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Extended SWIR (eSWIR) High Performance and High Definition Colloidal Quantum Dot Imagers

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Abstract

We summarize CQD[®] sensor technology, introduce eSWIR imaging technologies, and then present, for the first time, solution processed colloidal quantum dot extended short wavelength infrared (eSWIR) 1920 x 1080 format cameras sensitive from 300 nm to 2000 nm wavelengths at a pitch of 15 microns. We describe the performance of this high-definition imager using a EMVA1288 machine vision testing approach and demonstrate pixel detectivities of 1 x 10¹² Jones and 32 fA of dark current when operating at room temperature [1]. These results show this monolithically integrated detector technology has sensitivity superior to most traditional epitaxial IR sensors used in the 1700 to 2100 nm band [2]. The straightforward and scalable fabrication processes employed have enabled the first commercially available room temperature 2.1 MP camera with sensitivity out to 2.0 μ m.

Introduction and Background to ACUROS[®] CQD Photodiodes

SWIR VISION SYSTEMS[®] Inc. has pioneered the development and commercialization of Quantum Dots (QDs) for high performance infrared camera sensors. The technology brings valuable new imaging solutions to difficult industry problems, specifically to commercialize the need for lower cost and higher resolution SWIR-band machine vision cameras. To accomplish these goals, the group has synthesized lead-sulfide (PbS) based QD nanoparticles, and processes these into very thin-layered photodiodes. The photodiodes and their underlying silicon CMOS circuitry form a novel photosensor, sensitive to light in the shortwave IR band. The PbS based photodiodes directly convert photons of incident light into electrons, which are subsequently read out by the circuitry within individual pixels. The QD particles are typically designed to provide an optimized spectral response tuned for the 400 to 1,700 nm visible-SWIR wavelength band. But some unique properties of QD's also enable focal plane array sensors to be pushed into the extended SWIR (or eSWIR) wavelength band, namely to 2000 nm and beyond. This paper will discuss this new technology innovation, and how new eSWIR products will be used in multiple industrial applications.

SWIR Vision's ACUROS CQD sensors are created by the monolithic integration of quantum dot-based photodetectors directly on CMOS readout integrated circuits (ROICs). The sensor fabrication process uses well-established, low-cost deposition techniques commonly found within the semiconductor industry. The process requires no hybridization, no epitaxial growth or exotic substrate materials, no pixel-level sensor patterning, and can ultimately be scaled to

wafer-level fabrication. Photodiode arrays with pixel pitch as low as 3 µm have already been demonstrated using this technology. The relative crystalline disorder of colloidal quantum dots currently results in lower quantum efficiency when compared to InGaAs cameras in the 900–1700 nm wavelength range, which may make these CQD-based cameras less suitable for photon-starved applications. However, in the majority of machine vision applications, a CQD sensor-based camera can be paired with relatively inexpensive active illumination, resulting in near InGaAs equivalent performance with a significant reduction in overall system cost. Figure 1(A) shows a conceptual representation of the basic technology as directly deposited on a CMOS ROIC, and shows an image of the ACUROS CQD eSWIR camera.



Figure 1. (Left) Simplified Conceptual Schematic of Colloidal Quantum Dot Imager Technology Directly Deposited on CMOS Readout Circuit and (Right) Image of the ACUROS CQD eSWIR Camera

The standard ACUROS camera products feature InGaAs equivalent noise, pixel operability greater than 99%, 15 μ m pixel pitch, and three different pixel array sensor formats (640 x 512, 1,280 x 1,024, and 1,920 x 1,080). The cameras are capable of imaging across a wide band (400–1700 nm) at speeds up to 380 fps via GigE Vision and USB3 Vision. The HD camera's 2.1 MP are 6.3 times higher resolution than today's InGaAs VGA cameras, providing users with richer imaging detail. The CQD SWIR camera sensors fabricated with low cost materials and CMOS-compatible fabrication techniques represent an advance towards broadly accessible high definition SWIR imaging. It is expected that the camera's lower cost points and its non-ITAR, EAR99 export classification to drive higher adoption rates globally, broadening the market for SWIR camera technology.

Stretching Out to the Extended SWIR (eSWIR)

SWIR VISION SYSTEMS has now extended these same high density, *full HD FPAs with responsivity out to 2000 nm*. This innovation increases the usable SWIR spectrum by >40% with wider spectral bandwidths still possible. To accomplish this, the company leveraged a property of its unique CQD sensor technology, whereby larger diameter quantum dot semiconductor particles are designed to broaden the sensor optical response to longer wavelengths. Broader bandwidth sensors open more capability for each of several SWIR Imaging applications (Figure 2).

Applications

SWIR band cameras are already deployed to inspect Silicon wafers and semiconductor die for void and edge defects. The technology is also used to detect moisture levels in packaged products, thickness and void detection on clear coat films, glass bottle imaging, bruise detection in fruits and vegetables, inspection of lumber products, detection of water/oil on metal parts, imaging through smoke and mist environments, surveillance and security monitoring, crop monitoring, glucose monitoring and many more applications. High resolution eSWIR imagers are also expected to enhance existing applications and open up many more applications including [4,5]:

- Chemical inspection
- Hydrocarbon and gas detection
- Plastic sorting
- High speed thermal imaging
- Medical imaging
- Long range imaging through summer haze, maritime haze, and fine dust for automotive, surveillance and agricultural applications
- Wafer defect inspection
- Laser beam profiling



Figure 2. Summary of Common NIR, SWIR Sensor Technologies and Application Space

Incumbent SWIR Technologies

Indium gallium arsenide (InGaAs) sensors built on indium phosphide (InP) substrates, currently dominate the SWIR imaging market. However, this material system imposes limitations on pixel size, pixel spacing, and sensor resolution. Practical InGaAs sensors tend to be limited to the 900–1700 nm wavelength band and are generally cost limited to relatively low resolution 640 x 512 sensor arrays.

Moving beyond the traditional SWIR Band into the eSWIR region, there are several existing technologies with responsivity beyond 1700 nm, including cameras featuring Indium Antimonide (InSb) and Type II Super Lattice (T2SL) based sensors.

Vendor Technology	SWIR Vision CQD Sensors	Vendor A T2SL	Vendor B InSb
Focal Plane Array	1920 x 1080	320 x 256	1280 x 1024
Pixel Pitch (μm)	15	30	12
Resolution (megapixels)	2.1	0.08	1.31
Bandwidth (nm)	350-2000	1000–2350	<1000 to 5300
Detectivity (Jones)	1 x 10 ¹² at 303 K[a]	1 x 10 ¹⁰ at 200 K[a]	3 x 10 ¹⁰ at 77 K
Dark Read Noise (Low Gain)	210 electrons	1000 electrons	n/a
Dark Current (e'/second)	200,000	80,000,000	n/a
Sensor Temperature (°C)	30 °C	−73 °C	−200 °C
Thermoelectric Cooling	Single Stage	4-Stage	Cryo-cooled
Power	6.5 W	<84 W	28 W
Weight	508 grams	1300 grams	<3180 grams

COMPARISON OF THREE COMMERCIAL eSWIR CAMERA PRODUCTS

[a] Estimate on Detectivity taken from: Dehzangi, et.al. at 1.9 μm https://doi.org/10.1088/1361-6641/aaf770

Figure 3. Comparison of CQD eSWIR Sensor to Type II Super Lattice and InSb eSWIR Sensors

Figure 3 compares the key performance metrics for a commercial camera featuring the ACUROS CQD quantum dot sensor from SWIR VISION SYSTEMS to two alternative commercial cameras, one with Type II Super Lattice (T2SL) sensor, and the other with an Indium Antimonide (InSb) sensor.

The CQD eSWIR sensor breaks through several barriers. First the camera has >25 times the resolution of the commercial T2SL camera. Next, the T2SL camera has 400X the dark current, and even then it must be cooled down to -73 °C to achieve this level of noise performance. The CQD sensor utilizes a standard 1-stage TEC, whereas the T2SL and InSb cameras use 4-stage TECs and cryogenic cooling methods respectively. The extreme cooling methods typically drive

the size, weight and cost of the alternative eSWIR cameras into only specialized and benchtop applications. These factors may make the cameras impractical for many commercial uses.

SWIR Vision's CQD sensors show detectivity performance second only to HgCdTe based sensors, with significant room for improvement in the device's dark current and quantum efficiency performances. The CQD eSWIR cameras are relatively compact, low weight and low power.

Next, we will present a technical study of the CQD eSWIR sensor. We believe the results show a strong opportunity for this imaging technology for multiple applications in the 1000–2000 nm band. The small size, low weight, low power, superior resolution, world-class detectivity, and low dark current will make these useful imaging tools for industrial, scientific, defense and surveillance applications. The inherently lower cost of CQD technology will now make eSWIR cameras more accessible for multiple uses.

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SWIR VISION SYSTEMS eSWIR Camera Evaluation and Results

Introduction

Colloidal quantum dots are solution suspensions of semiconductor quantum materials where the size of the component particles is reduced below their de Broglie wavelength [3]. Their nanomaterial properties allow the creation of an image sensor technology that is not limited by hybridization coefficient of thermal expansion; that skips the difficulties of fine pitch small pixel bump bonding to CMOS readout; and that is capable of spectral bandgap tunability. These traits enable imagers that have low cost, size, weight, and power consumption for applications that are traditionally served by InSb, MCT, and T2SLs [4].

Spectral Responsivity

This paper describes a 1920 x 1080 colloidal quantum dot imager based on 1900 nm first excitonic feature quantum dots processed directly on a CMOS readout at 15 μ m pitch.

Unfettered by substrate absorption the imager converts photons to electrons over a wide spectral range from UV to extended SWIR. Figure 4 shows the responsivity curve of the imager from 300 nm to 2.1 μ m.



Figure 4. The Plot Shows the Measured Spectral Responsivity of This Device at 303K

EMVA1288 Imager Testing

In this report we performed 1550 nm monochromatic time based EMVA1288 testing at 30 $^{\circ}$ C and at 15 $^{\circ}$ C in low gain mode. Analysis Figures 6, 7, 8, and 9 show the photon transfer, SNR, dark current, and linearity curves taken at 30 $^{\circ}$ C.

From the photon transfer curve, we observe the response of this device follows Poisson statistics and has a system gain value of ~ 18.7 e/DN (electrons per digital number) [7]. The SNR curve shows the ACUROS CQD eSWIR camera has photon sensitivity over four orders of magnitude at 14 bit A/D. The dark current curve shows the device's pixels exhibit a typical dark current of 200308 e/s or 32 fA with a temporal dark noise of ~211 e. Finally, the linearity curve shows this device to be linear to within $\pm 3.5\%$.



Figure 5. Photon Transfer Curve Showing Fit Range and Saturation Value



Figure 6. SNR Curve Showing Minimum Photon Flux Sensitivity and Saturation Flux Sensitivity



Figure 7. Dark Current Curve Showing Dark Current and Temporal Dark Noise



Figure 8. Linearity Curve as a Function of Photons per 15 μ m Pitch Pixel

Quantum Efficiency and Sensitivity

Low quantum efficiency has been presented as the driving sensitivity shortcoming of colloidal quantum dot imager technology. Quantum dot-based devices typically do not achieve QEs that are comparable to that of thick epitaxial material systems.

Though quantum efficiency addresses the transduction capability of a photodetector material in converting photons to electrons, it is not the standard for photodetector application sensitivity. The colloidal quantum dot technology presented here exhibits impressive dark current performances at room temperature, which contributes to excellent sensitivity. We next describe the Dstar (D*) sensitivity of our imager and contrast it against other state of art detector technologies as a function of temperature.

Imager Pixel Noise Equivalent Power and D* at 303K

We can compute an imager dark noise contribution [8] by

$$n_{dark} = \sqrt{\sigma_d^2 + \frac{l_d t}{q} + \cdots}, \qquad (eq. 1)$$

where is the temporal dark noise variance, I_d is the dark current, t is the integration time, and q is the electronic charge.

We compute the Noise Equivalent Power of the device by

$$\mathsf{NEP}\left[\frac{\mathsf{W}}{\sqrt{\mathsf{Hz}}}\right] = \frac{\mathsf{n}_{\mathsf{dark}}}{\mathsf{t}\;\mathsf{QE}}\left[\frac{\mathsf{p}}{\mathsf{s}}\right]\frac{\mathsf{hc}}{\lambda}\left[\frac{\mathsf{J}}{\mathsf{p}}\right]\sqrt{2\mathsf{t}}\;\left[\frac{\mathsf{1}}{\sqrt{\mathsf{Hz}}}\right],\tag{eq. 2}$$

where QE is the device's quantum efficiency, and units are indicated in square brackets. When the dark noise contribution is dominated by dark current shot noise the above simplifies to

$$\mathsf{NEP}\left[\frac{\mathsf{W}}{\sqrt{\mathsf{Hz}}}\right] = \frac{\sqrt{\frac{2\mathsf{I}_{\mathsf{d}}}{\mathsf{q}}}}{\mathsf{QE}}\left[\frac{\mathsf{p}}{\mathsf{s}\sqrt{\mathsf{Hz}}}\right]\frac{\mathsf{hc}}{\lambda}\left[\frac{\mathsf{J}}{\mathsf{p}}\right]. \tag{eq. 3}$$

From its NEP, the Sensitivity of the Imager is Given by

$$D * \left[\frac{cm \sqrt{Hz}}{W} \right] = \frac{\sqrt{A}}{NEP}, \qquad (eq. 4)$$

where A is the device area.

Using dark current data from the EMVA1288 analysis we compute the average imager D* from 400 nm to 2000 nm to be 1 x 10^{12} Jones at 303K, labelled with a star and contrasted with other detector technologies in Figure 9. This D* is superior to InSb, InGaAs, InAs, and non-quantum confined PbS imagers. Only MCT appears to be superior in PV performance at 295K.

Figure 10, expresses the D* of this device at 303K as a function of wavelength.



Figure 9. The Star Symbol Indicates the D* of This Colloidal Quantum Dot Imaging Device at 303K Relative to Other Detector Technologies. Background Image Source [2]



Figure 10. The D* of This Colloidal Quantum Dot Imaging Device at 303K as a Function of Wavelength

Conclusion

In this paper we have presented the characterization of colloidal quantum dot extended short wavelength infrared solution-processed semiconductor 1920 x 1080 format cameras. This technology has the potential to address large practical markets by virtue of its scalable fabrication processes, high resolution and fine pitch CMOS ROIC integration in ways that challenge traditional epitaxial approaches to this spectral band. We described the performance of this imager using EMVA1288 machine vision testing methods. The results show detectivity performance second only to MCT with significant room for improvement in the device's dark current and quantum efficiency performances. The results show a strong opportunity for this technology to be used in imagers that are competitive with MCT, InSb, and T2SL imagers.

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