Colloidal Quantum Dot Photodetectors for Large Format NIR, SWIR, and eSWIR Imaging Arrays

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Abstract

In 2019 SWIR Vision Systems introduced its 2.1 MP Acuros cameras to the industrial imaging market, becoming the first company globally to commercialize high resolution, quantum-dot based image sensors. Since this product introduction, SWIR Vision Systems has continued to advance the performance of its colloidal quantum dot detector architecture. These advances include demonstrating detectors with 940 nm QE's > 50% and extended wavelength eSWIR detectors with spectral response from 350 nm to 2100 nm. This paper will provide an overview of our approach to fabricating focal plane arrays, will describe recent results fabricating Vis-SWIR and eSWIR CQD® detector arrays, and will show imaging demonstrations of these sensors in a variety of applications.

Author Keywords

Colloidal Quantum Dot Sensors, Shortwave infrared, SWIR, CQD, SWIR Image Sensors, SWIR Focal Plane Arrays, NIR Image Sensor

1. Introduction and Background

SWIR Vision Systems' thin-film colloidal quantum dot photodiode array technology is depicted in Figure 1. This figure shows the photodetector structure on the surface of a Si readout integrated circuit.

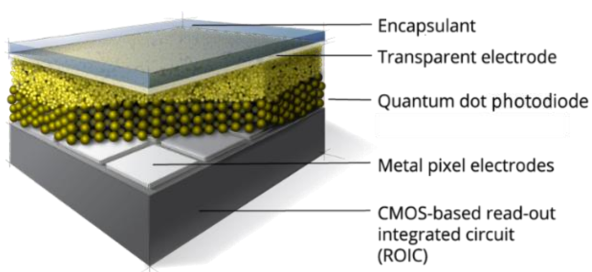

Figure 1. Image depicting the CQD photodiode structure fabricated on the surface of the ROIC. Note that the drawing is not drawn to scale.

The colloidal quantum dot material used in this diode structure is a broadband absorber with a band-gap that can be tuned during colloidal quantum dot synthesis across the spectral range from the near infrared (NIR) to the extended shortwave infrared (eSWIR). Today, SWIR Vision Systems produces cameras with visible (Vis)-SWIR response from 400 to 1650 nm and has recently released a Vis–eSWIR sensitivity camera with response from 350 to 2100 nm.

The photodiode structure is a thin film stack composed of colloidal quantum dot layers and other material layers that are used to improve charge transport and charge extraction. The processes used to deposit the materials for the diode are all processes that are found in standard CMOS wafer processing. Owing to the monolithic integration of the colloidal quantum dot photodiode array, the low cost of colloidal quantum dot solution synthesis, and the large area deposition processes used in their fabrication, colloidal quantum dot photodiode arrays offer a straightforward path for fabricating large format FPAs at the wafer scale.

SWIR Vision Systems traces its roots to a multi-year corporate-funded R&D effort at parent company RTI International. Starting up as an independent company in March 2018, the company manufactures and ships the Acuros® CQD SWIR cameras globally from its operations center in Durham, North Carolina. The CQD focal plane arrays (FPAs) and imaging systems that SWIR Vision Systems manufactures include the only commercially available 1920×1080 full-HD SWIR camera, full-HD eSWIR cameras, and full-HD laser-beam compatible cameras.

2. SWIR Sensor and Camera Performance

SWIR Vision Systems' standard SWIR image sensors are fabricated using CQD material with a first excitonic peak at approximately 1500 nm. The spectral response of these sensors follows the optical absorption properties of the colloidal quantum dot material, which, like traditional semiconductor materials, contain a density of electronic states above the optical bandgap, enabling photon absorption from the SWIR down to UV wavelengths. Figure 2 shows the spectral response of the standard SWIR image sensor.

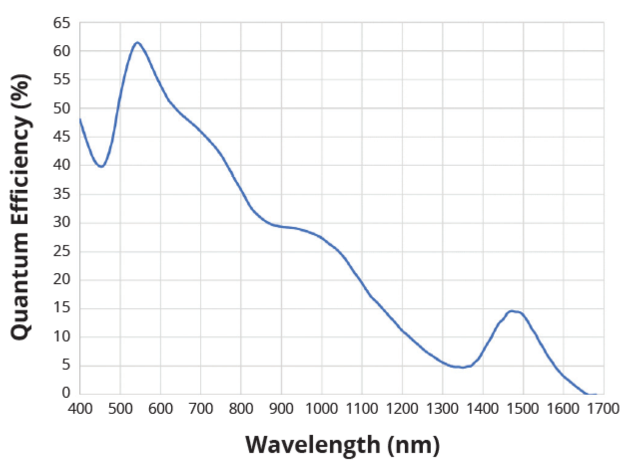

Figure 2. Spectral response of the standard SWIR image sensors being offered today in the Acuros camera product line.

One should note that the quantum efficiency (QE) of the CQD diodes is lower than traditional SWIR InGaAs-based sensors.

However, this is not a fundamental limit of the CQD material system, and substantive development efforts to increase the QE performance are anticipated. Early results from this work are bearing fruit and will be reviewed later in the paper.

The dark and illuminated current-voltage characteristics of a test pixel structure containing a standard SWIR photodiode are shown in Figure 3. In it one can see that the diode structure developed by SWIR Vision Systems can be operated at relatively low bias voltages, and owing to the *pn* junction diode characteristics and built-in charge separating potential, can be interfaced to most standard pixel amplifier designs.

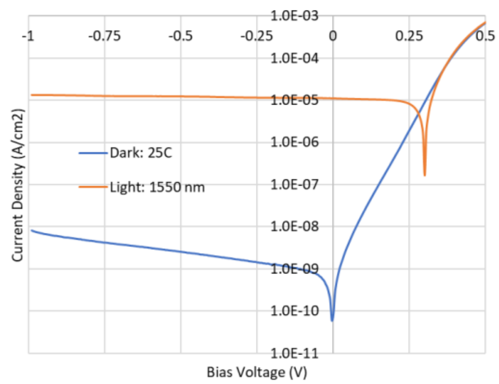

Figure 3. Representative dark and illuminated log-linear current-voltage curve for a standard SWIR test pixel structure. The dark curve is measured at room temperature and the light curve is measured at room temperature with 1550 nm monochromatic illumination.

To produce focal plane arrays and cameras, CQD photodiodes are fabricated on the surface of read out ICs (ROICs) which contain an array of amplifiers, multiplexing circuitry, and other functions needed to produce a digital image. In the Acuros product line the ROIC is a 15 µm pitch design and contains three analog gain modes corresponding to three different full well capacities of 550 ke-, 110 ke-, and 25 ke-. The sensors feature a global snapshot shutter and full frame rates of 60 fps for the HD sensor. Operating the sensor in windowed operation with a smaller region of interest can enable higher frame rate operation with the frame rate scaling inversely with the number of total pixels being read-out during a frame.

The read noise performance of the sensor is reduced by the implementation of a correlated double sampling architecture in the ROIC. The dark current of our CQD diode structure is about 5 nA/cm^2 at 25C which starts to be a significant contributor to total system dark noise for exposure times greater than about 20ms. Below these exposure times, the dark noise performance is dominated by the ROIC read noise. A summary table showing the performance of the Acuros 1920 camera under different operating modes can be seen in Table 1.

One of the benefits of fabricating focal plane arrays using CQD materials is the relaxation of the coefficient of thermal expansion (CTE) constraints found in traditional heterogenous semiconductor systems (such as InGaAs) during bonding and operation on a silicon ROIC. The relaxed CTE constraints in the CQD material system enables the fabrication of very large area arrays without the limitations imposed by thermally-induced stress due to CTE mismatches. A further benefit of the CQD fabrication process is the monolithic integration of the diode stack on the silicon ROIC without the need to form a metal solder connection between each infrared photodiode and each silicon pixel amplifier input – a process known as hybridization. These two differences lead to fabrication of large format image sensors with very high pixel yield.

Table 1. Summary of the Acuros 1920 Camera Performance in each of its three analog gain modes

	Full Well Capacity	**Total dark noise per pixel (Note 1)**	**Noise Equivalent Power (Note 2)**	**Dynamic Range**
Low Gain	550 ke-	183 e-	12 nW/cm^2	70 dB
Med Gain	110 ke-	76 e-	5 nW/cm^2	67 dB
High Gain	25 ke-	65 e-	4 nW/cm^2	32 dB

Note 1: Total input referred dark noise measured at a sensor operating temperature of 30 C and 16.6 ms exposure time.

Note 2: Measured using 1550 nm illumination and 16.6 ms exposure time with a 30 C sensor temperature.

The Acuros SWIR cameras were designed for applications in industrial inspection and automation, security and surveillance, and scientific instrumentation. They are built with a feature set intended to provide a flexible platform for system integrators to configure, control, and customize the implementation of the cameras. A portion of this feature set can be seen in Table 2.

Table 2. Acuros CQD SWIR camera features

Feature	**Value**
Shutter mode	Global Snapshot
Firmware NUCs	Yes, 2-point, user configurable
Temperature monitoring	Yes
Bit depth	8, 10, 12, or 14
Max frame rate	60 fps/110 fps/360fps for the Acuros 1920/1280/640 sensors
ROI	Yes, max frame rate scales with ROI size
Hardware trigger control	Yes TTL, Edge triggered or pulse width modulated
Data Output	USB3 or GiGE
GeniCam Compliant	Yes

3. Acuros Extended SWIR Cameras

SWIR Vision Systems has recently released a new series of cameras that offer a spectral response spanning 350 nm to 2100 nm. These cameras share a common feature set with the standard Acuros cameras with the same resolution options, well depths, and camera features. The extended SWIR photodiodes that SWIR Vision System builds for these sensors have room temperature dark current densities in the 5 nA/cm^2 range. This leads to excellent noise performance without the deep cooling found in traditional extended SWIR cameras made with InSb, HgCdTe, or Type II Superlattice detectors. A plot of the responsivity of the eSWIR cameras can be seen in Figure 4.

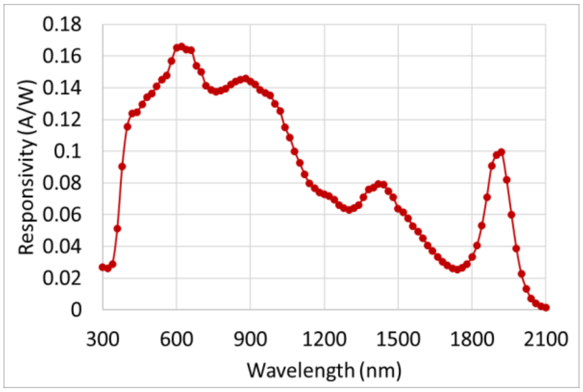

Figure 4. Spectral response of the Acuros eSWIR cameras

4. Acuros L-Series for Laser Characterization

The Acuros L-Series cameras were released in late 2020 to offer a solution for laser beam profiling applications for laser component manufacturers, laser-based production lines, and laboratory environments. It features a sensor that has been designed to reduce optical interference fringes with a housing designed for easy access to the sensor surface. This provides flexibility for the positioning of sources and devices under test in close proximity to the sensor surface. Figure 5 shows a laser beam profile image collected with an Acuros L-series camera and an image of the camera and sensor surface.

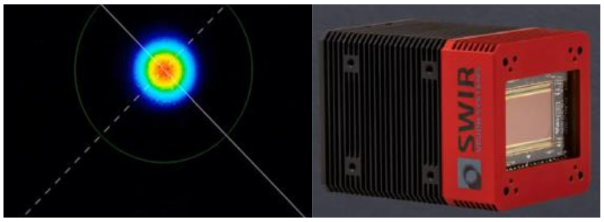

Figure 5. (Left) Image of 1550 nm laser beam taken with the (Right) Acuros L-series camera. Note: Laser beam profile image is courtesy of DataRay Incorporated.

The large sensor area (29 mm x 16 mm) of the Acuros CQD 1920L camera enables the imaging of multiple laser sources or optical fibers in parallel. It also allows for longer working distances for un-collimated laser sources. Its fast response time and global shutter allow for the measurement of pulsed laser sources and it exhibits excellent linearity and low crosstalk for high spatial resolution measurements.

5. Advances in CQD Photodiode Performance

The quantum efficiency of CQD-based photodiodes has typically lagged behind that of traditional CMOS and InGaAs detectors. This is primarily a function of the incomplete optical absorption that occurs in the relatively thin films used to fabricated CQD detectors. Increasing the QE by increasing the CQD film thickness is challenged by the short charge transport lengths found in the ensemble of nanometer-scale crystal domains formed in CQD films.

The SWIR Vision Systems team has worked to improve the QE of the CQD detectors by focusing on the underlying physics of charge transport within the CQD films. Indeed, one of the great opportunities for improvements in CQD device performance lies in the ability to control the electronic properties of CQD films through the manipulation of the chemical properties of individual dots. Utilizing this characteristic, the SWIR Vision team has made strides in producing higher QE detectors. The team has made enhanced QE photodiodes on test arrays and has characterized their spectral response, dark current, and other performance characteristics. The spectral response of one of these devices with a first excitonic peak at approximately 1500 nm can been seen in Figure 6.

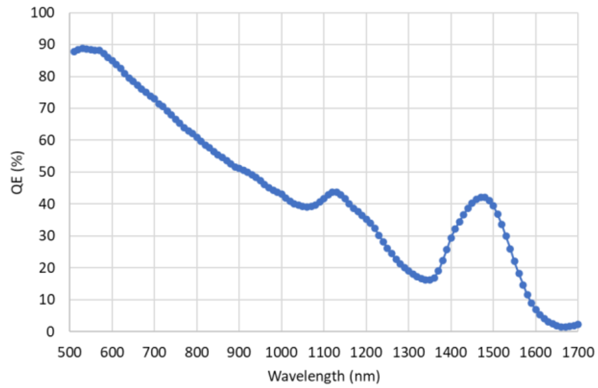

Figure 6. Quantum efficiency spectrum of enhanced QE CQD photodiodes demonstrated on small pixel array test devices. The dark current density for this device was measured to be 8 nA/cm^2 at 25C.

SWIR Vision Systems has also worked to develop CQD photodiodes with a band-edge closer to 1000 nm in order to demonstrate the potential use case of these detectors for near infrared systems using active optical sources at 940 nm, such as those found in facial recognition and other 3D imaging systems in consumer and automotive applications. The spectral response of one of these detectors, fabricated on a test array, can be seen in Figure 7.

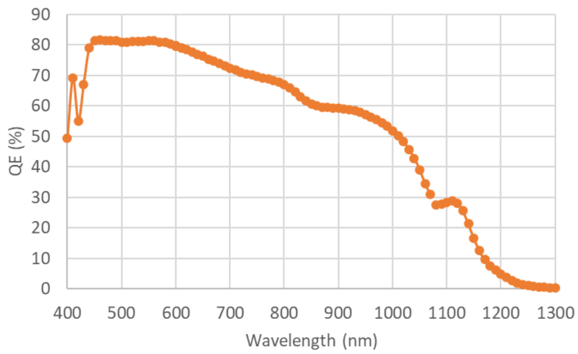

Figure 7. Quantum efficiency spectrum of near infrared-optimized CQD photodiodes demonstrated on small pixel array test devices. The dark current density for this device was measured to be 4 nA/cm^2 at 25C.

Although the quantum efficiency at 940 nm in CMOS image sensors has been shown to be in the 40% range in commercially released products, it comes with increased cost as the NIR-enhanced CMOS detectors are fabricated using a back-side illuminated, stacked sensor design with higher material costs and fabrication complexity than the simple thin film structure used to achieve high NIR QE in the CQD detectors reported here.

6. Application Images and Use Cases

Today SWIR Vision Systems sells its cameras into applications where the properties of the longer wavelength photons in the SWIR spectral region (as compared to those in the visible and NIR) have a different absorption/reflection/transmission behavior for a given material or structure and as a result provide additional information that cannot be obtained with CMOS image sensors.

For example, the ability of SWIR photons to readily pass through silicon wafers is an advantage for defect inspection in the solar cell industry and the semiconductor IC fabrication industry. An example of this application can be seen in Figure 8.

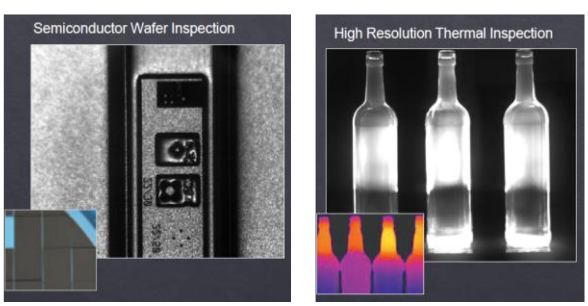

Figure 8. (Left) Image of a buried alignment mark in a bond-wafer pair inspection application. Inset shows image of device with a visible wavelength camera (Right) SWIR image of hot glass bottles showing high resolution thermal information. Inset shows thermal image obtained with long wave bolometer-based image sensor.

The Acuros SWIR cameras are also being used for high speed, high resolution thermal imaging of objects with temperatures greater than about 150 C. An example of this can be seen in Figure 8 where hot glass bottles are being imaged to provide quality control information.

The ability of SWIR photons to be absorbed by water in the 1420 nm spectral region is an advantage for moisture measurements in the wood products industry or fill level monitoring in the pharmaceutical industry. An example of this can be seen in Figure 9. Also shown in Figure 9 is an example of ability for SWIR light to show increased optical transmission through plastics and dye used in consumer-goods packaging.

In outdoor imaging applications, SWIR wavelengths provide an advantage in degraded visual environments where the physics of scattering mean that longer wavelength SWIR photons have a longer path length through haze, dust, smoke, and other particulates than the visible, shorter-wavelength photons utilized by CMOS sensor systems. An image of one such scenario where SWIR provides additional long-range information can be seen in Figure 10.

Figure 9. (Left) Image of vials with a clear water-based liquid with the liquid appearing dark due to the SWIR absorption feature around 1420 nm. The inset shows the same vials with a visible camera. (Right) Inspection images of a food product where the SWIR photons are used for their increased transmission through plastics and dyes. Inset shows the product imaged with a visible camera.

Figure 10. Acuros camera imaging through a rain storm across an ocean inlet. The inset shows the same scene as seen through a CMOS camera.

In recent years there has been a growing interest in new photodetectors capable of providing response in the NIR-SWIR spectral region. A handful of companies have entered the SWIR market with a variety of detector technologies. A table comparing some of these technologies can be seen in Table 3.

In parallel with serving the industrial and scientific market, SWIR Vision Systems is preparing its technology for emerging high volume market opportunities in consumer electronics and automotive sensor systems. This work includes increasing the storage and operating temperatures of CQD sensors, scaling up manufacturing capacity, increasing sensor yields, and improving the efficiency, noise, and uniformity.

Table 3. Comparison of technologies targeted at high resolution, high volume NIR/SWIR sensing applications.

Group/ Tech	Status	Spectral Response (nm)	QE (Note 1)	Dark Current (nA/cm^2)
SWIR Vision Systems CQD Photodiode	Prototype	350 – 1250	60%	4
	Prototype	350 – 1650	45%	8
	Production	400 – 1650	15%	2
	Production	350 – 2100	6%	3
IMEC CQD Detector [1]	Prototype	350 – 1500	13%	300
InVisage CQD [2]	Prototype	300 – 1100	40%	4 (Note 2)
TriEye Plasmonic [3]	Prototype	400 – 1550	2%	10,000

Note 1: Reported QE is at the first excitonic peak except for the TriEye device which is reported at 1300 nm.

Note 2: InVisage device is reported operating in a switched bias mode wherein dark current is reported at a different bias voltage than QE.

7. Conclusions

In summary, we have presented an overview of the CQD detector technology that SWIR Vision Systems offers in its family of high resolution SWIR and eSWIR cameras. These cameras are being utilized for applications including laser profiling, semiconductor inspection, long range outdoor imaging, and other machine vision applications. We have shown results of work advancing the properties the CQD detectors and report prototype demonstrations of high QE detectors (940 nm QE = 60%, 1550 nm QE = 45%). Finally, we expect that a continued focus on device development will yield further advances in the performance of CQD-based photodetectors.

8. References

[1] Lee, J., Georgitzikis, E., et. al., "Imaging in Short-Wave Infrared with 1.82um Pixel Pitch Quantum Dot Image Sensor," *IEEE IEDM*, vol. 16.5.1, 2020.

[2] Barrow, L., Bock., et. al., "A QuantumFilm based QuadVGA 1.5um pixel image sensor with over 40% QE at 940 nm for actively illuminated applications," in *IISW Dig. Tech*, 2017.

[3] Desiatov, B., Goykhman, I., et. al., "Plasmonic enhanced silicon pyramids for internal photoemission Schottky detectors in the near-infrared regime," *Optica*, vol. 2, no. 4, 2015.