CMOS-compatible Imager for FLIM and TOF Applications

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An image sensor with 256x256 pixels and a pitch of 6.3 µm, suitable for resolving ultra-short optical phenomena, was developed in a standard CMOS process. The pixel comprises a pinned photo diode and three transfer gates allowing for versatile sensor operations such as repetitive exposure and integration. Demodulation of signals at the pixel level with contrast higher than 92% at up to 100 MHz has been achieved. Fluorescence lifetime imaging microscopy (FLIM) and 3D time-of-flight (TOF) imaging have been demonstrated.

Three-dimensional time-of-flight (3D-TOF) range imaging has gained a lot of interest over the last decade especially in machine vision, automotive, and space industries. But also the consumer market is in demand for new solutions for various ranging applications. Fluorescence lifetime imaging (FLIM), which is quite a different application field, has almost identical requirements with respect to the detector demodulation capabilities. While for 3D-TOF imaging solutions based on CMOS or hybrid CCD/CMOS processes are already available on the market, demodulating detectors have not yet been able to fulfill the requirements of FLIM in terms of sensitivity as well as spatial and temporal resolution.

This work aims at developing a general purpose image sensor for resolving ultra-short phenomena. As megapixel resolution should be achievable at low cost, this first prototype features a small pixel pitch of 6.3 µm and is realized in a standard CMOS process with pinned photodiode (PPD) option. It can generate 3D-TOF and FLIM images with monoexponential luminescence decays from image processing of only two frames at video rate.

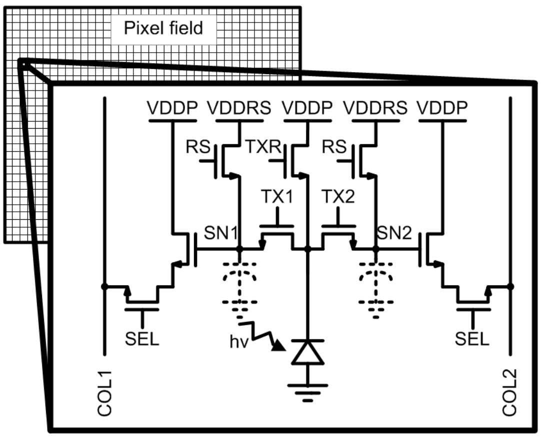

Figure 1: Schematic of the pixel

The imager features 256x256 pixels, each containing a pinned photo diode and three transfer gates (see Figure 1). The pixel layout development was based on thorough finite-element simulations executed with Synopsys TCAD tools. The alternating activation of the gates TX1 and TX2 separates the photo-electrons depending on their time of arrival into the two sense nodes. TXR works as a global photo-diode reset to drain charges from the PPD while activated. Thus FLIM autofluorescence is suppressed and charge integration is stopped during read out. The charge transferred to the two sense nodes is converted into two voltages and read out with source followers. The differential imager output signals are proportional to the charge difference between the two sense nodes of every pixel.

The imager has been tested as well in a FLIM and in a 3D-TOF application. Fluorescence lifetime imaging was executed on two samples of CdTe quantum dots (Plasmachem GmbH) with maximum spectral peak of 530 nm and 640 nm and fluorescence lifetimes of 6.9 ns and 53.0 ns respectively. FLIM images were generated at 35 frames per second. The measured lifetime was 11.5 ns and 54.0 ns respectively and proved to be independent of the optical signal intensity. The measurement of the shorter lifetime is shown in Figure 2. Its deviation from the nominal value is due to some mismatch of the time delay in the transfer-gate control signals, and will be corrected on- or off-chip in future work.

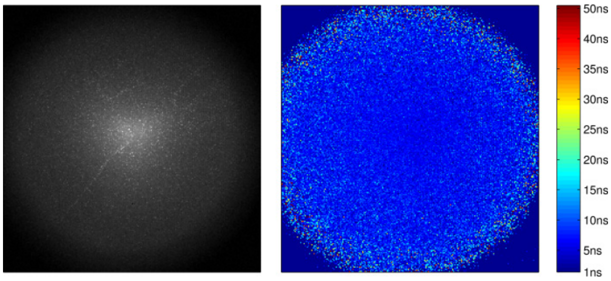

Figure 2: Intensity and FLIM image of quantum dot solution

The 3D-TOF setup includes an illumination source at 850 nm peak wavelength operated at 16 MHz. This limit was imposed by the driving circuit and not by the sensor, which demonstrated excellent demodulation capability up to 100 MHz [1]. The imager was evaluated in a dark lab with a target board fixed on a rail system, allowing automated distance sweeps from 1 m to 4 m. The imager has a low sense-node saturation capacitance of nearly 10 ke, which limits its performance with respect to the distance resolution and especially the background signal immunity. Under optimum conditions the standard deviation of the depth information is as low as 20 mm, which is very close to the physical limit given by the photon shot noise.

This work was executed within the frame of a PhD thesis [2]. The feasibility of large-array CMOS imager for optical temporal waveform analysis suitable for FLIM and 3D-TOF was successfully demonstrated.

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[1] L.-E. Bonjour, M. Kayal, N. Blanc, D. Beyeler, “CMOS demodulation image sensor for nanosecond optical waveform analysis”, IEEE Sensors Journal (2013) – accepted, to be published

[2] L.-E. Bonjour, "CMOS demodulation image sensor for nanosecond optical waveform analysis", Ph.D. dissertation, EPFL Swiss Federal Institute of Technology (2013)