SWIR VISION SYSTEMS

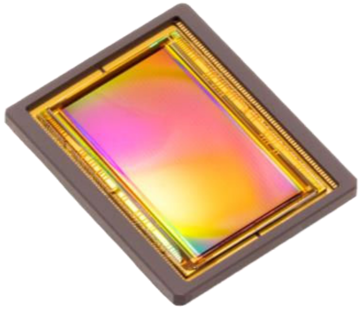
SWIR Vision System CQD Sensors
Image Sensors Europe
March 2023

Overview

- Introduction
  - SWIR Vision Systems and its CQD detector technology
  - Camera and sensor products
- Applications
  - Design tradeoffs for SWIR and NIR-based systems in consumer and automotive
- High speed CQD detectors
  - Characterization of CQD SWIR high speed detector performance
- Reliability
  - Progress towards consumer and automotive qualification and solder reflow compatibility
- Summary and Outlook

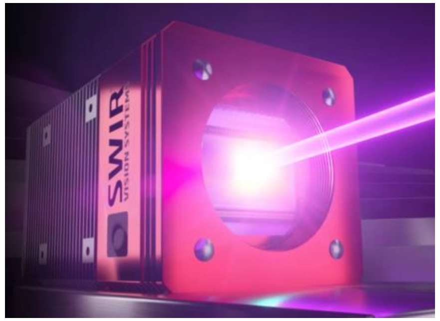
SWIR Vision Systems’ detector technology enables high-resolution IR applications in consumer and automotive markets

Acuros CQD SWIR Sensors and Cameras

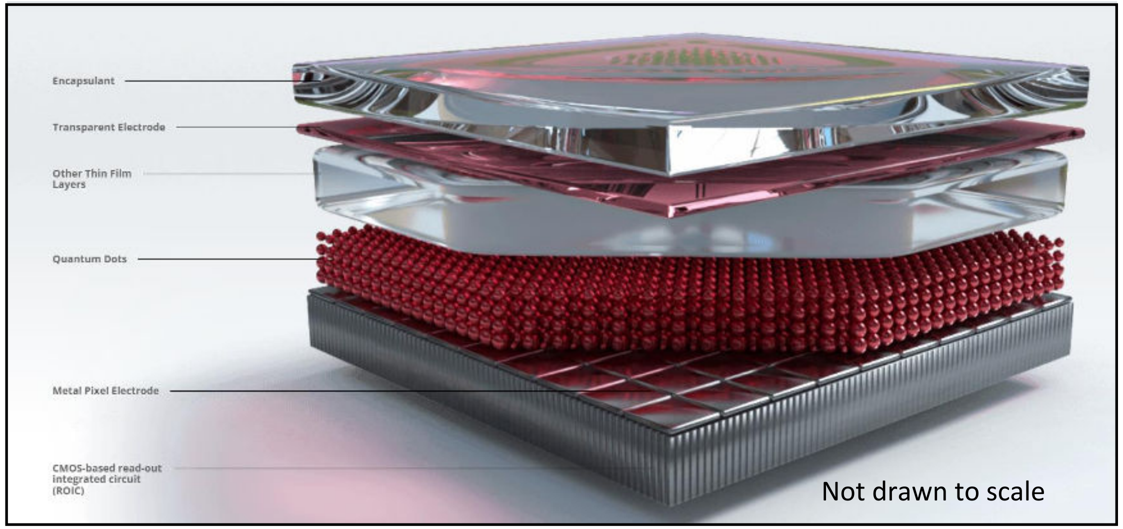


Acuros® CQD® SWIR sensor

SWIR Vision has successfully commercialized quantum-dot based CQD® SWIR sensor technology



Acuros® CQD® SWIR camera



SWIR Vision's patented CQD quantum dot photodiode structure delivers critical performance advantages

Acuros® CQD® short wavelength infrared cameras inspect semiconductors, lasers, and Li:Ion batteries

Long range imaging – CMOS vs Acuros eSWIR

CMOS Visible camera

Acuros 1920 eSWIR camera

Acuros 1920 eSWIR camera aerial image

SWIR VISION SYSTEMS

Infrared Sensing and Imaging Applications

SWIR VISION SYSTEMS

Applications

Driver Monitoring & LIDAR Systems

Facial Recognition

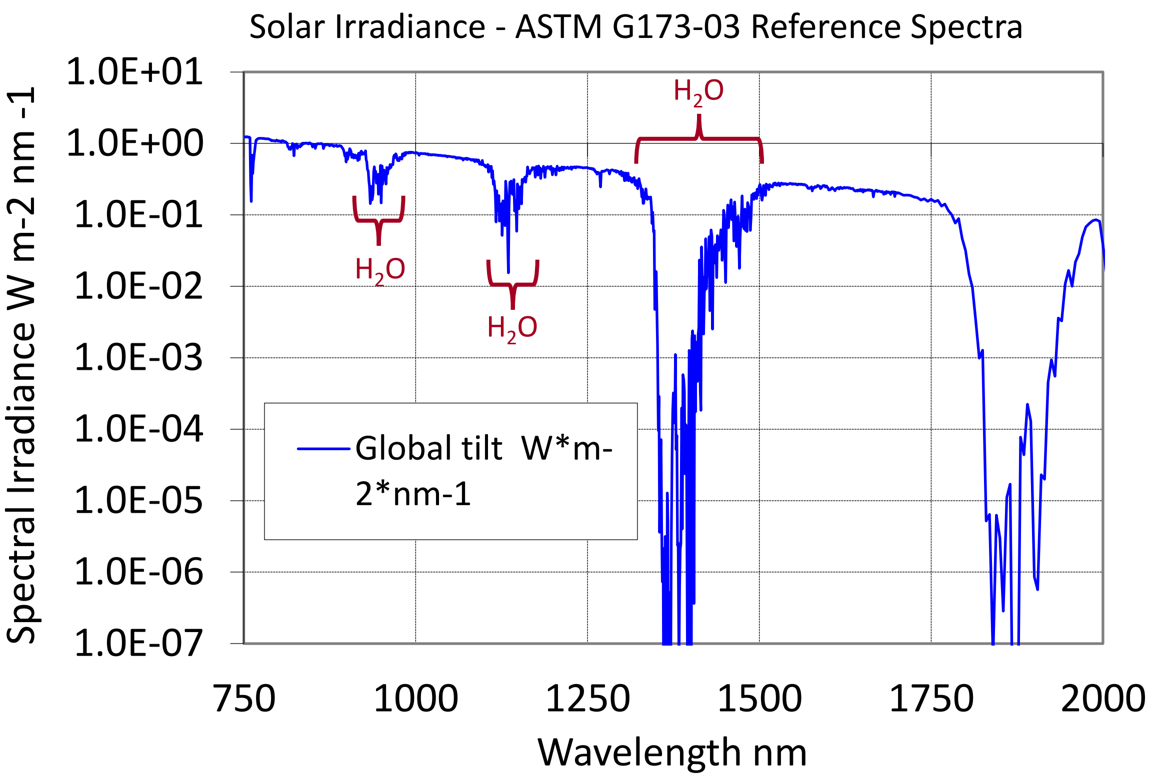
Eye-Tracking

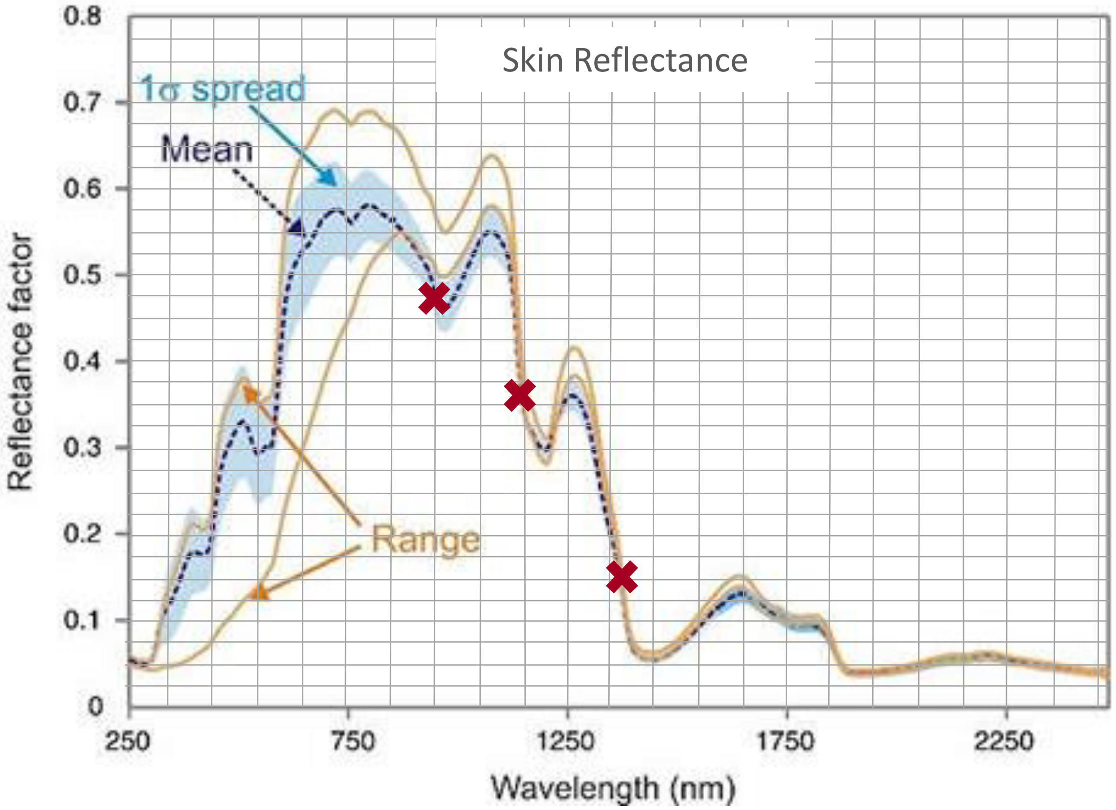
Skin-spectroscopy Blood monitoring

Attribute	NIR (<1000 nm)	SWIR (1000-2500 nm)	Notes
Sunlight power	Medium to High	Low (or very low)	Background sunlight dominates ‘noise’ level in active illumination systems
OLED burn-in/damage	Yes (at 940 nm)	No	Under-OLED sensor systems desirable for mobile and automotive applications
Eye safety	OK	Excellent	Very high damage threshold for SWIR wavelengths
Skin detection	Yes	Yes	First high-volume consumer deployment of SWIR sensors (not ours), in 2021
Chemical signatures	Some (Water)	Water, glucose, Hydrocarbons, etc.	

- Systems that utilize active light source can be designed around NIR or SWIR wavelengths
- System tradeoffs exist for the selection of the illumination wavelength
- Table shows considerations for utilizing NIR or SWIR-based active illumination system

IR Active Illumination Wavelength Tradeoffs





Conclusions:

Systems designed for sensing/imaging in outdoor conditions can benefit from the low background light (i.e. noise) that exists at 1130 nm and 1380 nm

Noise benefit is partially offset by reduction in skin reflectance at 1130 and 1380 compared to 940 nm

Wavelength	Sunlight Power (W/m²/nm)	Skin Reflectance	OLED Display Damage
940 nm	0.2	0.475	Yes
1130 nm	0.07	0.35	TBD
1380 nm	0.00000004	0.15	No

Cooksey, C. , Tsai, B. and Allen, D. (2015), Spectral reflectance variability of skin and attributing factors, Proceedings of SPIE Defense and Security Symposium, [online], https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=918494

SWIR and NIR System Applications System Needs

SWIR VISION SYSTEMS

Application/Use case	Active or passive illumination	Resolution / pitch	Under OLED	Indoor/ outdoor	Wavelength(s)	Bandwidth/ Exposure time	Low power req	NIR/SWIR deployment today
Proximity Detection	Active	1 pixel	Yes	Both	940, 1380, 1550 nm	High (ns)	Yes	NIR and SWIR
Skin detection	Active	2 pixels	Yes	Both	1100 + 1400 nm	Low (ms)	Yes	SWIR
Face ID – Structured light	Active	1MP+, <3um	Yes	Both	940, 1130, 1380 nm	Med (us)	Yes	NIR
Face ID – ToF	Active	VGA+, <5um	Yes	Both	940, 1130, 1380 nm	High (ns)	Yes	NIR
Face ID – 2D image	Active/Passive	1MP+, 2 um	Yes	Both	940, 1130, 1380 nm	Low (ms)	Yes	NIR
Eye/gaze tracking	Active	1MP+, 2um	No	Both	940, 1130, 1380 nm	Med (us)	Yes	NIR
Auto-driver monitoring	Active	1MP+, 4um	Yes	Outdoor	940, 1130, 1380 nm	Low (ms)	No	NIR
Auto-2D long range	Passive day/Active night	1MP+, 4um	No	Outdoor	1000-2400 nm (passive) 1550 nm (active)	Low (ms)	No	NIR
Auto-3D dToF/iToF	Active	VGA+, TBD	No	Outdoor	940, 1550 nm	High (ns)	No	NIR and SWIR
Skin moisture monitoring	Active	1MP+, 2 um	No	Indoor	1420 nm	Low (ms)	Yes	No
Blood glucose	Active	TBD	No	Indoor	1700 - 2200 nm	Low (ms)	Yes	No
Other spectroscopy	Active	TBD	No	Indoor	800 – 2500 nm	Low (ms)	No	NIR

Majority of these applications served by a technology that can offer:

Multi-megapixel formats, small pitch, under OLED, 800-1600 nm spectral sensitivity, nanosecond response time

SWIR Eye and Face Images

- Images on following slides were taken with Acuros CQD SWIR cameras
  - Sensor format: 1920 x 1080, 15 um pitch
- Unless noted, sensor temperature was held at 30C
- Image shown were single frame captures (no averaging)
- LED-illuminated images were captured using a Genesi multi-wavelength (SWIR GEVXD) IR light source

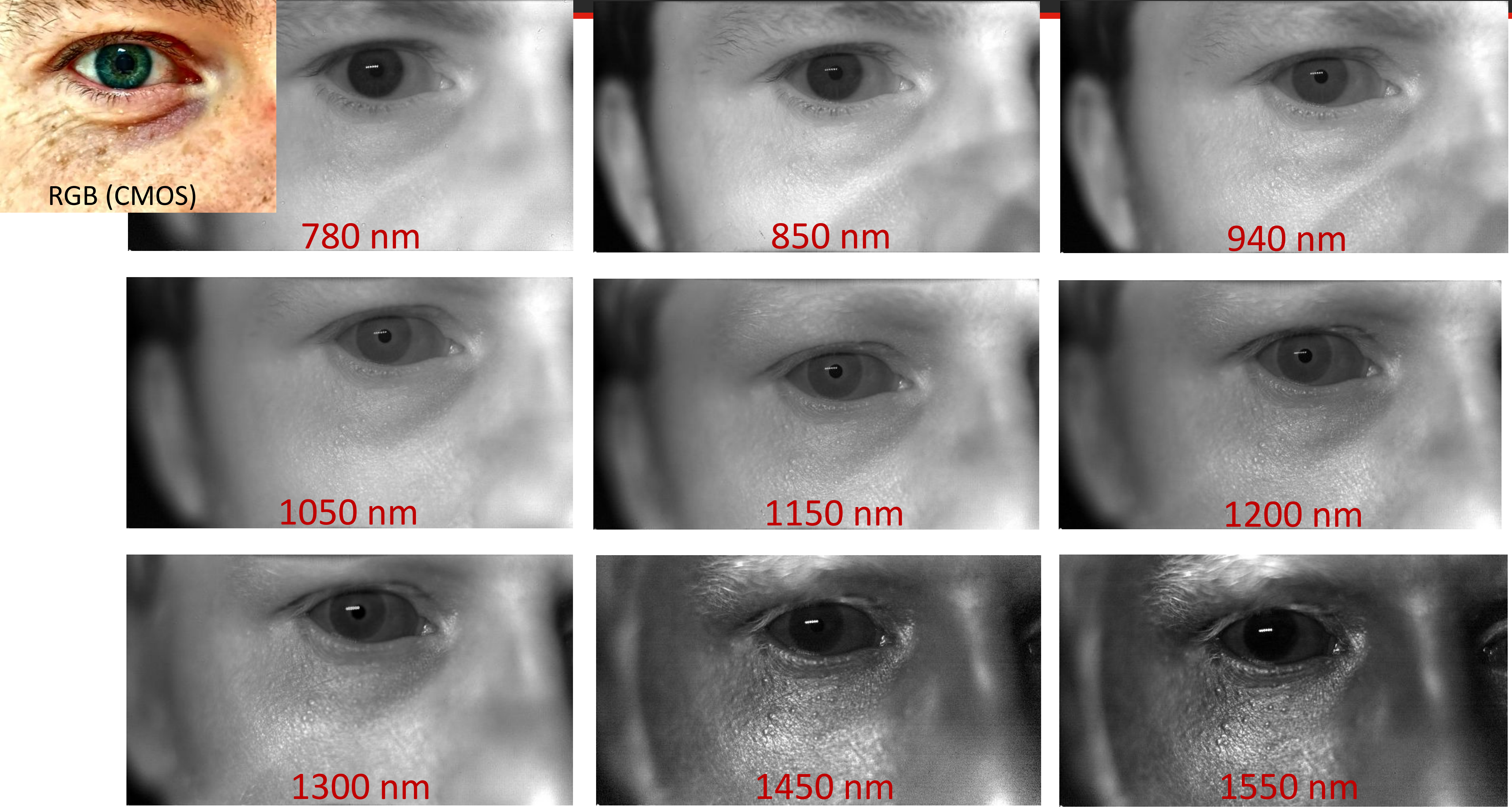
Acuros® 1920 CQD® SWIR Camera

Conclusion:

- Our CQD SWIR detectors can generate high quality images of eye/face using SWIR wavelengths found in atmospheric absorption bands

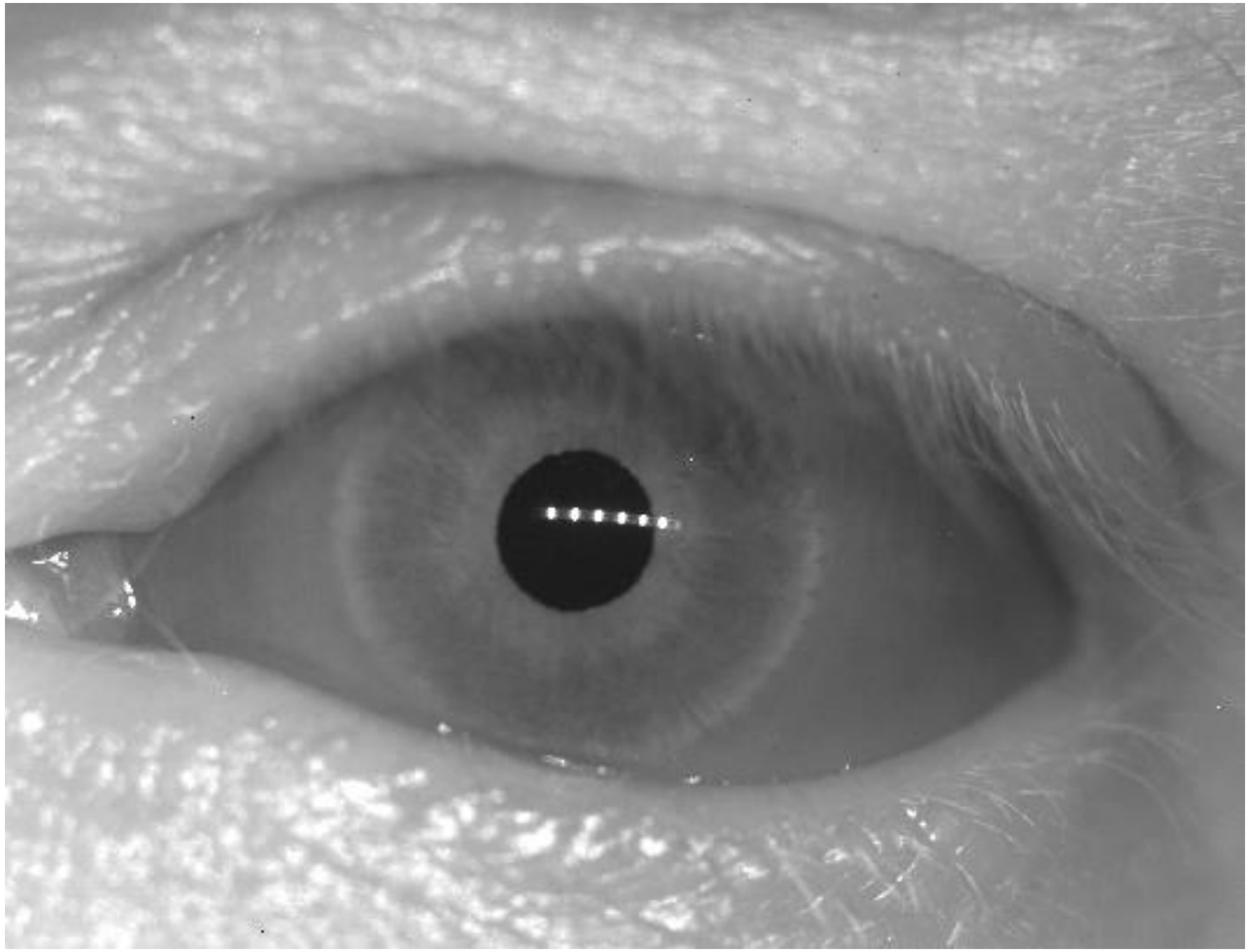
Eye/Face Images in NIR and SWIR

SWIR VISION SYSTEMS



Face and Eye SWIR Images – 1150 nm LED

1150 nm LED, 5 ms exposure

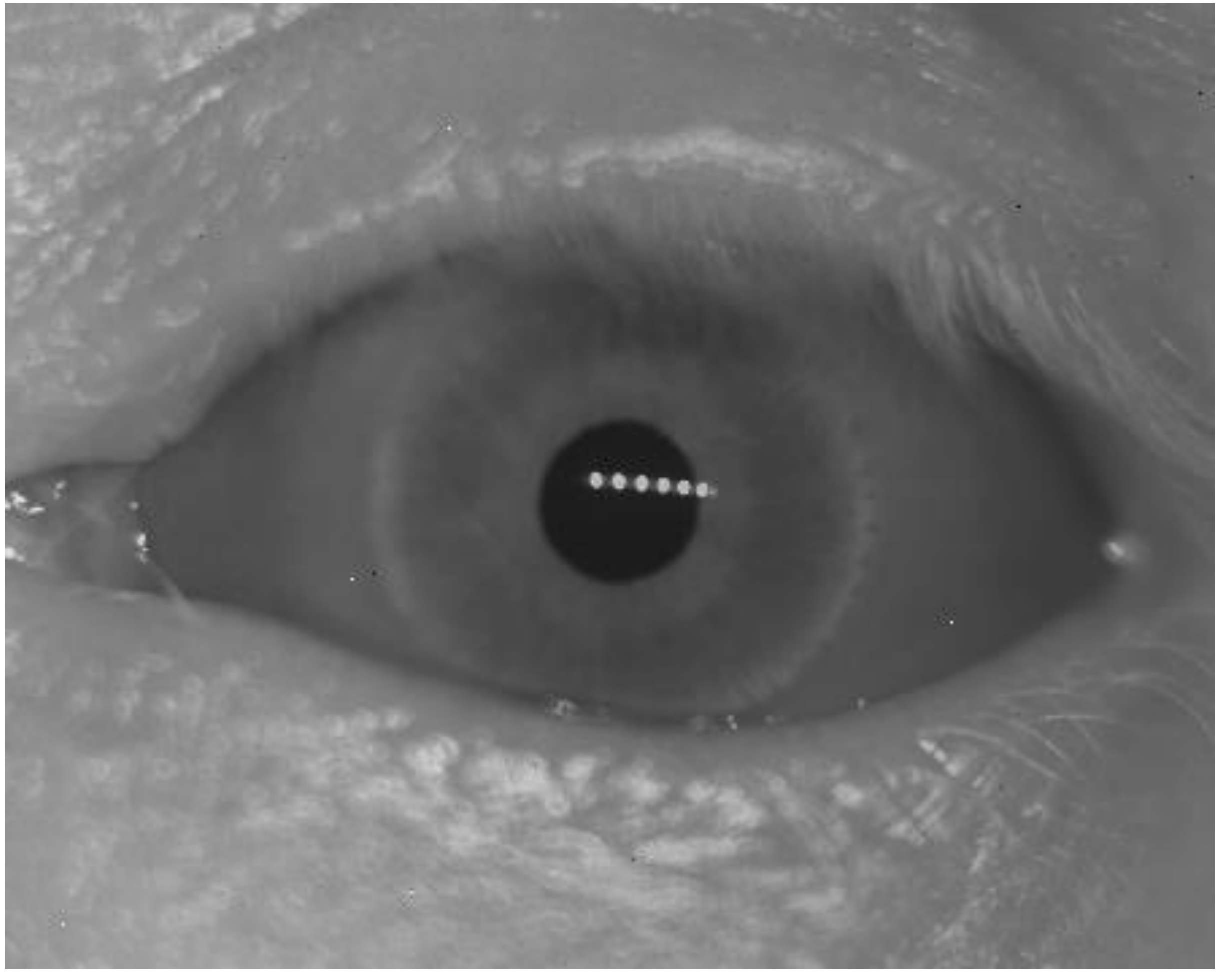


1150 nm LED, 5 ms exposure

Face and Eye SWIR Images – 1300 nm LED

SWIR VISION SYSTEMS

1300 nm LED, 10 ms exposure



1300 nm LED, 10 ms exposure

Face and Eye SWIR Images – 1370 nm Laser

1370 nm laser + diffuser, 15 ms exposure

Note: Speckle from diffuser contributes to fixed pattern noise seen in image

Emitter wavelength/power tradeoffs

- Applications requiring outdoor functionality must emit enough optical power to overcome the background solar noise present at the detector
- We compare the electrical power needed at three emitter wavelengths to generate a SNR of 1
- Assumptions:
  - Pixel Pitch = 2 um
  - Exposure time = 10 ms
  - 30 nm BPF on detector
  - Lens optical throughput assumed to be equivalent for each proposed system

	Emitter wavelength	Solar irradiance	Detector QE	Solar shot noise	Detector dark noise	Background noise (total)	Received signal for SNR = 1	Received peak power for SNR = 1	Emitter efficiency	Skin reflection
	nm	W/cm^2	%	e rms/pixel	e rms/pixel	e rms/pixel	photons/pixel	W/cm^2	W/W	%
Si CMOS	940	1.2E-03	20	661	2	661	3309	1.7E-06	0.4	48
SVS CQD	1130	5.0E-04	40	559	5	559	1988	1.0E-06	0.25	35
SVS CQD	1380	3.4E-07	30	17	5	17	58	3.0E-08	0.15	15

Results of Analysis:

Systems using SVS CQD and a 1380 nm light can save 85% of the power needed by 940 nm light source in a CMOS system

Systems using SVS CQD and a 1380 nm light can save 87% of the power needed by 1130 nm light source in a CMOS system

Acuros sensor 85C operation

- Operation at 85C (and higher) is required for consumer applications
- SWIR Vision's CQD detectors can operate at 85C (and above)
  - InGaAs and Ge need active cooling (i.e. TEC's) to operate in 85C environments
- Images shown here were collected with Acuros CQD SWIR Sensors held at 85C

	Jd Doubling temp	Jd at 25C	Jd at 85C
InGaAs	7 C	5 nA/cm^2	
SVS CQD	11 C	5 nA/cm^2	

Texp = 1.5 ms, Tsensor = 85C

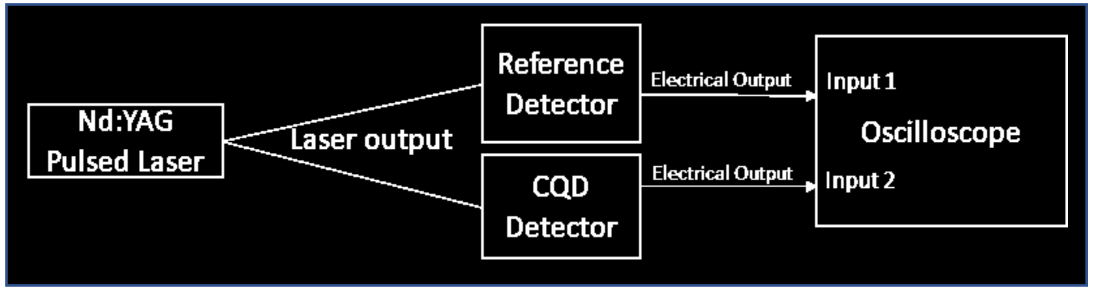
Texp = 2.0 ms, Tsensor = 85C

Texp = 2.5 ms, Tsensor = 85C

- Acuros™ CQD™ SWIR Camera
- Optical filter: 1100 – 1200 nm
- Halogen Light

CQD diode response time measurements

Response time measurement setup



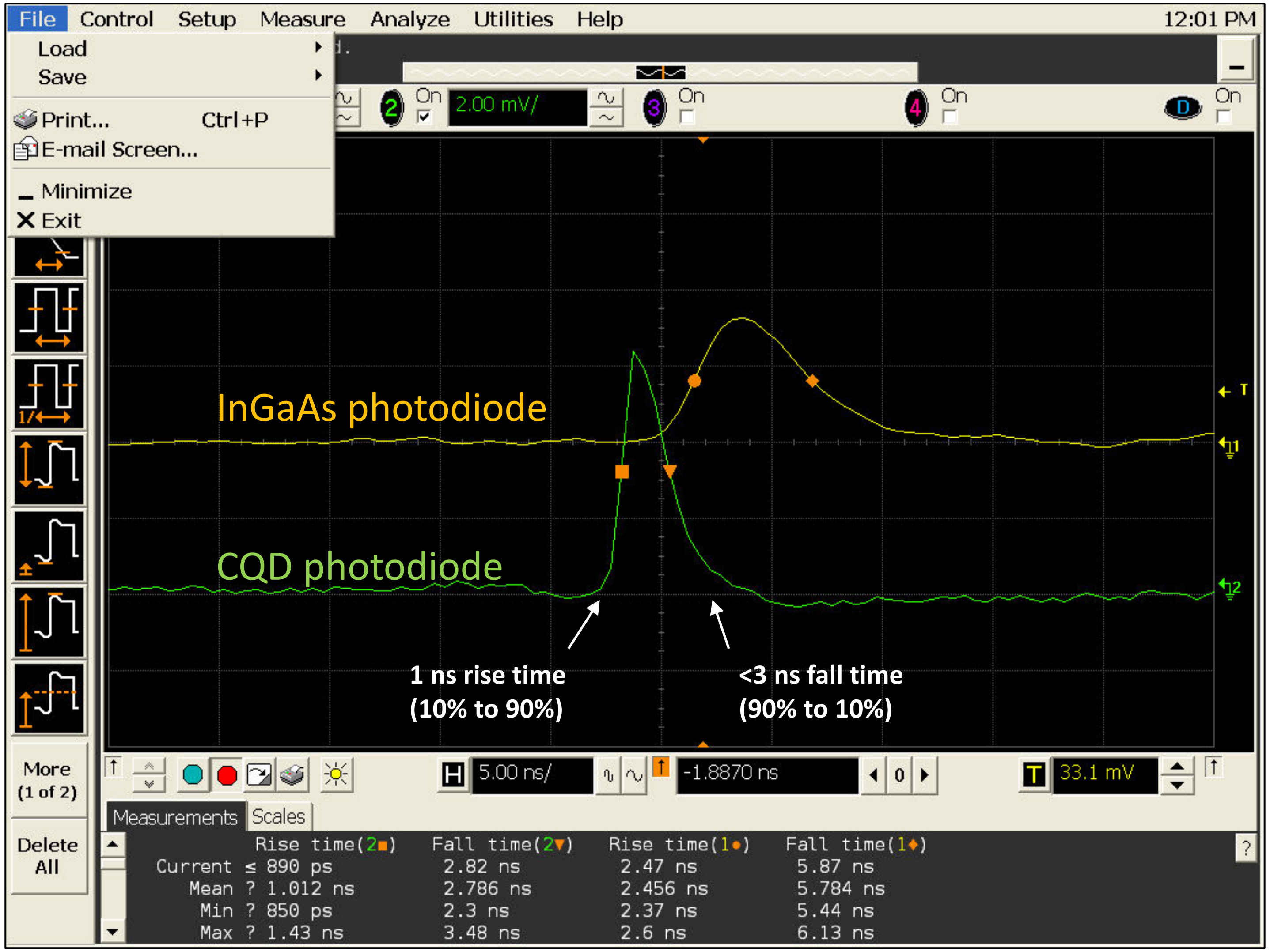
SWIR Vision Systems CQD photodiode:

- 200 um x 200 um pixel size
- 15 pF measured capacitance (using LCR meter)
- 400 nm to 1600 nm spectral response
- Dark current density: 5 nA/cm^2 @25 C

Reference photodiode:

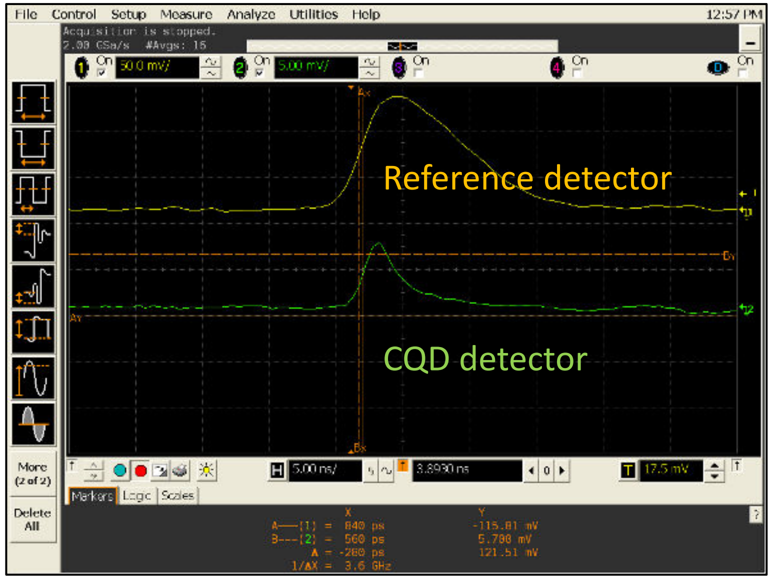
- Thorlabs FGA015 InGaAs
- 150 um diameter
- 2 pF capacitance (from datasheet)

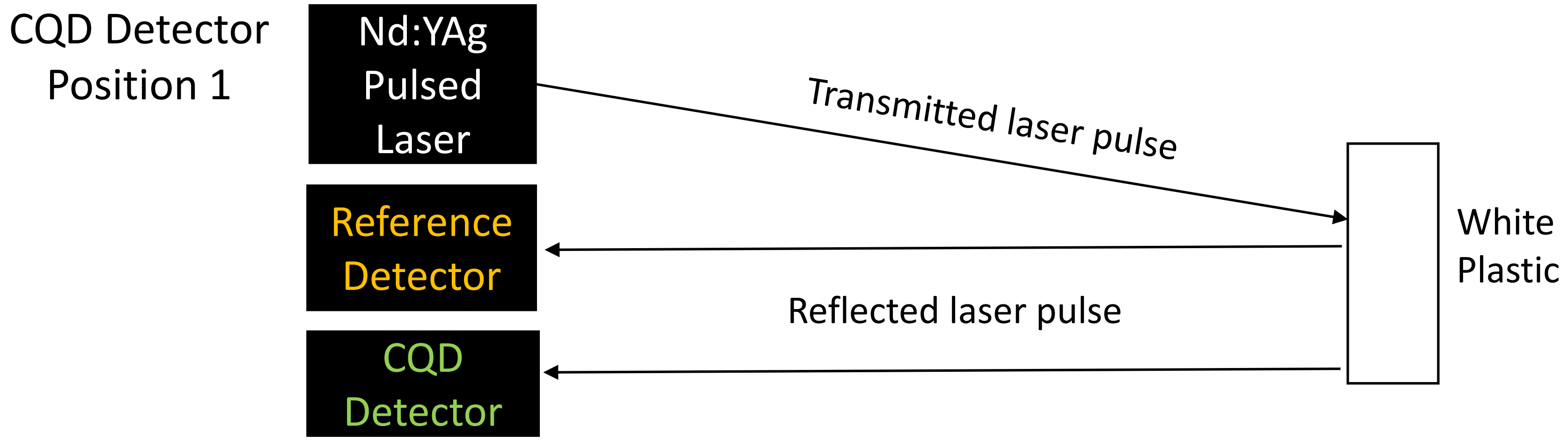
Nd:YAG pulsed Laser, 1064 nm, 5 Hz rep rate

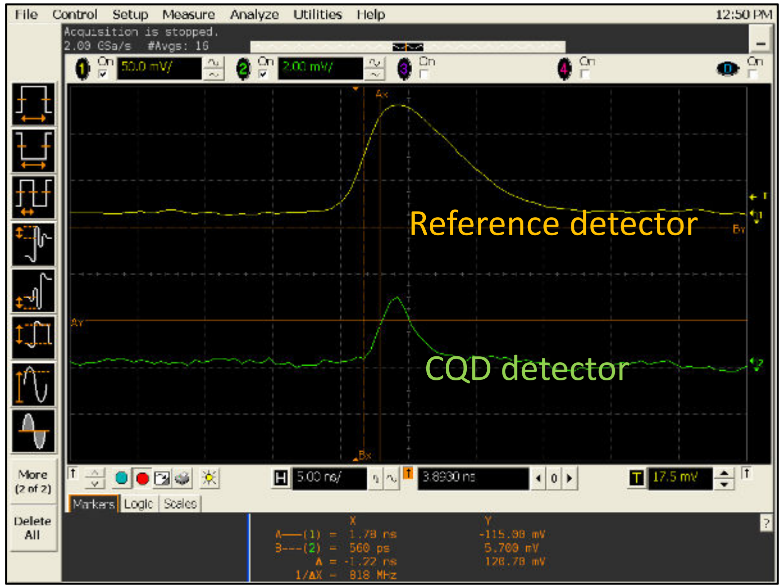


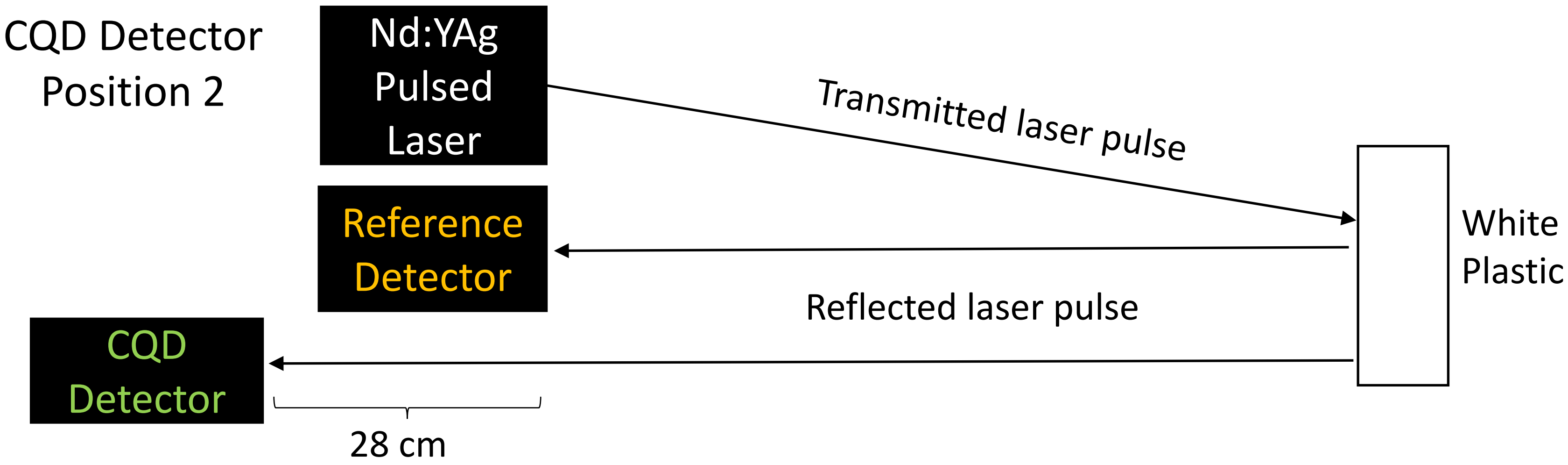
Agilent MSO8104A

SWIR Vision CQD dToF measurement demonstration









0.94 ns change in pulse arrival time at CQD detector - > calculated distance = 28.2 cm

Reliability Testing Summary

SWIR VISION SYSTEMS

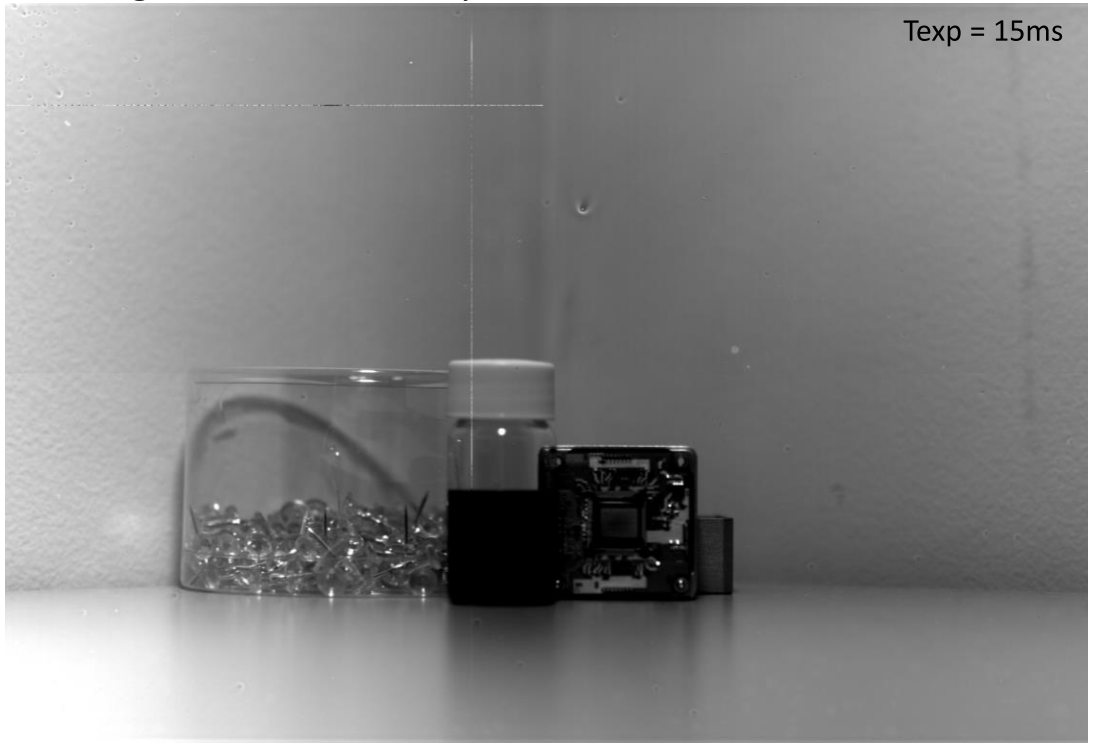
Temperature	JEDEC Requirement (consumer)	AEC-Q100 G2&3 Requirement (automotive)	SWIR Vision Status	Notes
High Temp Storage Life (HTSL)	125C 1000 hrs	125C 1000 hrs	Demonstrated	Milestone achieved Q1 2023
Temperature Humidity Bias (THB)	85%RH/85C 1000 hrs	85%RH/85C 1000 hrs	Demonstrated (unbiased)	Based on our understanding of the THB failure mechanisms, it's unlikely that our low detector bias (~100mV) will increase failure rates
Thermal Cycling	-40C-125C 1000 cycles	-55C-125C 1000 hrs	Not yet tested – med risk	Early data suggests cycling did not accelerate failures seen during HTSL
Unbiased HAST	110C/85% RH for 264 hrs	110C/85% RH for 264 hrs	Not yet tested – low risk	
High Temperature Operating Life (HTOL)	125C 1000 hrs biased		Demonstrated at 70C – 125C low risk	Now that we can pass HTSL, we will test HTOL at 125C. Industrial cameras in the field looking at lasers and LEDs 24/7

- The SVS reliability team is focused on demonstrating JEDEC and AEC specs.
- Assumed a TEC will not be used for consumer and automotive markets and CQD photodiode will need to survive standard downstream processes (packaging, color filters, etc.)
- Since the CMOS process and packaging are mature products with long histories of passing reliability quals, we focused on the risks associated with our novel CQD photodiode structure.

Solder Reflow – Sensor Testing

- Acuros 2MP sensor testing began with small number of devices
- Data here shows image after 200C reflow process

Imagery taken with sensors that have been through a 200 C reflow cycle

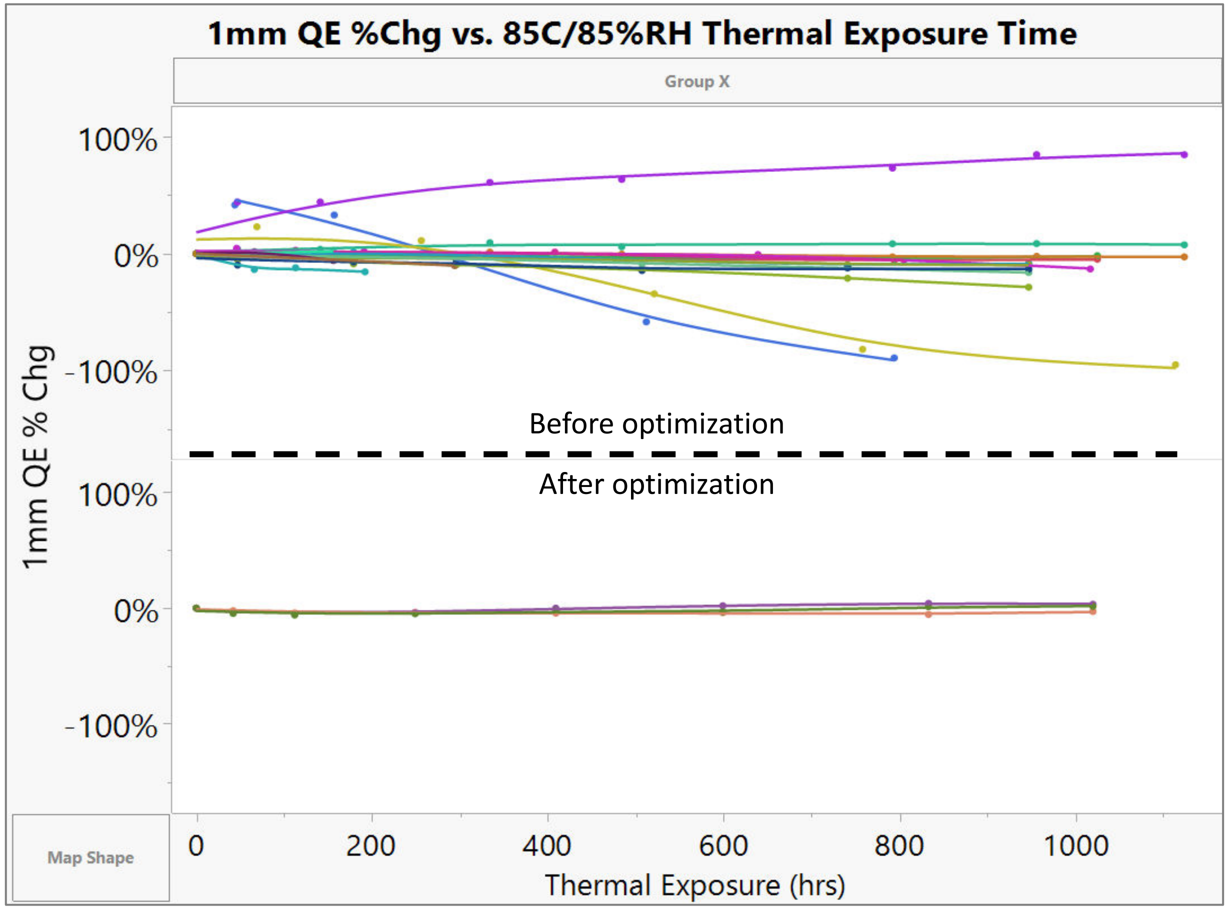


Conclusion:
- 200C reflow cycle demonstrated on focal plane array

Next Steps:
- Develop and demonstrate 250C reflow-compatible CQD diode

QE - Temperature Humidity (TH) – 85C/85% RH

SWIR VISION SYSTEMS



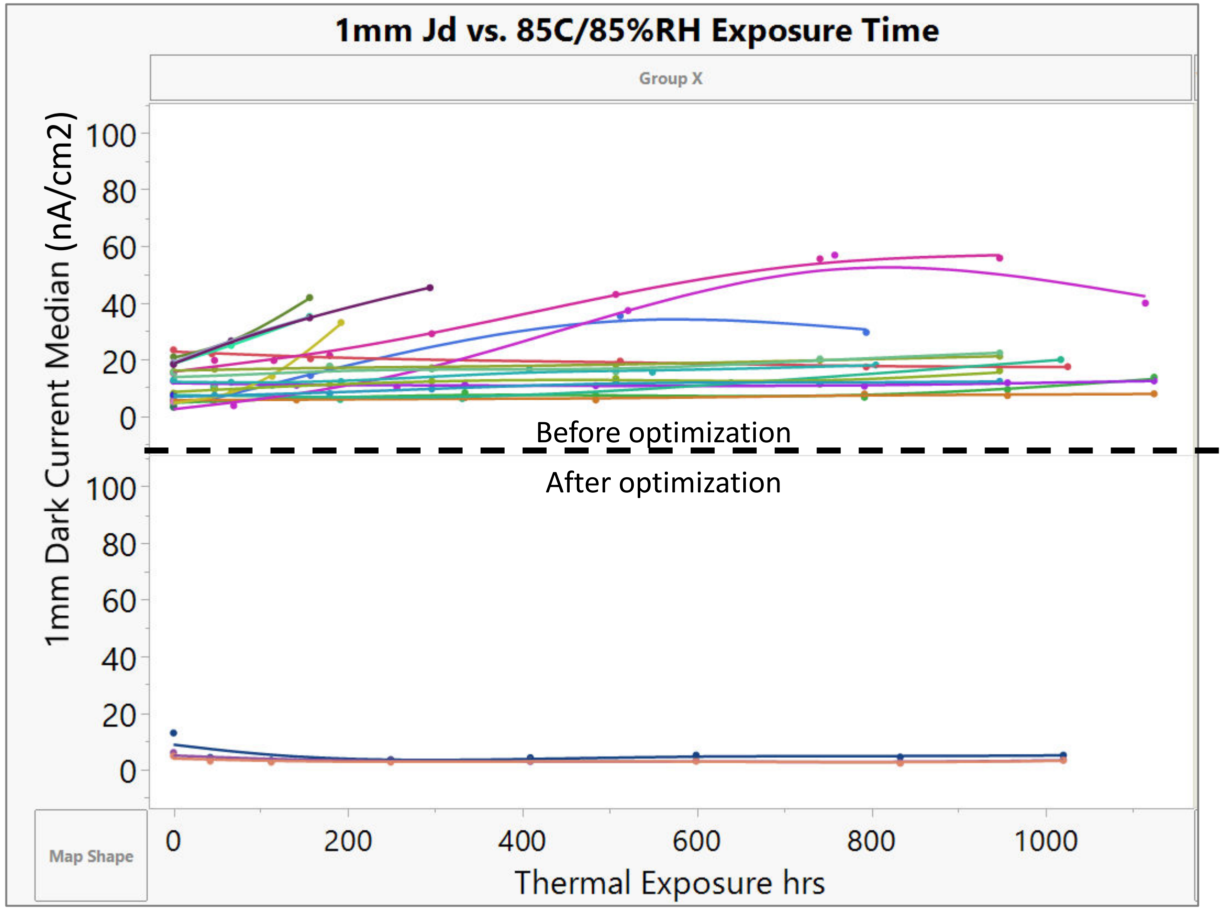
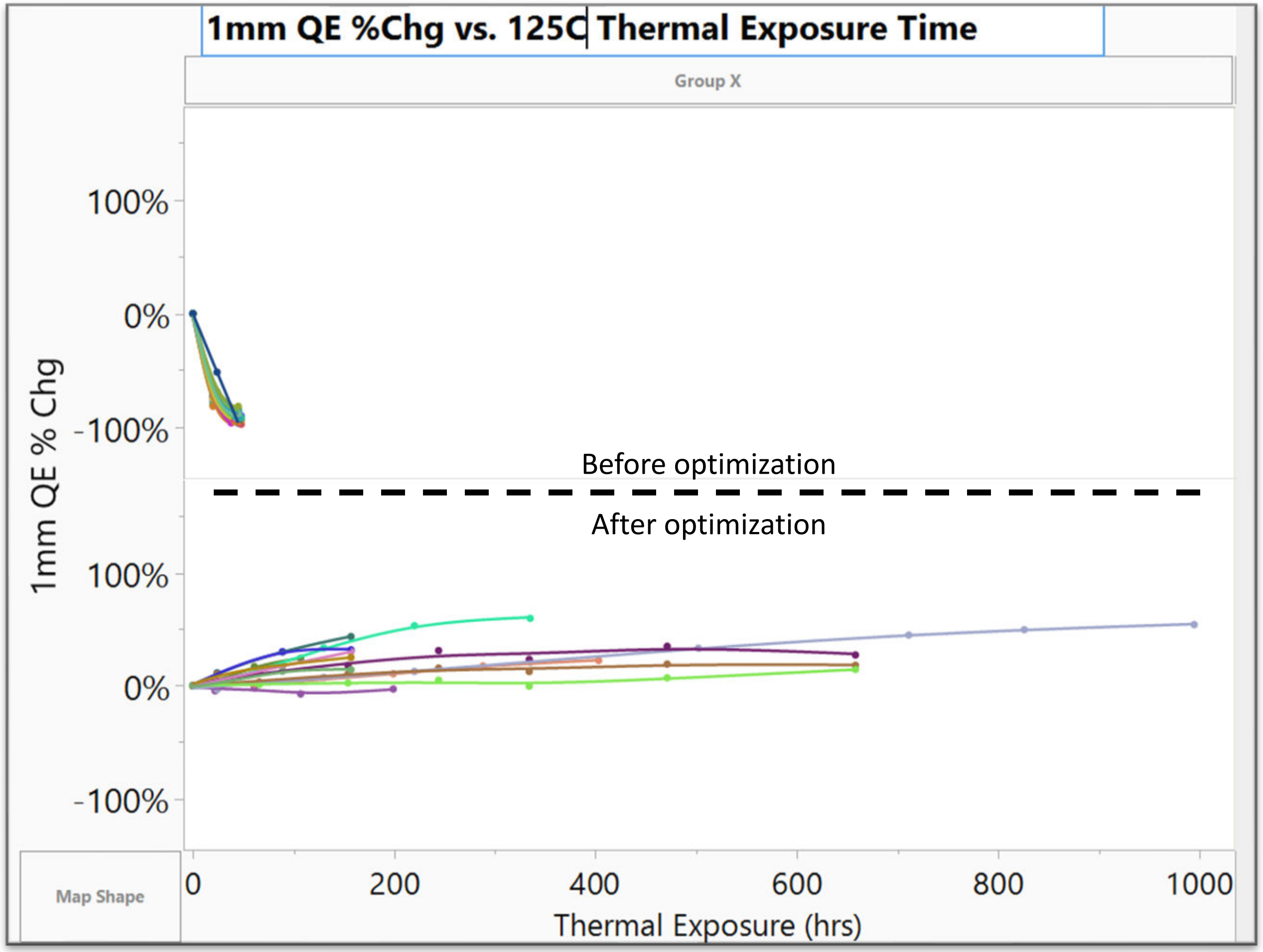


Table of QE% change vs 85C/85%RH stress time. Each line represents a separate passive substrate. Four 1mm x 1mm diodes measured on each substrate. Median value of the four diodes is reported.

Conclusion:

- 85C/85% humidity demonstrated

QE - High Temperature Storage Life – 125C



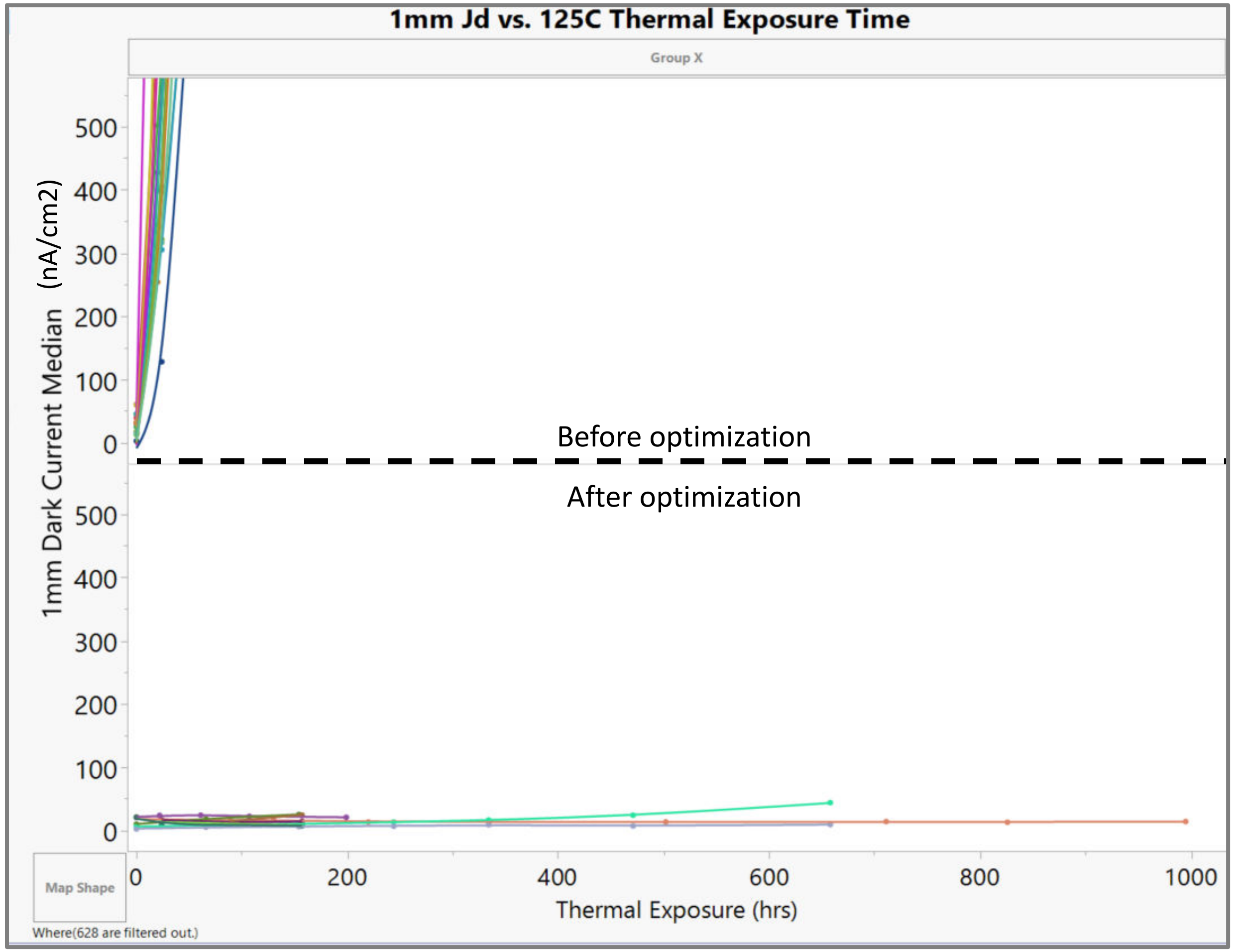


Table of QE% change vs 125C stress time. Each line represents a separate passive substrate. Four 1mm x 1mm diodes measured on each substrate. Median value of the four diodes is reported.

Conclusion:

- CQD photodiode shows stability at 125C accelerated stress temps.

Summary and Conclusions

SWIR VISION SYSTEMS

SWIR's CQD detectors offer the performance and scalability needed for multi-megapixel, small pitch, 2D and 3D IR systems

Metric	Value	Notes/Measurement Structure
Photodiode structure	Type-II photodiode	*pn* junction using PbS CQDs capable of photovoltaic operation
Bandwidth	>350 MHz	1 ns rise time and 3 ns fall time measured on 200 um x 200 um test diodes. Enables Direct ToF 3D depth sensing
Dark current	<5 nA/cm^2, 25 C	Typical dark current density measured on 15 um pixels in 2MP image sensors and on 200 um x 200 um test diodes
Spectral response	400 to 2200 nm	Bandgap of detectors can be selected during fabrication to match system requirements.
Quantum Efficiency	15% to 45% at 1550 nm depending on diode type	Diode structure and bandgap can be tailored to enhance QE for specific wavelength regions
Bias Voltage	<0.1 V	Reverse bias voltage typically used in 2MP image sensors and 200 um x 200 um test diodes
Capacitance	<15 pF	Measured using 200 um x 200 um test diodes
Linearity	< +/-1.5% deviation	Evaluated on 2MP image sensors using array response to 1550 nm light source
Pixel Yield	> 99.95% typical > 99.90% min	Evaluated on 2MP image sensors. Bad pixels are those with light or dark response >+/-25% of mean array response
Commercial availability	Yes	Acuros family of CQD sensors and cameras shipping globally since 2018

- High volume applications exist today for infrared imaging and sensing systems
  - Majority of these applications today utilize NIR light sources and CMOS detectors
- Systems that utilize an active light source can be designed around NIR or SWIR wavelengths
  - Early examples of SWIR-based sensing have recently entered the consumer electronics market
- Systems designed for outdoor conditions can be lower power due to the lower background light in the 1130 and 1380 nm regions
- SWIR's detectors have the response time needed for ns pulse detection in ToF systems
- SWIR's detectors have demonstrated 125C stability and 200C solder reflow compatibility