Organic- and QD-based image sensors integrated on 0.13 µm CMOS ROIC for high resolution, multispectral infrared imaging

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Thin-film materials with absorption in the NIR and SWIR wavelength range enable monolithically integrated, high resolution CMOS image sensors with infrared sensitivity. This work describes imagers using polymer (organic) and lead sulfide quantum dot (PbS QD) absorbers. With different thin photodiode stacks (<300 nm), we report EQE values of 30%, 31% and 15% at the target wavelengths of 940, 1050 and 1450 nm, respectively. Photolithographic patterning of thin-film stacks allows wafer level upscaling and high pixel density. Here, we demonstrate isolated thin-film islands with pitch down to 40 µm and resolution of 640 ppi and we present the concept of incorporating different absorbers in adjacent pixels for multispectral focal plane arrays. Finally, image acquisition is demonstrated on 5 µm pixel pitch FPA using custom, 130 nm technology node CMOS readout.

As imaging is evolving into information acquisition, there is greater need for low cost IR sensors with compact form factor. The spectral region between 0.9 and 1.8 µm is of particular interest due to water absorption windows in the atmosphere. Thin-film materials are a promising alternative for imaging in this range compared to the costly and resolution-limited III-V based sensors, as they can be monolithically integrated directly on top of CMOS read-out. Previous reports showed integration of organic [1] and QD [2] absorbers in imagers.

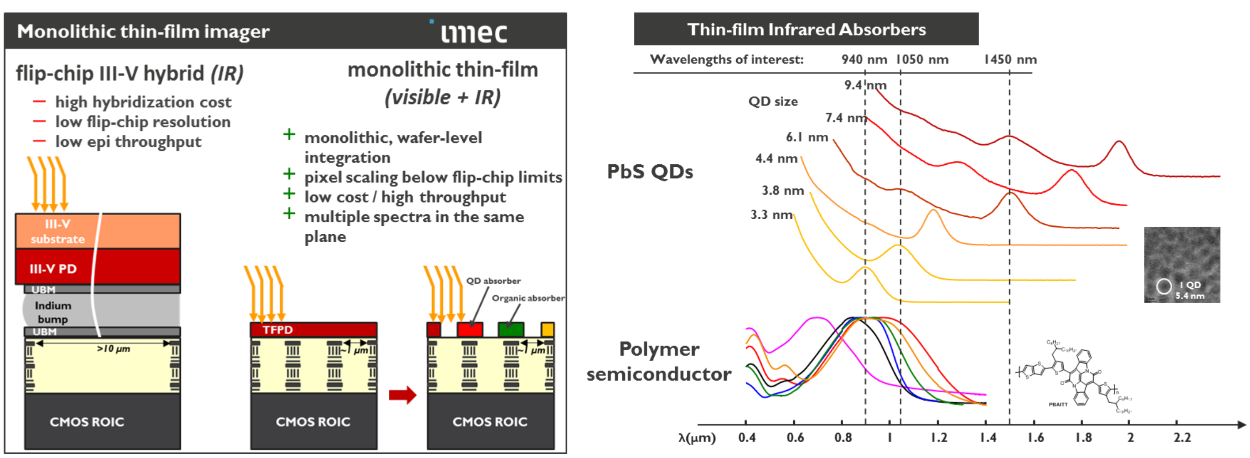

Figure 1. Monolithic integration of thin-film on CMOS (left) and absorption spectrum of selected infrared sensitive thin-film materials (right). The absorption peak of quantum dots can be tuned with their size, targeting the NIR and SWIR regions, while bay-annulated indigo (BAI) based polymers offer a broad peak in the NIR region.

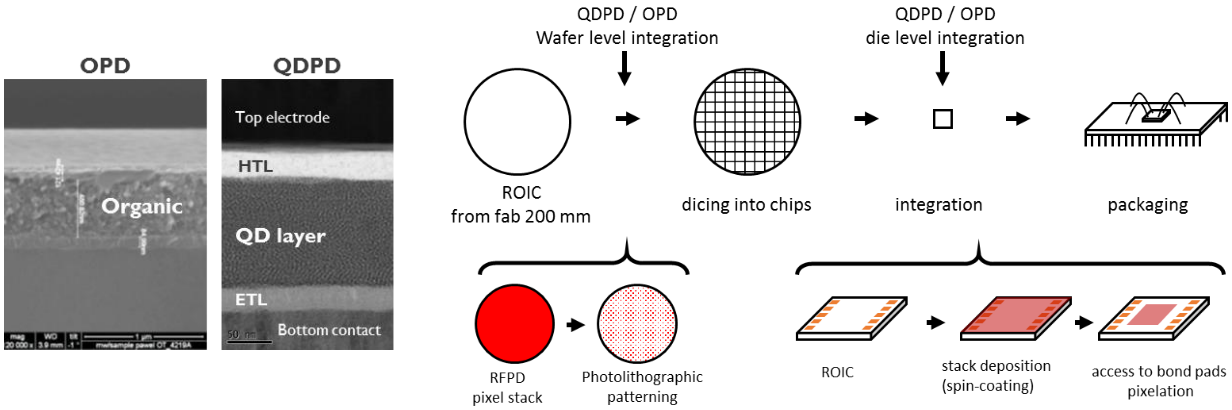

Figure 2. Scanning electron microscope cross-sections of selected photodiode stacks (left) and integration roadmap of the thin-film image sensors (right). The TFPD stacks presented here were monolithically integrated on top of the CMOS read-out integrated circuit (ROIC) on die level. IMEC is furthermore working on wafer level processing route of these stacks.

This work describes the successful integration of thin-film photodiodes (TFPD) on CMOS for extension of the sensitivity spectrum into the NIR and SWIR, enabling also detection of multiple wavelengths in the same plane. The materials of choice are polymers and PbS QDs. For the polymers, bay-annulated indigo (BAI) was employed for the preparation of organic semiconductors with broad absorption in the NIR [3]. The QDs take advantage of the quantum confinement enabling tunable absorption peak at different wavelengths depending on the quantum dot size, targeting the NIR and SWIR regions up to 2 µm (Fig. 1).

For the photodiode fabrication, a multilayer stack was developed. The IR absorber layer was deposited from solution and over large area using low cost techniques such as spin coating. Electron and hole transport layers (ETL/HTL) were employed for the formation of an n-i-p diode and the suppression of dark current [4]. A CMOS-BEOL bottom contact with high IR reflection was developed with fab-compatible metals and the stack was finalized with an optimized transparent top contact. Scanning electron microscopy cross-sections (SEM) of selected photodiode stacks reveal the formation of thin-film stacks not exceeding 400 nm in thickness (Fig. 2).

For the monolithic integration of the TFPD stack on top of the CMOS read-out integrated circuit (ROIC), a photolithography-based route compatible with wafer-scale fabrication is being developed as shown in Fig. 2. The thin-film stack can be deposited either on die or wafer level. Photolithographic patterning enables the access to bond pads required for the wire-bonding and packaging processes. Furthermore, patterning can be applied at the pixel level. High resolution TFPD pixel arrays were formed using PbS QDs achieving 640 ppi with pitch down to 40 µm and pixel size of

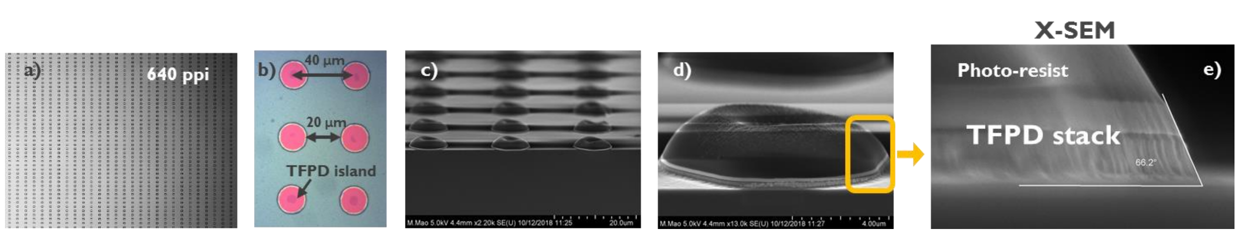

Figure 3. Microscopy pictures of patterned TFPD pixels using PbS QDs: a, b) top view of high resolution islands of 40 µm pitch and c-e) SEM pictures of top view and cross-section of the stack after etching using 300 mm tools.

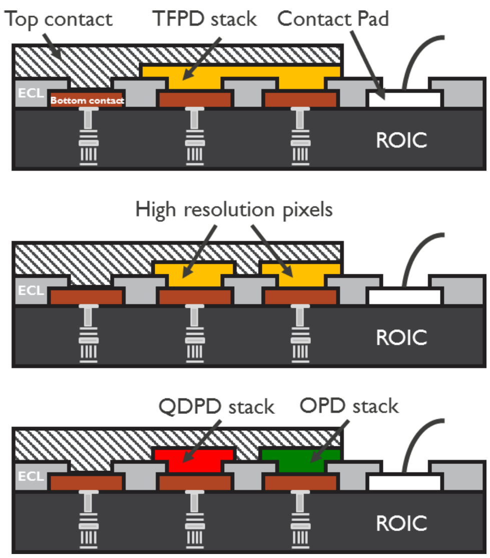

Figure 4. Photolithographic patterning of the TFPD stack per active area (top), per pixel (middle) and with a different absorber stack per pixel (bottom).

Table 1. Summary of performance characteristics for thin-film photodetectors on Si substrate with only BEOL.

TFPD stack	OPD 1050 nm	QDPD 940 nm	QDPD 1450 nm
J_{dark} at 300K	60 nA/cm^2	30 nA/cm^2	1 uA/cm^2
EQE	31%	30%	14%
Rise time [10%-90%]	25 µs	57 µs	13 µs
Fall time [90%-10%]	30 µs	86 µs	41 µs
D^* [cm Hz^{½} W^{-1}]	1.9×10^{12}	2.3×10^{12}	3×10^{11}

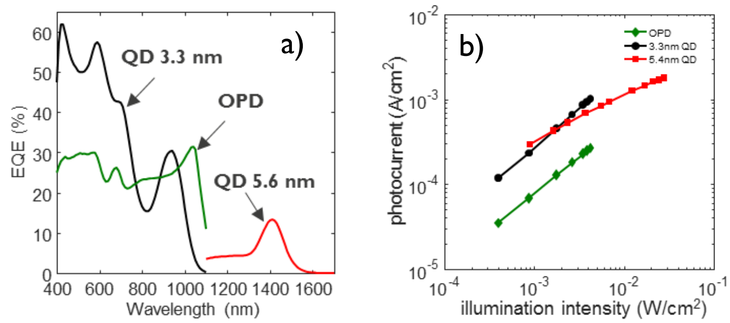

Figure 5. a) EQE of photodetectors on Si using three different types of thin-film absorbers, b) Linearity of the photocurrent for varying illumination intensity. A 940 nm LED is used for the 3.3 nm QD and the OPD, while a 1450 nm LED is used for the 5.6 nm QD.

20 µm (Fig. 3 a-b) [5]. Patterning was performed using 300 mm wafer tools. SEM pictures of top view and cross-section of the stack after etching confirm the survival of the TFPD stack and the formation of isolated pixels without any over-etching effects (Fig. 3 c-e). The patterning concepts are summarized in Fig. 4. In the first case, a large thin-film island is formed, covering the entire focal plane area. With this method, the pixel pitch is defined solely by the ROIC enabling state-of-the art sub-micron pixel pitch. Isolated organic pixel arrays fabricated using photolithography patterning have been shown with pixel pitch down to single micrometers [5]. This approach can lead to improved imager performance by canceling potential cross-talk between adjacent pixels. Additionally, individual TFPD pixel patterning can allow the incorporation of different absorber pixels next to each other such as an OPD stack next to a QDPD stack. This concept opens the way for the development of low cost multispectral infrared imagers.

For the evaluation of the electrical performance, single pixel photodiodes with different sizes down to 20x20 µm^2 were fabricated on test silicon substrates mimicking the ROIC. The results are summarized in Table 1. The EQE is ≥30% at the target wavelengths of 940 nm (3.3 nm diameter QD) and 1050 nm (OPD) and 15% at 1450 nm (5.6 nm diameter QD), in combination with dark currents of 30 nA/cm^2, 60 nA/cm^2 and 1 uA/cm^2 (Fig. 5a). The speed of the photodiodes was characterized with pulsed IR LEDs and the rise and fall times of all the

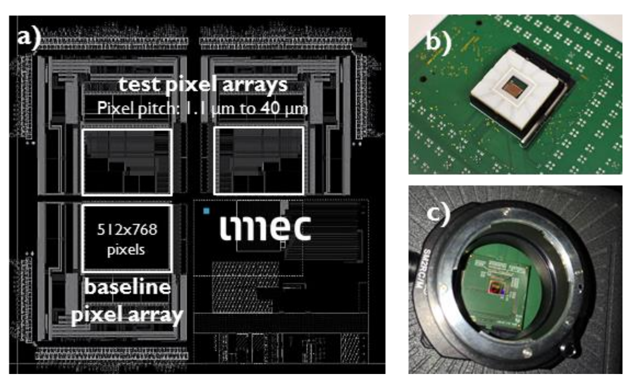

Figure 6. Image sensor a) design with baseline pixel array of 5 µm pixel and test arrays for pixel scaling (1.1 µm to 40 µm) and b, c) imaging setup.

devices were measured to be between 13 and 86 μs. Additionally, linear behavior of the photocurrent for varying illumination intensity is observed (Fig 5b).

Finally, the developed thin film photodiodes were integrated on die level on top of ROICs processed on 200 mm wafers using 130 nm technology node (Fig. 6). Image acquisition in visible light and under IR illumination is demonstrated on a 512x768 pixel focal plane array with 5 um pixel pitch using polymers and colloidal quantum dots (Fig 7, 8).

In summary, thin-film photodiodes are being developed at imec using polymer semiconductors and colloidal quantum dots for NIR and SWIR light detection. A full process flow compatible with wafer-level processing has been developed and imaging under visible and IR illumination was demonstrated. Finally, photolithographic patterning of the TFPD allows the formation of pixelated arrays and opens the way for incorporating different absorbers in adjacent pixels for multispectral focal plane arrays.

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Figure 7. Image from a polymer semiconductor based image sensor, under visible light and under illumination from a NIR LED. Paper ink is not visible in the IR light.

Figure 8. Light scene pictures taken from a quantum dot based image sensor under visible light and under illumination from a NIR LED.