

Colloidal Quantum Dot Infrared Sensors for Next-Generation Consumer Electronics

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Abstract

Colloidal quantum dots are increasingly employed in display systems for their unbeatable light output quality. At the same time, their light absorbing qualities are highly appreciated in photodetector and sensor systems, especially in the infrared wavelength spectrum beyond the silicon cut-off at 1100 nm. In this paper, we introduce Pb-free absorbers in thin-film photodetector stacks with external quantum efficiencies above 30% in the short-wave infrared (SWIR) range. These devices are integrated in high-resolution and high pixel density image sensors enabling augmented vision.

Author Keywords

Quantum dots; infrared; short-wave infrared; SWIR; imaging; photodetectors; image sensors

1. Introduction

Quantum dots (QDs) have been making great strides to disrupt display technology, with their large-area processing capability compatible with flat panel display (FPD) industry. The contrast, color purity and conversion efficiency are already producing state-of-the-art light output. Related families of colloidal quantum dot (CQD) materials are also disrupting photodetector and image sensor technology, where their superb absorption properties enable new types of sensing devices. High absorption coefficient makes it possible to achieve high external quantum efficiency (EQE) even with thin films (<500 nm), facilitating integration on different readout backplanes. Tunability of the absorption spectrum by adjusting the nanocrystal size makes it possible to both select the cut-off wavelength and match the absorption maximum to a particular light source (e.g. light emitting diode or laser used as an illuminator) [1,2].

Especially the possibility of extending the sensitivity range beyond 1100 nm has garnered a lot of attention to CQD. This absorption edge of silicon has been a limiting factor for a more widespread adoption of short-wave infrared (SWIR, Fig. 1) sensors that are very interesting for several applications: seeing through materials (e.g. some plastics, smoke, fog) or better discriminating materials (e.g. recognition of different types of plastic that appear the same in the visible range) [3]. After initial demonstrations of CQD sensors for the visible and near infrared (NIR) range, the focus of the community shifted to SWIR [4,5]. The possibility to fabricate sensors via solution processing monolithically on the readout backplane is particularly attractive.

Incumbent SWIR imager technology [6] employs epitaxially grown III-V or II-VI compound semiconductors (e.g. InGaAs) on small wafer sizes (<4 inch) that are then hybrid bonded by die-to-die or die-to-wafer flip-chip process. Even though a lot of progress has been shown recently [7], this approach makes for typical cost of a SWIR camera in excess of several thousand dollars and prevents applications in consumer electronics. By monolithic integration of CQD stacks on full wafers (8- or 12-inch), the cost can dramatically decrease to even single-digit dollars once high-volume manufacturing ecosystem is established. In the FPD process, CQD stacks can also be deposited onto readout backplanes using fairly standard equipment. Furthermore, it can be foreseen to integrate thin-film photodetector (TFPD) based photodetector sub-pixels into displays for fully integrated additional sensing functionalities [8].

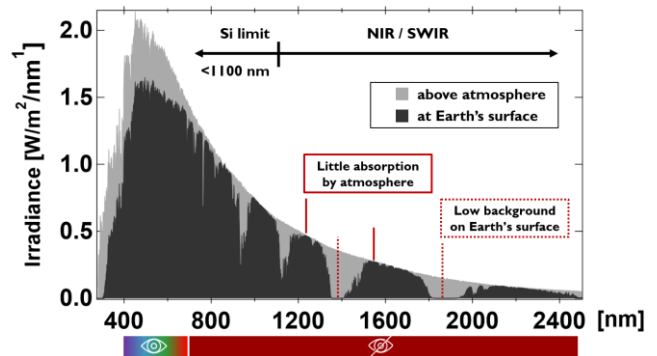


Figure 1. Short-wave infrared (SWIR) irradiance from the Sun with characteristic absorption peaks.

2. Quantum dot photodetector platform

Thin-film photodetectors (TFPD) should be seen as a platform where the photodiode can be optimized separately from the readout. The stack consisting of absorber (quantum dot-based, but also possibly organic or perovskite [9]) is sandwiched between electron and hole transport layers. The order of those ETL and HTL depends on the polarity – for the readout circuit (ROIC) collecting either electrons (“e2ROIC”) or holes (“h2ROIC”). They can be made using different thin-film materials depending on the appropriate electrical and optical properties, with typically organic or metal-oxide compounds. For the most typical

implementations on silicon ROIC, the top contact should be transparent and the bottom contact is the interface to the complementary metal-oxide semiconductor (CMOS) chip (and should be reflective at the wavelength of interest). In FPD implementations, also a transparent bottom contact for bottom illumination through the substrate is an option.

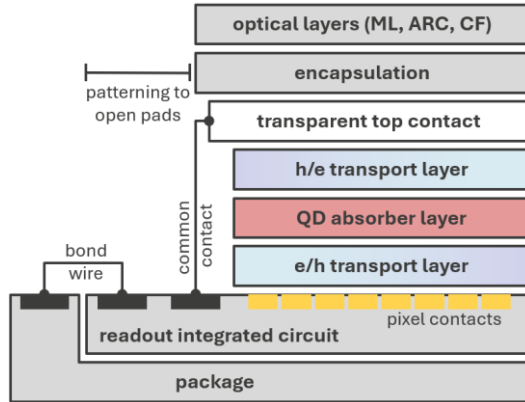


Figure 2. Schematic cross-section of a thin-film photodetector (TFPD) device.

CQD photodetectors and image sensors initially were mostly based on PbS absorber [10]. This material can be considered a “1st generation” absorber (Fig. 3) and has allowed to demonstrate high technology readiness level (with manufacturability on 300 mm wafers in high-volume environment [11]) with advanced image sensors implemented in commercial cameras [12,13]. At the same time, one of the hurdles for entering the consumer space has been the use of lead. This is why the “2nd generation” absorbers aim at Pb-free label, with most focus on compounds such as InAs [14-16], InSb [17] and AgTe [18]. HgTe contains restricted materials, but in turn allows sensitivity further into even the mid-wave infrared (MWIR) [19]. In this paper, we focus on InAs as the contender material enabling SWIR sensitivity, fast time response and potentially good thermal and environmental stability.

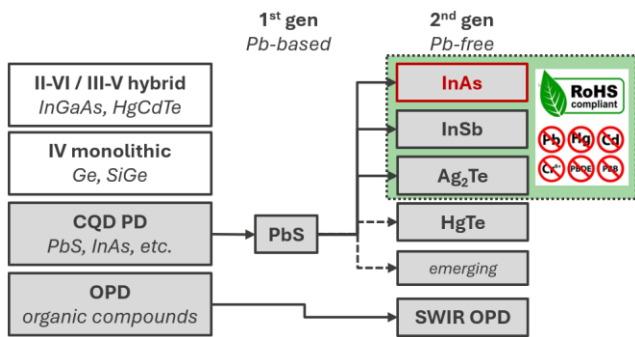


Figure 3. Sensor technologies enabling SWIR sensitivity, highlighting two generations of CQD absorbers: Pb-based and Pb-free.

3. Results

In our work, we typically start stack development on 3x3 cm² glass substrates with ITO bottom contacts (Fig. 4). The single pixel photodetector test structures have multi-mm² area to facilitate calibrated EQE measurements. This approach is also relevant to further upscaling to FPD-type glass or plastic

backplanes. In our research, the main focus has been on CMOS integration, thus the next step is transferring the stack to a silicon substrate with fab-compatible bottom contacts (e.g. TiN), emulating a CMOS ROIC. In this phase, we redevelop the stack for top illumination through a semi-transparent top contact (e.g. ITO) and optimize the bottom contact for reflection at the wavelength of interest to boost the in-stack absorption. The final step towards image sensor proof-of-concept is integration on custom-design readout chip, where the bottom contacts are arranged in a focal plane array with the pixel pitch relevant for the application, and where all bottom contacts are routed through the back-end-of-line (BEOL) structures to the pixel transistors and readout circuitry. Our typical test image sensor has a resolution of 768x512 pixels with 5 μm pixel pitch. One of the implementations we have demonstrated (with a PbS stack) is a 1.5 megapixel array with 1.62 μm pixel pitch. Such miniaturization shows the path towards very compact SWIR imagers.

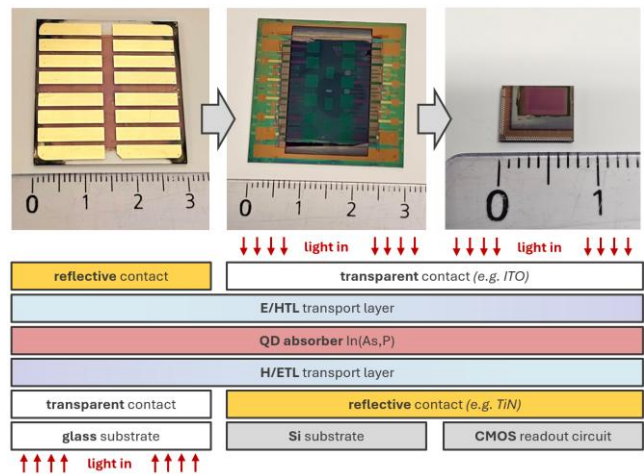


Figure 4. Methodology for QD stack optimization: glass substrates for initial material screening and bottom illuminated stack development (left); silicon substrate for top illumination (middle); and CMOS ROIC for image sensor proof-of-concept and integration optimization (right).

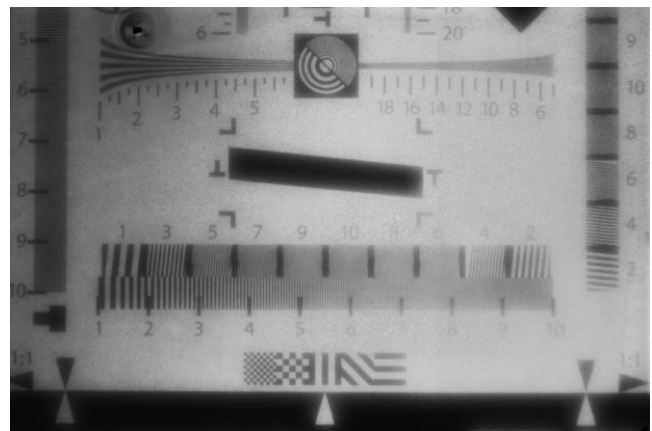


Figure 5. PbS QD SWIR image sensor prototype with 1.5 MPx resolution and 1.62 μm pixel pitch.

The InAs QDs have been optimized for deposition in a single step using the solution-phase ligand exchange approach. This way, the takt time can be greatly improved as compared to the more typical

solid-state ligand exchange process used typically for earlier PbS stacks. The stack optimization focuses on opto-electrical performance of the photodiode, with signal-to-noise ratio (SNR) as the main criterion. At this point, the InAs stack shows dark current density of $7.5 \mu\text{A}/\text{cm}^2$ at the reverse bias voltage of -3 V . The corresponding EQE at 1220 nm reaches 38% , with rise and fall time in the range of $2 \mu\text{s}$. These results are very encouraging towards further development targeting SWIR image sensors based on Pb-free quantum dot absorbers.

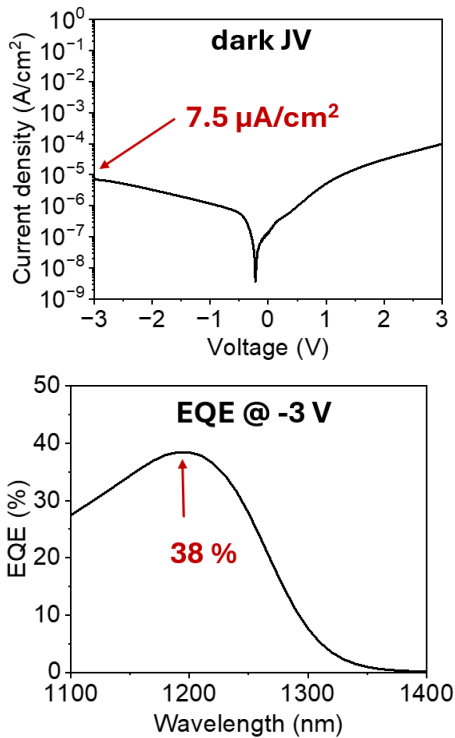


Figure 6. InAs photodiode results: dark current density (top); and external quantum efficiency (bottom).

InAs photodiode stack has been also integrated on the custom readout with 768×512 pixels and $5 \mu\text{m}$ pixel pitch (Fig. 7) [15]. The test scene was constructed to highlight sensitivity in the SWIR range: the main object was hidden behind a silicon wafer that only becomes transparent beyond Si absorption edge around the wavelength of 1100 nm . After illumination with a halogen lamp, it was possible to clearly resolve the objects hiding behind the silicon wafer. The imager exhibited dark read noise of $33 e^-$, dark current of $51 \mu\text{A}/\text{cm}^2$, conversion gain of $8.5 \mu\text{V}/e^-$, full well capacity of 75 Ke^- and a dynamic range of 67 dB . The image quality from the first demonstrations looks promising, with external quantum efficiency of 28% and the photoresponse non-uniformity was 8.1% . These results are a milestone towards further optimization of Pb-free stacks for SWIR image sensors.



Figure 7. Proof-of-concept InAs image sensor for the SWIR range: test scene acquired with a CMOS camera (top); and InAs QD image (bottom).

4. Conclusions and outlook

We have introduced the thin-film photodetector (TFPD) platform that can employ different types of absorbers such as colloidal quantum dots. This approach is especially interesting for disrupting imaging in the short-wave infrared (SWIR) range, beyond the absorption edge of silicon. We have demonstrated proof-of-concept image sensors based on InAs absorber, considered to be the 2nd generation QD material in the pursuit of new Pb-free absorbers. This, together with establishing of volume production ecosystem, can enable cost-effective, miniaturized SWIR imagers that could be integrated into consumer electronics. Examples of applications include eye-safe eye trackers for AR glasses, spatial awareness sensor suite with improved ranging at longer wavelengths, see-through visibility (e.g. eyes through sunglasses, objects through smoke or fog) and better material and object discrimination (e.g. material contrast in wearable devices).

The vision for QD SWIR image sensors (Fig. 8) includes introduction of multi-band per-pixel functionality [20], low-noise readouts with pinned photodiode [21] and miniaturization of the camera module to allow for seamless system integration.

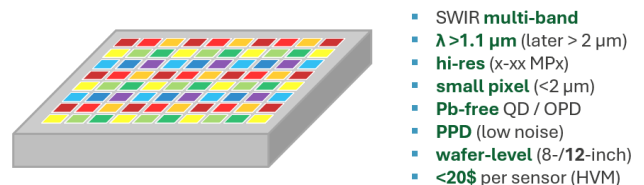


Figure 8. Future directions for further development of QD SWIR image sensors.

5. Acknowledgements

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