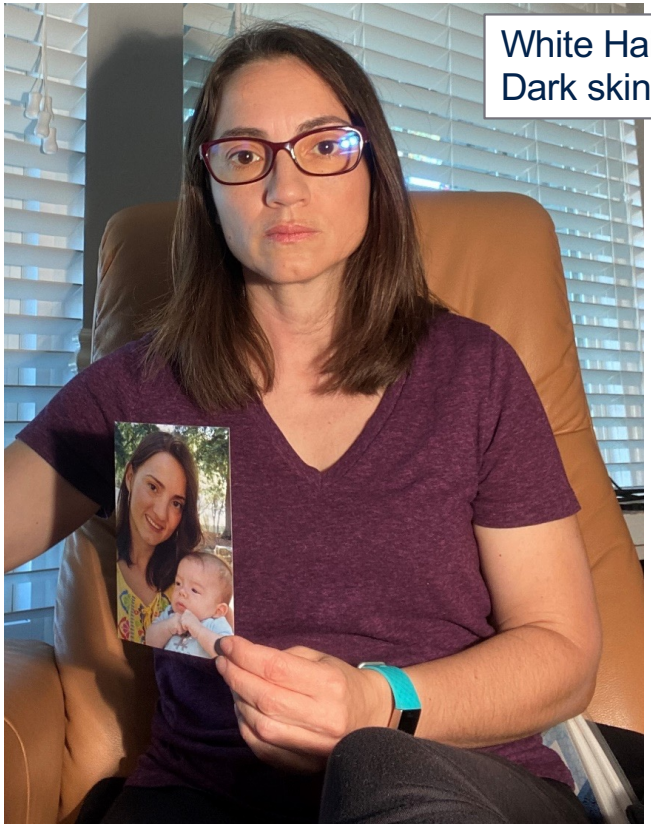
SWIR photography provides different contrasts and reveals material details that are not visible at shorter-wavelengths, especially in outdoor environments

SWIR imaging: biometry and anti-spoofing

SWIR light is able to distinguish authentic human skin reliably from other material, independent of the skin type

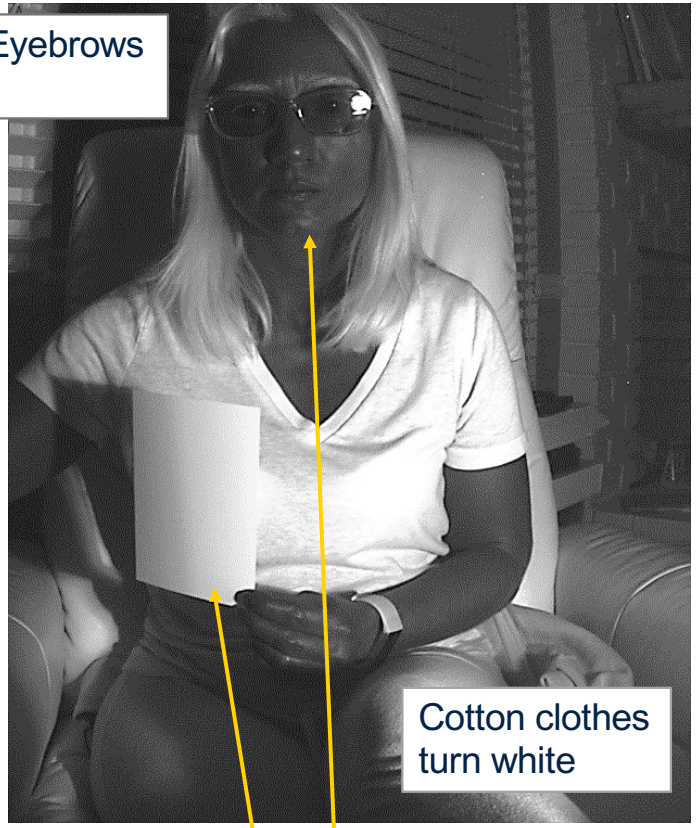
- Most color fabrics/clothes turn white
- Human hair/eyebrows/beard turn white whatever their color
- All skin and eye colors turn dark
- Sunglasses become transparent
- Teeth turn darker

Smartphone



Illumination: IR lamp

QF1400



Face vs photo: photo “disappears”

SWIR imaging: eye tracking and iris recognition

Potential advantages using SWIR for eye tracking and iris recognition

1. Safer for the eye vs. Vis/NIR
2. Less ambient background light vs. Vis/NIR = better signal-to-noise
3. More contrast for most non-human materials

=> Real hair/skin/eyes vs. rubber/plastic/wood/metal

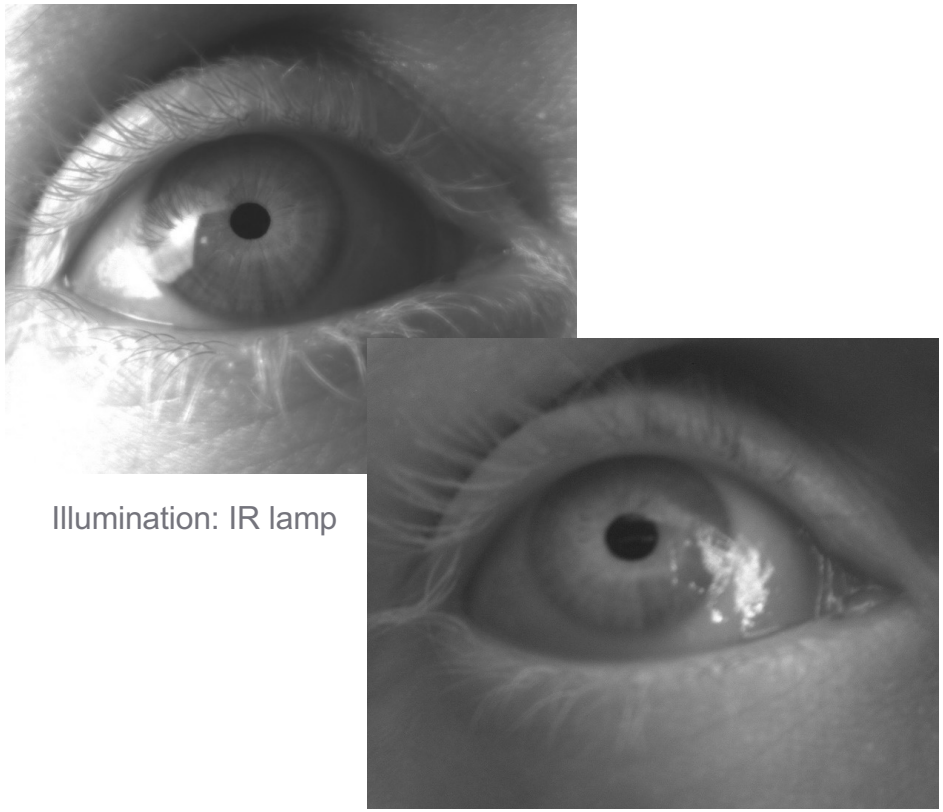
ST VD56G3 at 940 nm

Illumination: IR lamp

QF1400

Illumination: IR lamp

QF1400



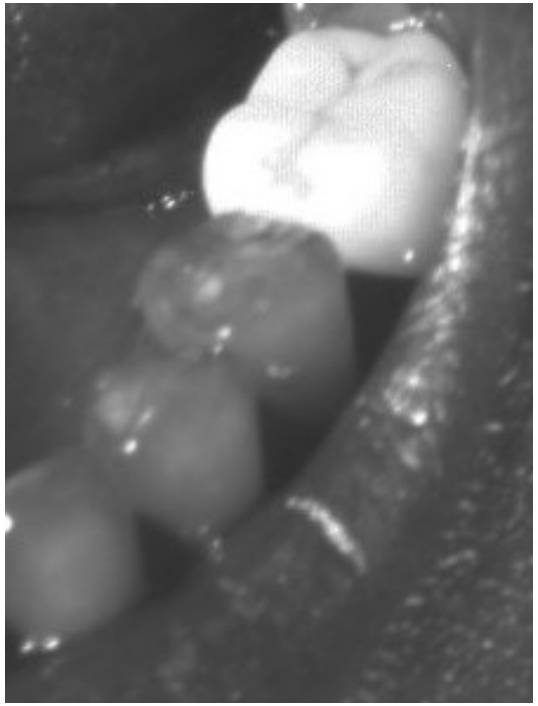
Illumination: Daylight

Using a SWIR long pass filter, the eye pupil clarity is very good while the skin darkens, and the hair turns white

SWIR imaging: teeth vs. crown

Smartphone

QF1400



Illumination: IR lamp

Major difference between crown and real teeth @1400 nm, not observed in other wavelengths

SWIR imaging: heat detection

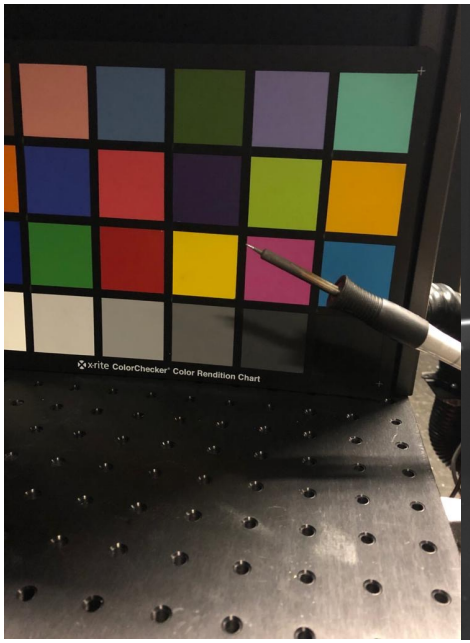
Toaster oven @ 350F

Smartphone

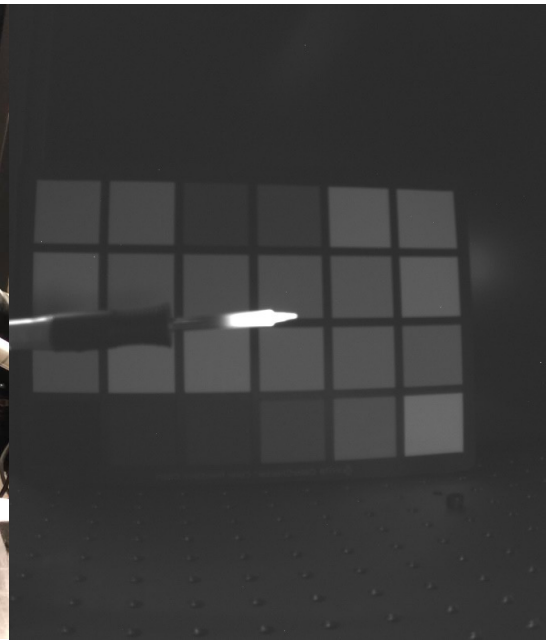
QF1400

Hot soldering iron

Smartphone



QF1400



Hot objects seen very clearly in SWIR when not detectable with human eye

SWIR imaging: food

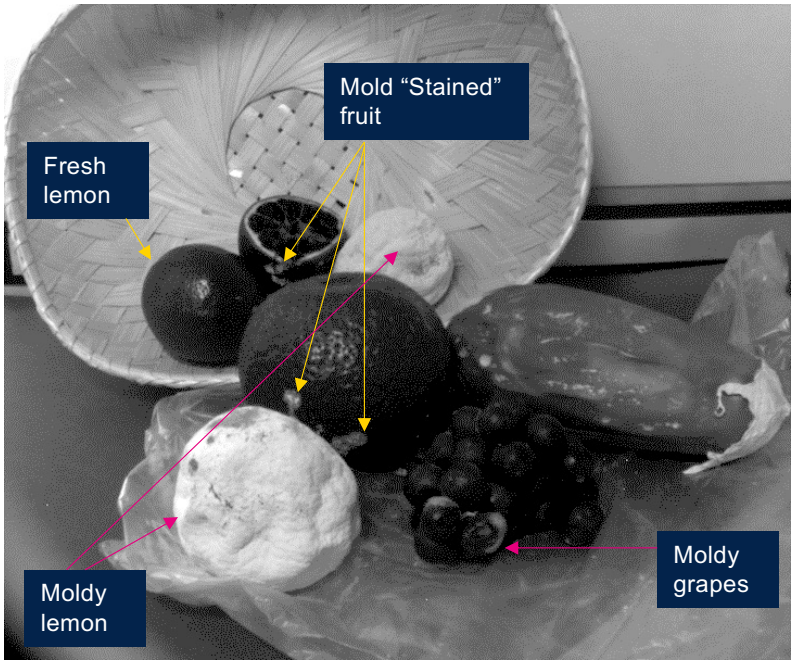
Smartphone

- No difference seen between dust and mold on grapes
- Due to color contrast, mold in lemons is very evident

ST VD56G3 at 940 nm

At 940 nm NIR image sensor shows no major contrast. Mold in grapes not visible at all

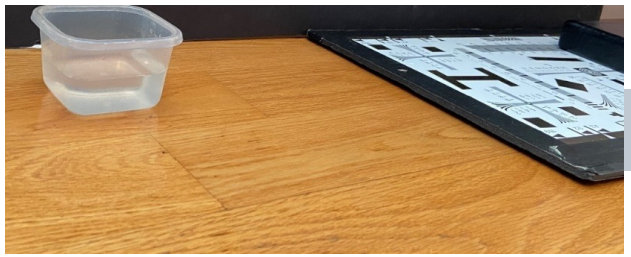
QF1400



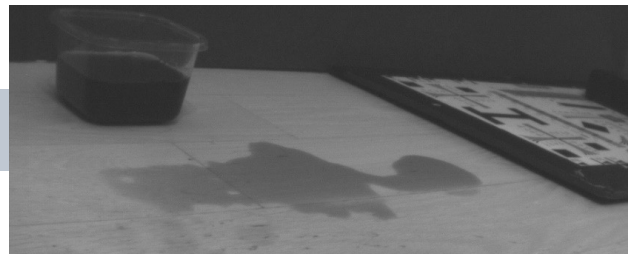
Mold and mold “dust” turns white while the fresh fruits turn dark @1400 nm

Illumination: IR lamp

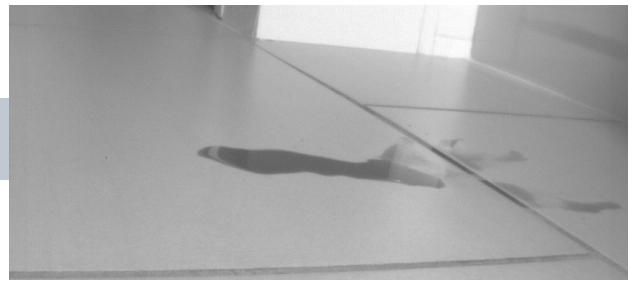
SWIR imaging: water on the floor

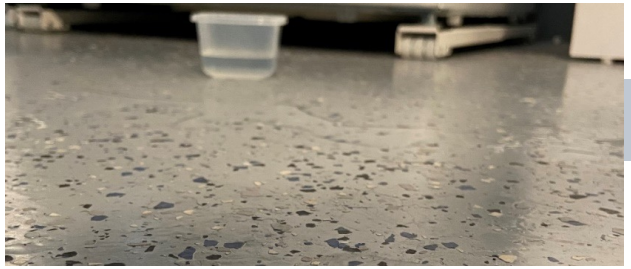


Wood



Tile





Epoxy

Smartphone **QF1400** Illumination: IR lamp

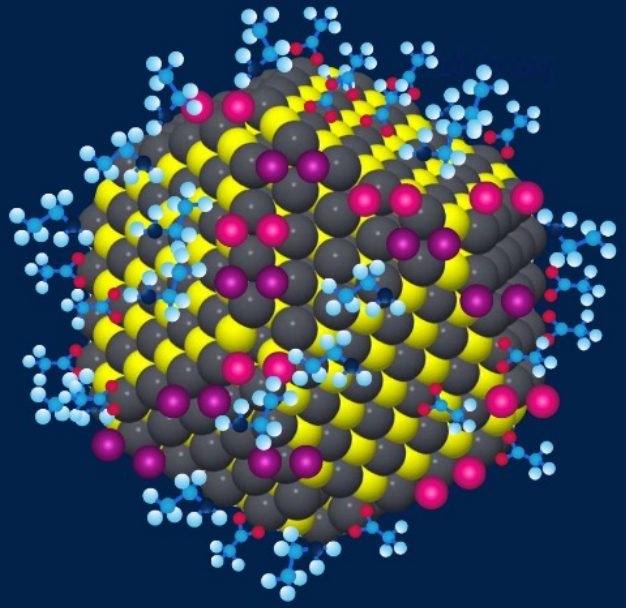
SWIR imaging: vision through foggy glass

Smartphone

QF1400

Illumination: Daylight

4 – Summary & conclusion



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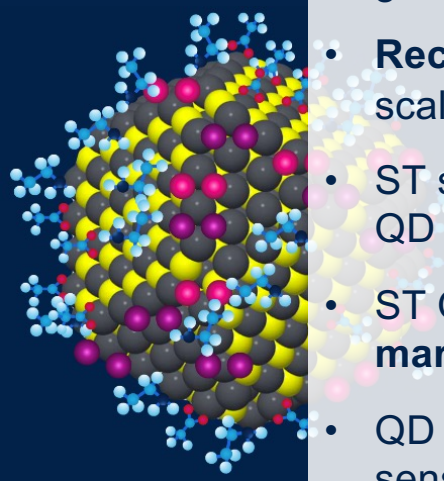
Summary & conclusion



- ST is actively engaged in the industrialization of a **low-cost, high-resolution, disruptive infrared imaging technology** based on colloidal PbS QuantumFilm (QF) technology
- ST QD image sensor technology enables **the highest resolution** (smallest pixel pitch) global shutter image sensors in the industry
- **Record QE and global shutter efficiency** have been achieved on our 300 mm wafer scale process with pixel sizes down to 1.62 µm pitch
- ST successfully overcame the challenges of integrating colloidal PbS solution processed QD materials in an **industrial semiconductor fab environment**
- ST QuantumFilm technology allows access to **new types of imaging capabilities and markets** that are impossible using visible light
- QD image sensors will **drive large SWIR imaging market growth** by enabling new sensing applications for large-volume consumer electronics use-cases driven by orders of magnitude lower price combined with high performance

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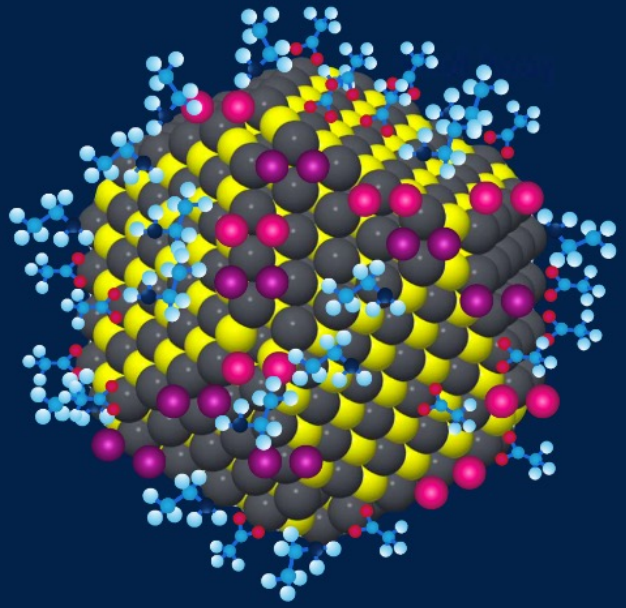
Jonathan Steckel
(Jonathan.Steckel@st.com)

Back Up Slides



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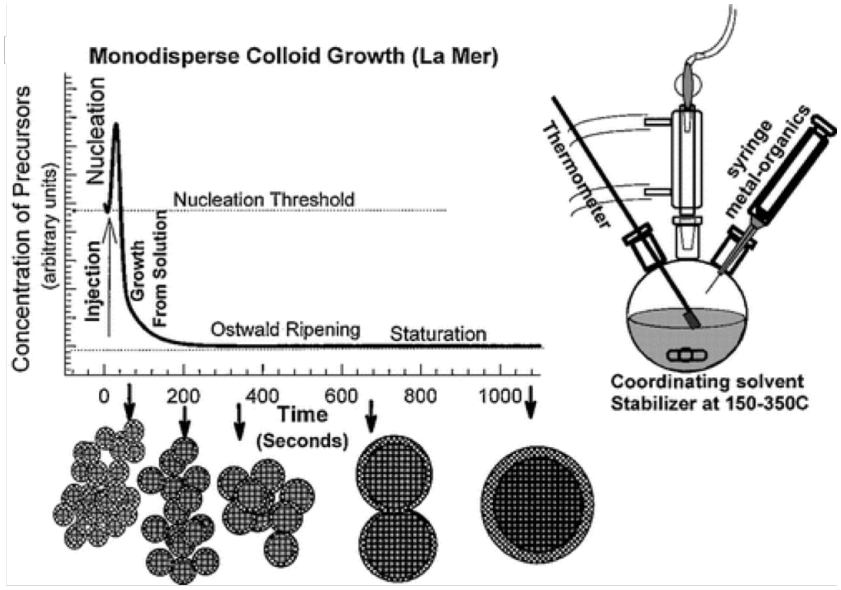
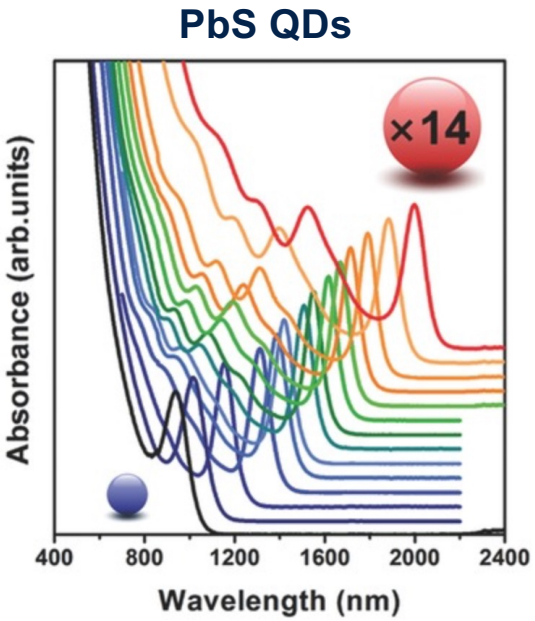
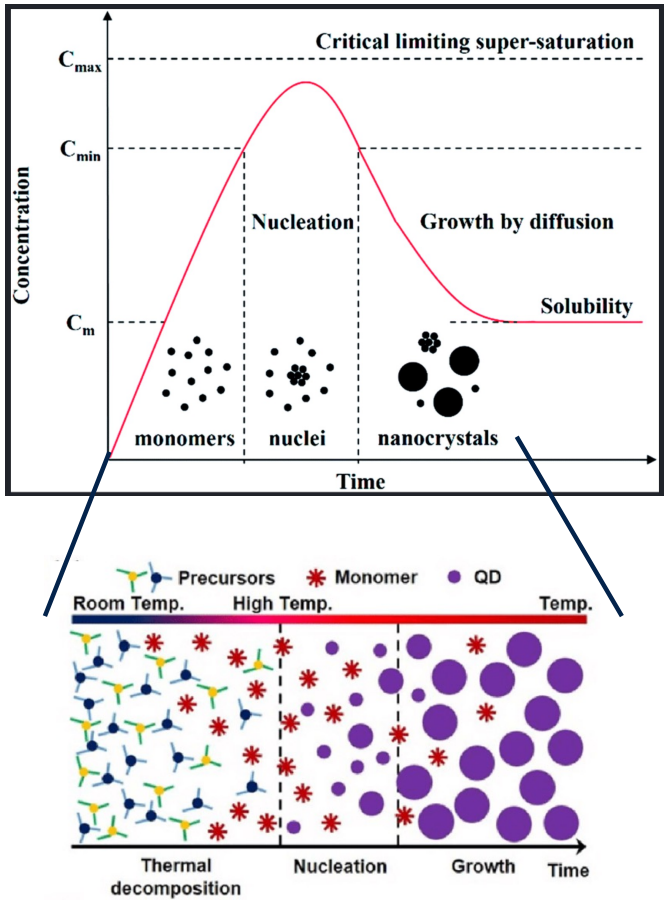
Colloidal QD growth
Tunability of the spectral response

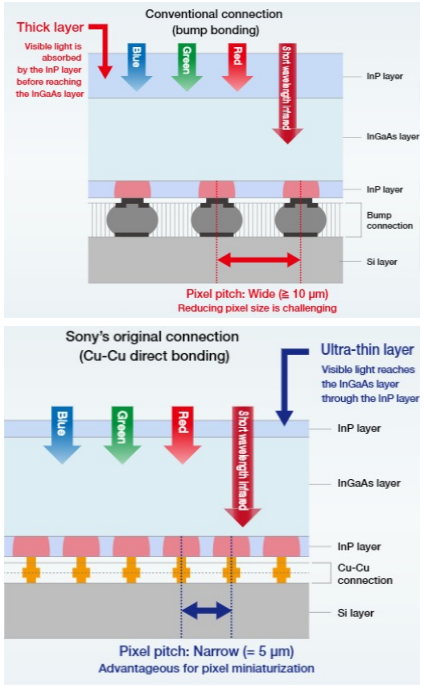






Current SWIR image sensor technologies

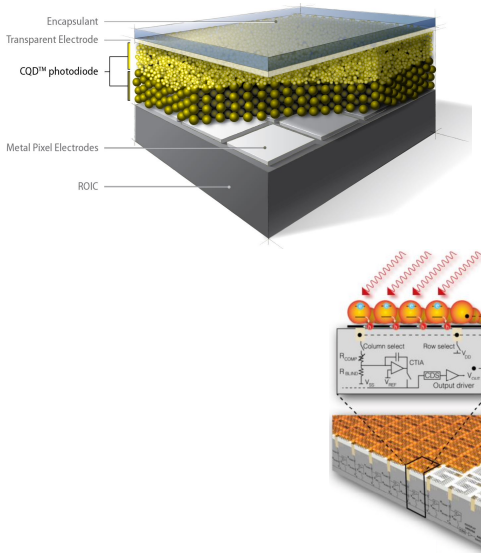
InGaAs technology



Companies leveraging this approach:

SENSORS UNLIMITED
A part of Collins Aerospace
LYNRED
SONY
Xenics
Infrared Solutions
HAMAMATSU
PHOTON IS OUR BUSINESS

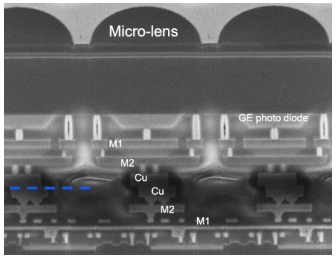
QD technology

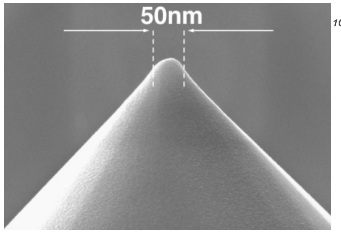


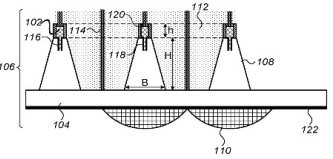
Companies leveraging this approach:

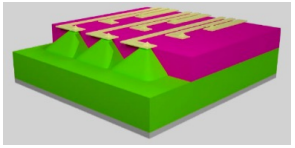
SWIR VISION SYSTEMS
life.augmented
imec
EMBERION
Quantum Science
The INFIQ® Technology Company
NIT
NEW IMAGING TECHNOLOGIES
Quantum SOLUTIONS™
QDI systems
qurv
Q Quantum

SiGe technology









Companies leveraging this approach:

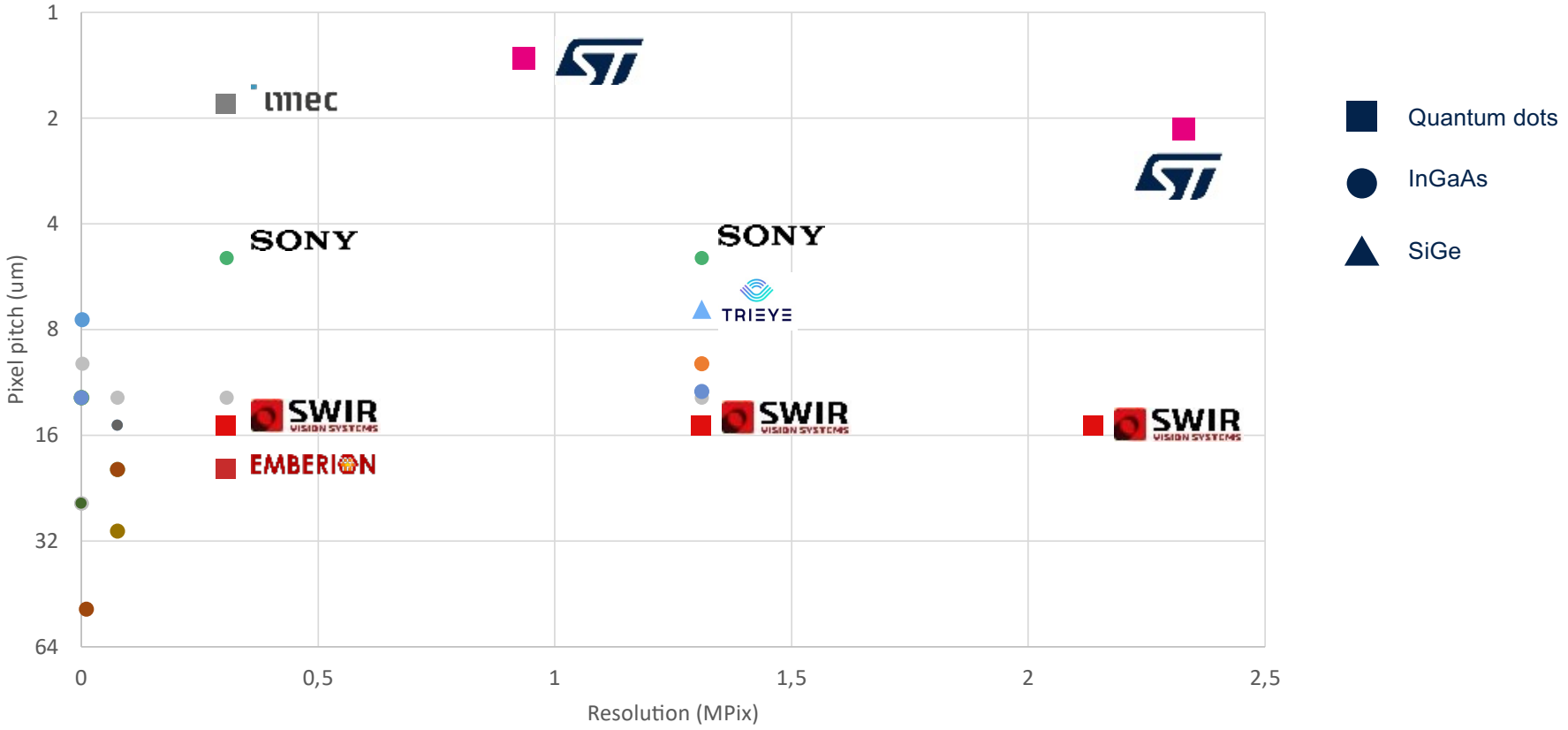
TRIEYE
ARTILUX
Tower Semiconductor
tsmc

SWIR image sensor technology performance comparison

	Pixel pitch	Spectral range	Quantum Efficiency	Dark current	Cost	Speed	Stability	Comments
InGaAs	-	+	++	+	--	+	++	• Best performance & most mature technology • Cost is very high (10^3 higher cost than QF) • Extended range is even more expensive (>1.7um) • Not compatible with the consumer market (cost, pixel pitch)
SiGe	-	+/-	-	-	+	+	+	• Higher dark currents • Limited SWIR wavelength range (<1.5 µm) • Lower pixel pitch and QE
Quantum Dots	++	++	+	+	+	+/-	+/-	• Scalable & compatible with CMOS production • High QE in the SWIR (>60%) • Compatible with consumer market integration requirements (cost, pixel pitch)

QD based Image sensors are **the most promising** to address the consumer electronics market to enable a **new class of imaging capabilities**

SWIR imaging technology mapping
QD vs. SiGe and InGaAs image sensors



ST QD image sensor technology enables **the highest resolution (smallest pixel pitch)** global shutter image sensors in the industry

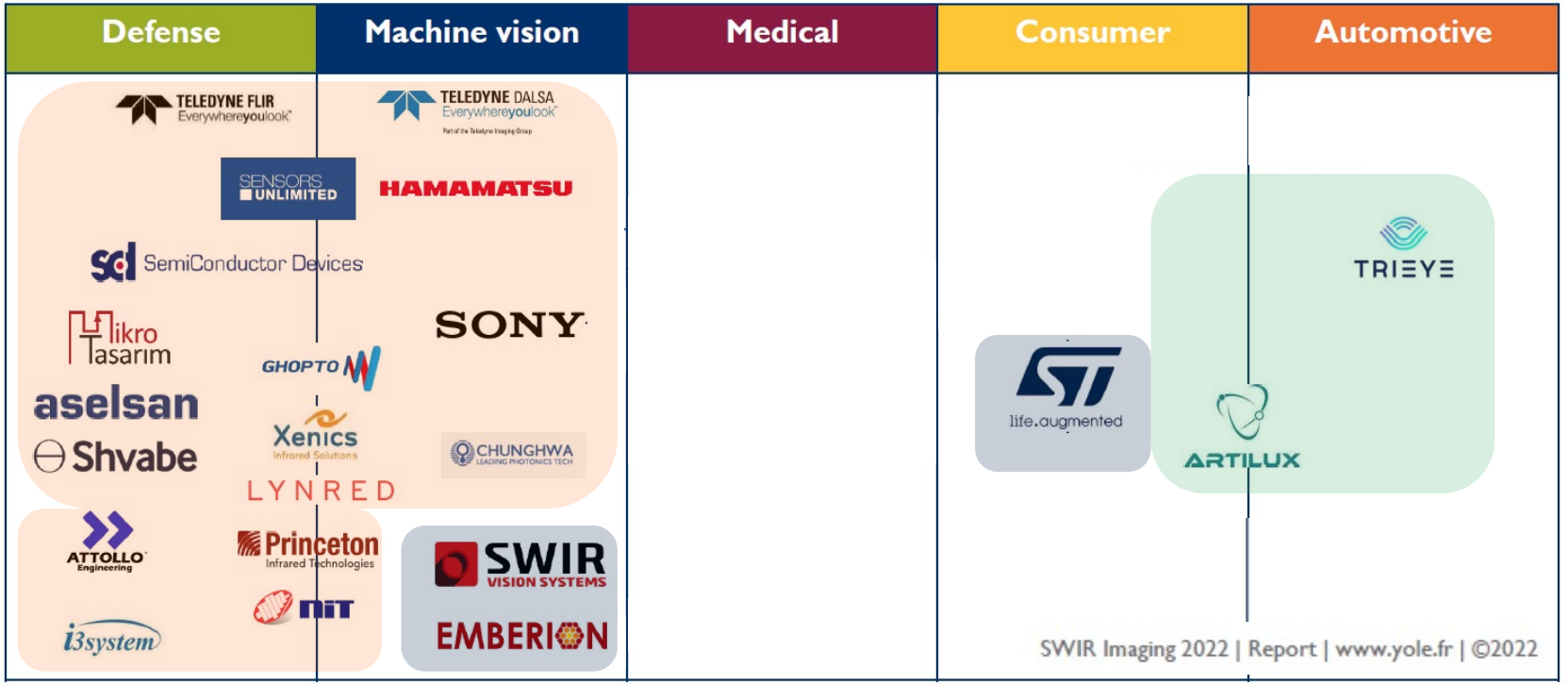
Comparison of QD image sensor technology performance

	Emberion	ICFO	IMEC	SWIR vision systems	STMicroelectronics Steckel, IEDM, 2021			
Peak wavelength	1850	1670	1450	1470	940	940	1400	1400
QD type	PbS	PbS	PbS	PbS	PbS	PbS	PbS	PbS
Pixel pitch (um)	20	-	5	15	2.2	**1.62**	2.2	**1.62**
Resolution (Mpix)	0.3	0.1	0.4	2.1	2.3	0.9	2.3	0.9
Conversion gain (μV/e-)	-	-	2.2	-	**52**	**52**	**52**	**52**
Dynamic range (dB)	**120**	>80	82	70	63.6	53.9	63.2	53.4
Full well capacitance (ke)	-	-	325	**550**	30	10	30	10
Dark current (uA/cm-2)	-	-	3.3 @25°C	5e-3 @ 25°C @ 0.1V	8e-3 @60°C @ 3V	**5e-3 @60°C @ 3V**	0.23 @ 60°C @ 3V	0.13 @ 60°C @ 3V
Read noise(e-)	-	-	25	210	**19.8**	20.3	20.7	21.3
PRNU (%)	-	-	2.4	-	**0.7**	0.8	**0.7**	1.4
EQE at peak (%)	20	-	40	15	50	50	**62**	**62**

Pejović , IEEE TED, 2022

Best reported performance

Established vs. emerging applications in SWIR imaging



InGaAs technology

SiGe technology

QD technology

Defense & machine vision

- Most established markets
- Niche markets where **cost is not a driver**

Consumer & automotive

- New emerging markets enabled by players from semiconductor industry focusing on **high volume markets**

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