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Augmented Vision Enabled by Imagers Based on PbS Quantum Dots

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Cameras are omnipresent in our daily lives, with several billions image sensor units deployed annually. The imaging revolution was possible with the introduction of CMOS (complementary metal-oxide-semiconductor) technology and streamlining the manufacturing process based on the semiconductor ecosystem. CMOS image sensors (CIS) are relying on light detection by a silicon photodiode, which is perfectly suited for replicating human vision (visible wavelength range) and beyond (e.g. NIR – near infrared or UV - ultraviolet). At the same time, longer wavelengths such as short-wave infrared (SWIR) are inaccessible by Si due to the energy bandgap, setting the cut-off wavelength at around 1100 nm.

SWIR range is typically defined above 1400 nm (which is the onset of "eye-safe" region as the human eye is several orders of magnitude less sensitive to radiation above that wavelength) until approximately 2500 nm (which is the onset of mid-wave infrared, MWIR) [1]. This range is interesting both for active and passive illumination systems. In the former case, one can take advantage of less background radiation coming from the Sun (with irradiance at 1400 nm significantly lower than at e.g. 940 nm typically used in systems such as FaceID). The latter can provide vision in low-light conditions (e.g. using "night glow"). Applications include recognition of visually similar materials (sorting), high contrast for water (moisture detection), vision through fog/smoke/clouds (driver assistance in automotive) or low-light imaging (security cameras).

The incumbent approach of accessing SWIR wavelengths was to use hybrid imagers with a CMOS readout chip flip-chip bonded to a detector chip. This detector chip would be made of low bandgap III-V or II-VI materials such as InGaAs or HgCdTe. The low throughput epitaxial growth process together with die-to-die bonding process result in very high sensor cost. This in turn results in SWIR range being limited to high-end applications in machine vision, scientific and space imaging, with global annual volumes estimated at around 11'000 image sensors. Recent advances focus on the bonding process to realize sensors with pixel pitch down to 5 µm [2].

An alternative approach is to realize "monolithic hybrid" integration of the detector material other than Si directly on the readout chip. From the family of thin-film photodetectors (TFPD), colloidal quantum dots (CQD) seem as a very attractive candidate material family [3]. Thanks to the tunability of the cut-off wavelength with the nanocrystal size, one can select the appropriate spectrum by tuning the material synthesis process. Deposition by coating directly on the CMOS readout wafer enables significant throughput increase with wafer-level manufacturing. This can lead to high volumes of image sensors driving the cost down to levels suitable even for consumer and automotive applications.

QD image sensors are composed of the readout front-end (circuitry) including the pixel engine and the photodiode stack. The stack contains the QD absorber, electron and hole transport layers and semi-transparent top contact, plus an encapsulation layer. Depending on the readout architecture, the QD photodiode may have different polarity: "e2ROIC" (readout accepting electrons) or "h2ROIC" (readout accepting holes). The QD absorber in most reported implementations is based on lead sulfide (PbS), as this material can be tuned from the quantum confinement peak at 940 nm all the way to above 2200 nm (Fig. 2). Other materials include InAs [4], which promises to deliver much faster response (even below ns) and HgTe, enabling cut-off wavelengths in the MWIR range [5].

We have fabricated QD image sensor prototypes with VGA+ resolution (768x512 pixels) and 5 µm pixel pitch. External quantum efficiency (EQE) in the current generation imager is around 40% at the wavelength of 1450 nm at the reverse bias voltage below -3 V and at room temperature. Some imaging examples in machine vision applications are shown in Fig. 3-6, highlighting possibilities in sorting and inspection. Fig. 7 shows our modular camera with interchangeable boards allowing to adjust the functionality to the specific use case. This system helps to define specifications required by different applications and customize the image sensor accordingly. One example of customization is reducing the pixel pitch to enable high image quality and compact for factors. We demostrated SWIR imagers with pixel pitch down to 1.82 µm [6], with the most recent publications reducing that further to 1.62 µm [7].

Quantum dot image sensors are a new approach to access the SWIR wavelength range. With the monolithic integration of PbS QD photodiode on CMOS readout, high pixel density and high-resolution focal plane arrays can be realized. Efforts to enable manufacturing upscaled to wafer-level show the path towards cost reduction allowing applications that could not implement SWIR imaging. Further improvements of maturity of this technology will bring miniaturized SWIR cameras to new markets and augment information acquired by vision systems.

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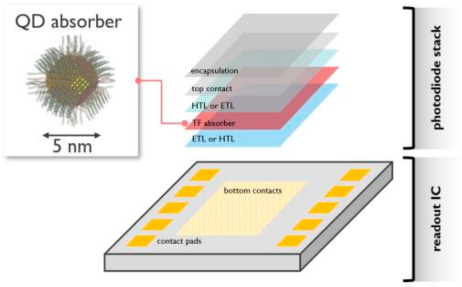

Fig. 1. Schematic structure of a "monolithic hybrid" quantum dot image sensor.

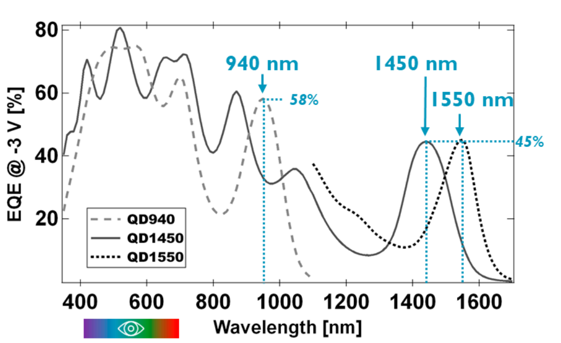

Fig. 2. External quantum efficiency (EQE) for photodiodes using different sizes of PbS QD.

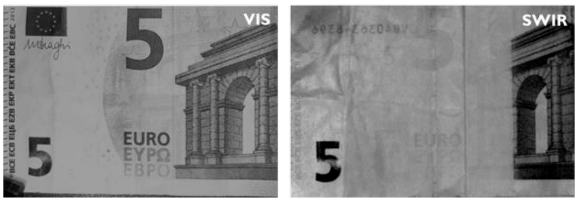

Fig. 3. SWIR imaging example: banknotes in the visible (VIS, left) and SWIR range (right).

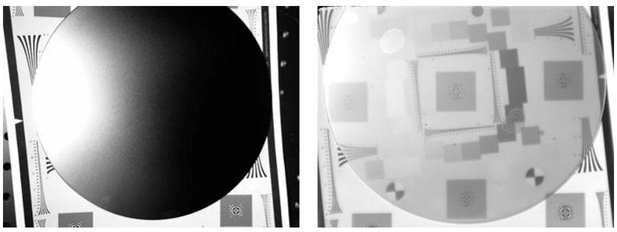

Fig. 4. SWIR imaging example: silicon wafer inspection (VIS, left) and SWIR (right).

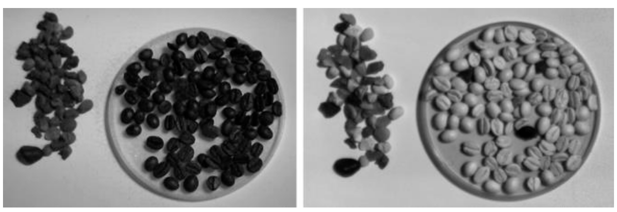

Fig. 5. SWIR imaging example: contaminants among coffee beans (VIS, left) and SWIR (right).

Fig. 6. SWIR imaging example: food inspection through plastic packaging (VIS, left) and SWIR (right).

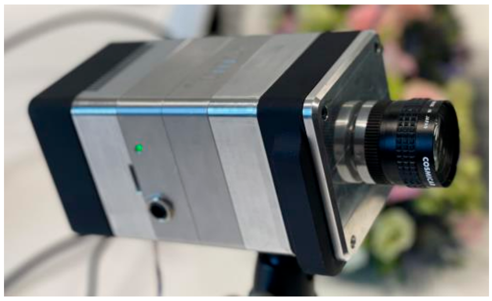

Fig. 7. Imec ModCam (modular camera) used for use case studies with QD image sensors.

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