Infrared Imaging and Sensing Using Colloidal Quantum-Dot Detectors

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Abstract

Photodetectors and image sensors based on colloidal quantum dots (CQDs) as the photosensitive elements have long been heralded as offering compatibility with cost-efficient and readily scalable manufacturing processes coupled with wavelength tunability extending far into the infrared. This tunability arises from a combination of quantum dot size and the base material.

Author Keywords

Colloidal quantum dots; CQD; image sensors; photodetectors; SWIR; CMOS integration.

1. Introduction

Compared to incumbent epitaxially grown semiconductors, colloidal quantum dots allow low-temperature solution-based processing and this enables scalable wafer processing that avoids high capital equipment costs. Early reports centred on the use of lead chalcogenides such as lead sulfide (PbS) and lead selenide (PbSe), and these materials offer sensitivity primarily in the short-wave infrared (SWIR) band (1400-3000nm). Operating at wavelengths up to ~2100nm, such materials offer a competitive alternative to InGaAs cameras at these wavelengths. Concerns about RoHS compliance mean that quantum dots of III-V compounds including indium arsenide (InAs) and indium antimonide (InSb) are actively being investigated, though as yet, CQD-based cameras using these materials have not been operated beyond ~1500nm in wavelength and primarily respond in the near infrared (NIR). More recently, there has been a great deal of interest in detection using mercury telluride (HgTe) quantum dots [1]. This is a semi-metallic material; however, the quantum confinement afforded by quantum dot dimensions opens a band gap that is size-tunable. The interest lies in the fact that the accessible wavelength range covers the SWIR and extends to the mid-wave infrared (MWIR) band (3000-5000nm) and beyond. Moreover, HgTe is more air-stable than materials such as PbS, which assists the material processing steps greatly.

2. SWIR imaging

The promise offered by quantum dot detection has now begun to be realised with a number of manufacturers offering infrared cameras utilising PbS CQD-based sensors commercially [2]. Early adoption areas include industrial machine vision and surveillance applications. SWIR band imaging is of increasing interest in product and process inspection since it opens up new detection possibilities. CQD SWIR cameras are now capable of operating at speeds in excess of 400 fps allowing their use on high-speed manufacturing lines. One important application in this area is the identification and detection of moisture. It is possible to identify the presence of water via its characteristic absorption bands at 1200nm, 1450nm and 1920nm, enabling product quality monitoring. This is demonstrated in Figure 1, where coffee beans are imaged using a SWIR camera. The use of a longwave bandpass filter, in this case centred at 1941nm, provides a strong optical contrast between areas intentionally contaminated with water droplets and the background.

Many polymers are transparent in the SWIR band, and this enables applications in both container inspection and fill monitoring. Figure 2 shows an example demonstrating how SWIR can be of use in such cases. The figure depicts a SWIR image of packaged glass vials, where the vessel fill level can be clearly seen through the opaque polymer packaging, helping to ensure product quality. In this case the liquid, which is water, is rendered opaque through the use of appropriate SWIR filtering.

Semiconductor wafer inspection is also an important application area for SWIR imaging as silicon is transparent beyond 1000nm allowing wafer defect inspection and enabling die alignment..

Figure 1 SWIR image of coffee beans acquired with a longwave bandpass filter. The high contrast between dark-appearing water droplets and the lighter background occurs via the water absorption peak at 1920nm.

Emberion is a pioneer in the application of this CQD technology, designing and manufacturing quantum dot cameras completely in-house. We design and implement every component of the camera from the sensor read-out-integrated circuit (ROIC), through the formulation and deposition of the CQD photodiode stack to the creation of the camera core and signal processing pipeline. This gives us direct control over every step in the chain allowing us great flexibility to optimise and customize according to need.

Our image sensor stack is based on a p-i-n photodiode

ISSN 0097-996X/25/5602-0764-$1.00 © 2025

implementation with PbS QDs sandwiched between suitable charge transport layers. We have optimized these layers for charge extraction by doping and ligand exchanging the QD layers to improve mobility and band alignment. The performance of such CQD-based image sensors is suitable for high-speed SWIR imaging and we have been able to achieve frame rates in excess of 1800fps in practise.

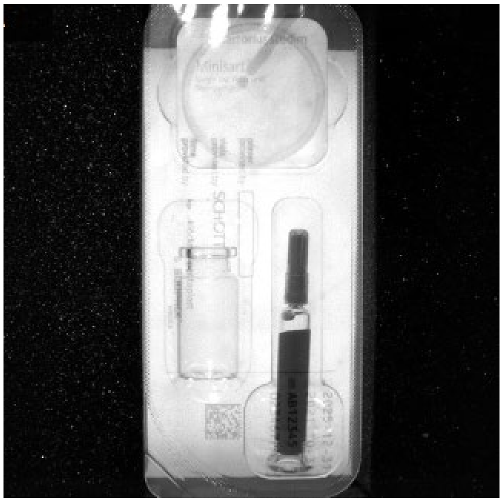

Figure 2 SWIR image of glass vials imaged through polymer packaging. The visible-transparent liquid vial fill level is revealed by the strong contrast provided by water's SWIR absorption peaks.

3. Thermography

We have recently investigated the use of a SWIR camera for thermography, allowing us to differentiate scene temperatures within an image. In this work the camera was used in combination with a 1921nm bandpass filter (FWHM 45nm) to image a soldering iron heated to temperatures ranging from 200 to 400°C (Figures 3 and 4). Through a suitable calibration, an NETD of 5°C was achievable over the 300-800 range for 10ms exposure times.

Figure 3 Experimental set up of the SWIR camera imaging a soldering iron

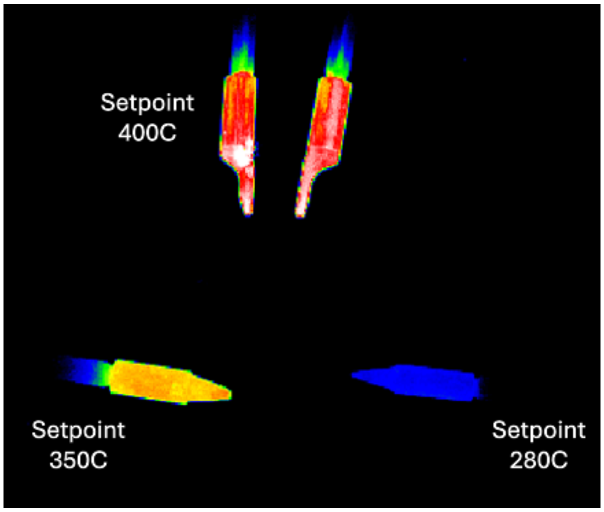

Figure 4 SWIR image of soldering iron tips with three different temperature setpoints acquired using a 1941nm bandpass filter and colour-coded according to the temperature calibration.

4. Multiband imaging

The use of colloidal quantum dots allows great flexibility in device processing allowing us to explore heterogeneous integration of materials in a facile fashion. We exploit this to extend the use of quantum dots to simultaneous multiband sensing, whereby different wavebands are imaged using a single focal plane array. This implementation is based on the use of our specially-designed 80x60 "superpixel" ROIC. This imager has three devices per 160µm x 160µm superpixel, consisting of two QD-gated graphene field-effect transistors (GFETs) and a third channel with serpentine electrodes designed for photoconductive device types (Figure 5). In this particular generation of devices we have dissociated the GFET and QD deposition by fabricating and encapsulating the array of GFET channels under a gate dielectric before QD processing. This removes a key challenge in QD-gated GFETs, which is that of controlling the QD-graphene interface. This interface strongly influences device performance as any defects and doping irregularities introduced on QD deposition dramatically affect the mobility of the graphene channel and also introduce hysteresis. Such imperfections are very difficult to control when solution-processing on graphene and so direct encapsulation immediately after graphene deposition is of great benefit. The graphene channel is instead gated via p-i-n QD diodes deposited subsequently.

This platform is very flexible allowing us to trial many materials, one combination using PbS QDs to gate the GFETs and HgTe QDs as a photoconductive film on the serpentine electrodes. In this configuration, the two PbS-based devices are used to detect the vis-NIR and SWIR bands respectively, whilst the HgTe device is used to detect MWIR. Such a device is depicted in Figure 5.

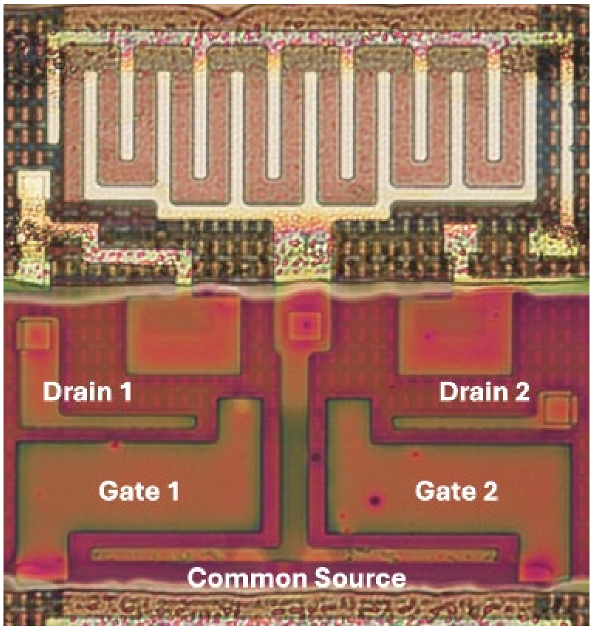

Figure 5 Photomicrograph of a single 160μm x 160μm superpixel of our multiband ROIC. The red band across the bottom of the image is a PbS QD layer deposited on top of the graphene channels of the GFETs, whose source, gate and drain electrodes are indicated. The golden serpentine electrodes at the top of the image are awaiting the deposition of HgTe QDs.

5. Conclusions

Imaging and sensing using photodetectors and imagers based on colloidal quantum dots are now making the transition from laboratory-based demonstrators into fully-fledged commercial solutions. These quantum dot detectors have particular relevance in the further reaches of the SWIR regime beyond 1700nm where existing technologies are not as competitive. In this paper we have outlined the general trend towards materials sensitive to such longer wavelengths, as well as discussed several novel sensing applications using quantum dot imagers.

6. References

1) Sergeeva KA, Zhang H, Portniagin AS, Bossavit E, Mu G, Kershaw SV, et al. The Rise of HgTe Colloidal Quantum Dots for Infrared Optoelectronics. Advanced Functional Materials. 2024, 2405307.

2) Allen M, Malik S, Bower C, Liu Y, Kallioinen S, Nenonen M, et al. Image sensors and cameras based on colloidal quantum dots (CQD) for visible-to-SWIR detection. Infrared Technology and Applications. L. 2024, 130460D