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Disruptive Infrared Image Sensors Enabled by Quantum Dots

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ABSTRACT

Sensors based on quantum dot photodiodes promise quality and accessibility improvement of infrared imaging. We demonstrate sub-2 μm pixel pitch arrays with EQE above 40% at 1450 nm. Monolithic integration enables high throughput and wide deployment of SWIR imagers in applications that previously could not afford them.

1 Introduction

Image sensors have always been more than reproducing human vision. Information hiding in "invisible" ranges is crucial in applications such as machine vision (e.g. sorting), spectroscopy, depth sensing (3D imaging) or surveillance (low-light imaging). Looking at the solar radiation detectable on Earth (Fig. 1), one can distinguish irradiance regions with very low intensity, where active illumination systems are operating to limit the background. Notable spectral lines in the near infrared (NIR) region are around 850, 905 and 940 nm. These are widely used for example in face detection by structured illumination approach. In the short-wave infrared (SWIR), the region around 1400 nm has even lower background. Another case are regions with a high light intensity, such as around 1550 nm. This latent light, invisible to human eye, can be used in passive illumination systems, for example in low-light imaging in security cameras [1].

NIR detection can be realized with Si-based CMOS image sensors, with the latest devices achieving even 50% external quantum efficiency (EQE) [2]. SWIR is inaccessible due to the limitation of the silicon bandgap (1.12 eV), making this material transparent above approximately 1100 nm wavelength. SWIR imagers are traditionally fabricated using II-VI (e.g. HgCdTe) or III-V (e.g. InGaAs) materials hybridized to the readout circuit by means of flip-chip bonding, where the connection between the chips is made with bumps. Even though this technology is very mature, with EQE above 80% and established market, there are still a lot of limitations, some fundamental for this approach. Even state-of-the-art InGaAs devices [3] are far away from what is typical in visible imaging, keeping SWIR imaging in a high-end category.

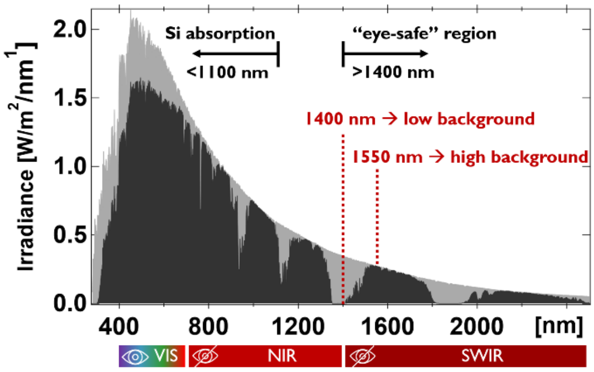

Fig. 1 Solar irradiance above the atmosphere (light grey) and on Earth's surface (black).

Thin-film photodetector (TFPD) technology is based on novel absorber materials that can access wavelengths not accessible to silicon. Ease of processing makes it possible to monolithically integrate stacks with such absorbers directly on the readout backplanes. One category of TFPD materials are quantum dots [4]. While changing the size of these nanocrystals, their optoelectrical properties can be changed. Lead sulfide (PbS) QDs can have the absorption peak tuned between 940 nm (for 3.3 nm size) to 1450 nm (5.4 nm) and further even beyond 2000 nm. The absorber layer is stacked between transport layers (Fig. 2), and the thicknesses are tuned to maximize performance.

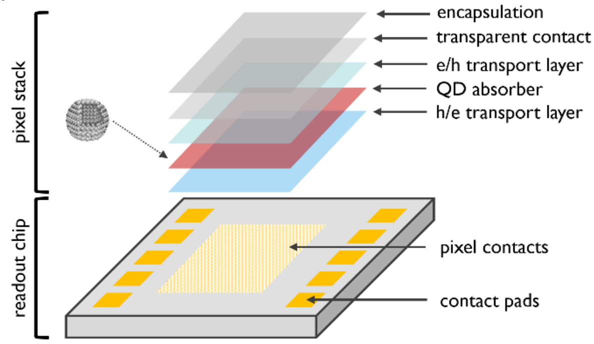

Fig. 2 Pixel stack based on quantum dot absorber

2 QD infrared image sensors

2.1 QD photodiode

Photodetectors based on the PbS QD absorber are optimized depending on the application. Fig. 3 illustrates the quantum efficiency of 6.25 mm^2 test devices fabricated on silicon substrate. The light is captured in a top illumination architecture through a semi-transparent contact stack, mimicking the image sensor configuration. One can see that all 3 stacks compared have high sensitivity in the visible range (with EQE approaching 80%). Then, the size-dependent absorption peak can be tuned for maximum EQE at 940, 1450 or 1550 nm, in all cases exceeding 40%. Depending on the system requirements, one can utilize the full broadband spectrum or select particular bands (for example when working with an illuminator). Even though the total thickness of the pixel stack is below 0.5 – 1 µm, the sensitivity can be excellent thanks to a proper electro-optical co-optimization [5, 6].

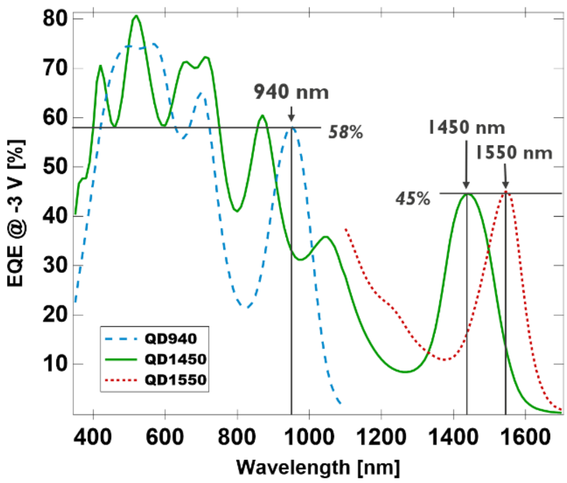

Fig. 3 External quantum efficiency of 6.25 mm^2 photodiodes on silicon (top illuminated)

2.2 Focal plane array integration

Focal plane arrays (FPAs) based on QD absorbers are gaining momentum, with some even reaching commercial maturity [7-9]. Here, the optimized pixel stack is transferred to a custom-designed readout integrated circuit (ROIC). The chips are fabricated in 130 nm technology on 200 mm wafers. The top contacts are customized to improve the planarity (electrode step height < 5 nm) and reflectivity (at the infrared wavelength of interest). The stacks can be patterned using standard photolithography and etching techniques to access the contact pads on the chip perimeter. Another option is to do full pixelation, which separates individual pixel stacks from their neighbors, which can eliminate the electrical crosstalk. Semi-transparent top contact and in-situ encapsulation are used to finish the device processing. The image sensors are then packaged (Fig. 4) and mounted in a camera system for characterization.

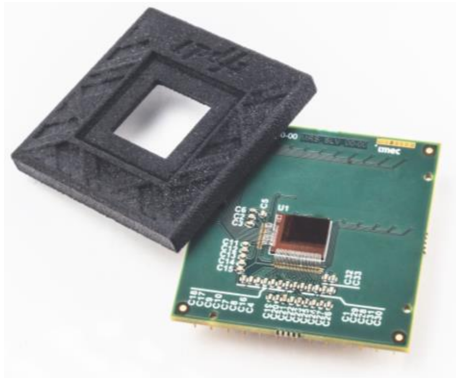

Fig. 4 Packaged QD image sensor

3 Results

3.1 Resolution

A sensor with 5.4 nm PbS QD absorber was used for image acquisition. The readout here has a resolution of 768x512 pixels, with a 5 µm pixel pitch. One can notice that the slabs, made of two types of plastic look identical in the visible range, while they appear black and white in the SWIR range (Fig. 5). This shows potential for material recognition in applications such as sorting. Another notable feature is high operability (pixel yield), which was achieved after reducing the defectivity of the QD film. The resolution can be easily increased as it is not limited by the hybridization process and is an important feature for applications that require a large field of view (FoV). The scaling works in the same way as in traditional CMOS image sensors, where resolutions above 100 megapixels are already available in consumer devices.

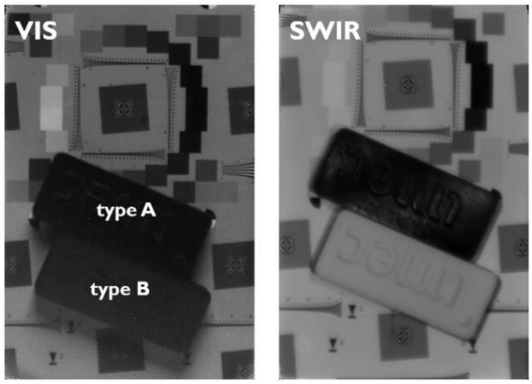

Fig. 5 Scene acquired with the same QD image sensor in the visible (left) and SWIR range (right). The latter is taken through a Si wafer.

3.2 Pixel pitch

The pixel density can be scaled in a similar way, as it is driven by the readout circuit design. We scaled down the 3T pixel engine towards the limits of our 130 nm technology. The result are focal plane arrays with the pixel pitch of 1.82 µm and a resolution of 128x128 px [10] (Table 1). In the same design, we fabricated 768x512 px FPAs with 5 µm pixels. Both showed EQE of 13% at 1400 nm. After further stack improvement [6], we fabricated baseline sensors with 40% EQE at 1450 nm. These devices are only around a factor 2 away from traditional InGaAs detectors in quantum efficiency, while they can achieve pixel density far beyond state-of-the-art.

Table 1 Imec QD SWIR image sensors comparison

Parameter	gen1 [10]		gen2 [6]	Unit
Pixel pitch	5	1.82	5	µm
Resolution	768x512	128x128	768x512	px
DR	84	63	82	dB
FWC	470	16.8	325	Ke^-
J_D	0.3	0.2	3.3	$\mu A/cm^2$
RN	33	12	25	e^-
PRNU	1.3	1.8	2.4	%
λ_{PEAK}	1400		1450	nm
EQE	13		40	%

***DR**: dynamic range; **FWC**: full-well capacity; **J_D**: dark current density; **RN**: read noise; **PRNU**: photo-response non-uniformity; **λ_{PEAK}**: peak wavelength; **EQE**: external quantum efficiency*

Small pixel size is desired to improve the manufacturing throughput. This way, more chips can be packed onto a wafer, reducing the sensor cost to levels that are acceptable for mass markets. At the same time, high pixel density significantly improves the image quality, as we demonstrated by comparing arrays with 5 µm and 2.5 µm pitch (Fig. 6). Line and space patterns can be much better distinguished by the array with the smallest pixel pitch.

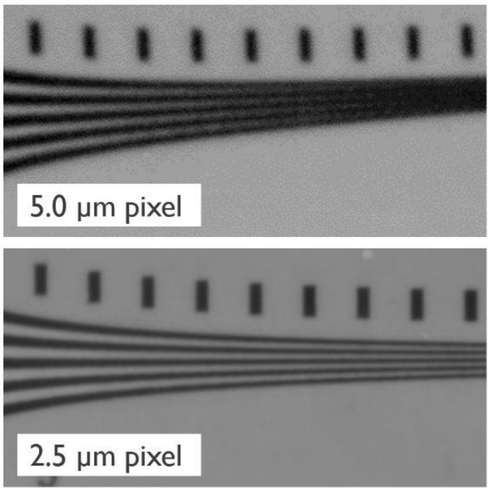

Fig. 6 Images acquired with QD image sensors with the pixel pitch of 5 µm (top) and 2.5 µm (bottom)

4 Conclusions

Image sensors based on thin-film absorbers are a new technology that has the potential to disrupt infrared imaging and make it accessible. Quantum dots can be tuned to maximize sensitivity at the wavelength of interest. The pixel stack is integrated monolithically, directly on the readout circuit, allowing for scaling down the pixel pitch and scaling up the resolution. QD sensors promise to bring SWIR imaging to new markets where such technology was previously unaffordable, and thus augmenting vision in new segments and opening new ones (Fig. 7).

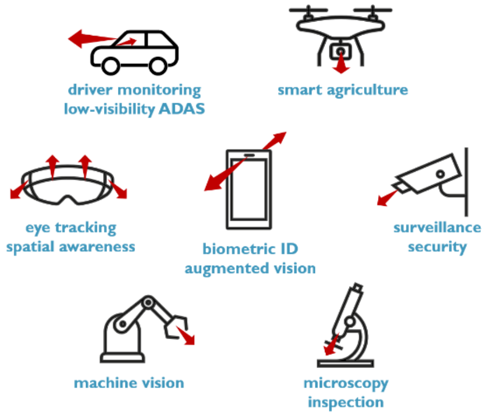

Fig. 7 Applications for SWIR QD image sensors

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