A 320x240 10um CAPD ToF image sensor with improved performance

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Introduction - In terms of system size Time-of-Flight (ToF) approaches have an advantage over triangulation – active or passive – depth acquisition technique [1], as there is no constraint on a baseline distance between the ToF sensor and the illumination source. For triangulation-based techniques, a baseline is required to create the disparity from which the depth is calculated. Time-of-flight 3D sensing solutions thus make, at least for size considerations, a good choice for compact 3D sensing modules for embedding in small mobile platforms such as smartphones, tablets or miniature drones. The module itself consists of a 3D ToF sensor, an illuminator – typically a VCSEL, and can be made as compact as the size of the individual components allows. In the z dimension, the module size is constrained by the lens dimensions which are indirectly defined by the sensor resolution and pixel pitch as well as optical requirements such as f-number, and FoV. In this design, the challenge was to maximize the relevant performance parameters given the constraints of a mobile system. Thus, this paper presents a QVGA ToF sensor fabricated in a 180nm process, and aimed at bringing high performance ToF depth acquisition to mobile platforms with reduced power consumption.

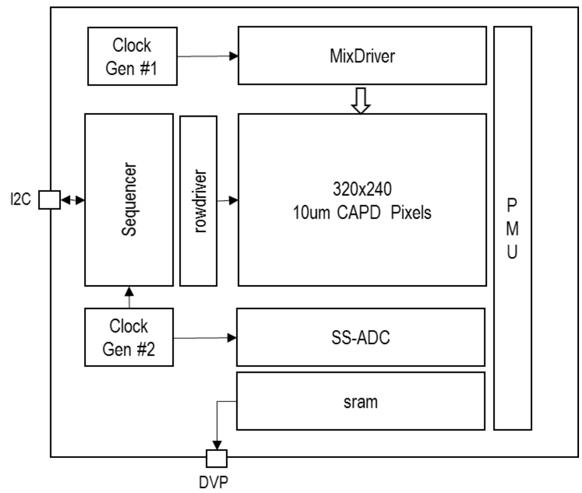

Figure 1- Block diagram of the device

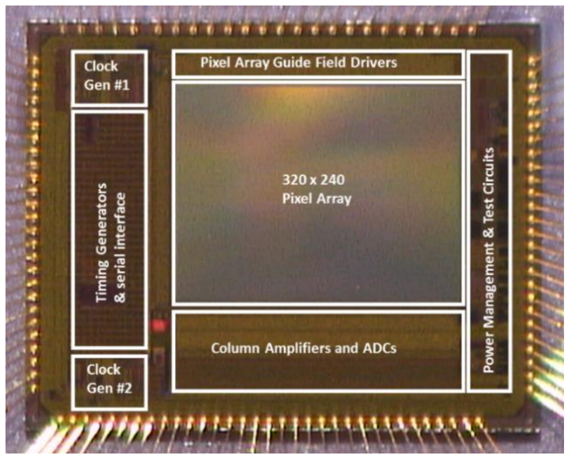

Figure 2 - Micrograph of the device.

Design - The block diagram and micrograph of the device are shown in Figure 1 and Figure 2 respectively. The optical area of the sensor consists of a QVGA resolution ToF pixel array. Each pixel is a 2-tap Current-Assisted Photonic Demodulator (CAPD). Additional dummy and reference pixels are implemented surrounding the active pixels. The sensor is controlled through an I2C interface for configuring the programmable sequencer optimized for generating ToF-specific exposure patterns, and a parallel digital video port (DVP) output port streams out the sensor data. Two clock generation blocks are designed, one for the sequencer and analog-to-digital convertor clock signals, and a separate clock-generator for the Time-of-Flight operation. The second clock-generator provides modulation clock signals for both the ToF pixel array and the illumination controller. The CAPD-based ToF pixel array behaves mainly as a resistive load, and so a dedicated Mixdriver buffers the modulation signals for the pixels. The illumination control interface is designed to support both

CMOS and LVDS interface. A single-slope ADC architecture was implemented to convert the data of the 2-tap ToF pixels and the data is provided off-chip using a typical DVP-type interface.

The core of the device is a 320x240 pixel array with 10um 2-tap CAPD [2] pixels. Each tap of the CAPD demodulator consist of a detector and a substrate terminal. The modulator operates in the charge domain in the epitaxial layer of the silicon by guiding the photo-generated electrons to the active detector by means of an applied potential across the substrate terminals associated to the detectors of each tap. A schematic representation of the pixel is shown in figure 3. Each tap operates as a conventional 3T pixel with the addition of an electronic shutter switch and a MOS device to increase the well depth. A dual conversion gain is obtained this way whereby the same charge can be read out with 2 conversion gains with approximately a ratio of 4. The column output lines then feed into the ADCs to extract differential and common-mode information.

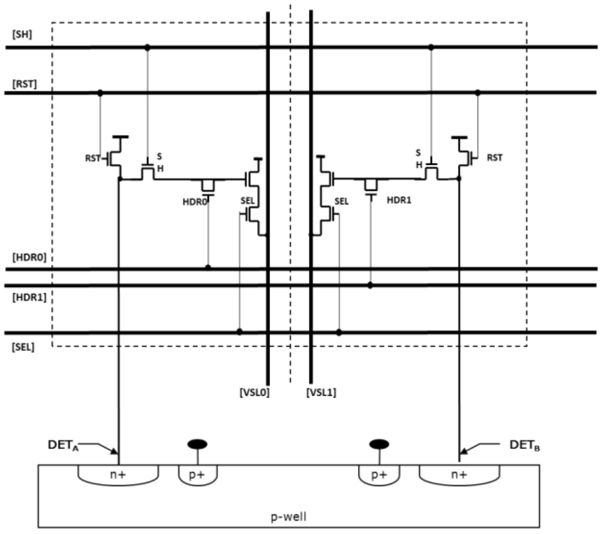

Figure 3 - Pixel schematic

And important metric defining to a large extent the performance of the eventual indirect ToF system is the modulation contrast at NIR wavelengths above 800nm. This metric describes the efficiency of the modulator at a given modulation frequency. [5] Provided the pixel receives a square wave modulation signal with frequency f_m and phase 0, if the pixel receives a square wave optical signal with the same frequency and phase, the modulator should create a differential signal of amplitude equal to the incoming signal. Differential signal is lost when the modulator has lower modulation contrast.

Figure 4 reports the modulation contrast using square wave continuous modulation for both pixel array and illuminator. The illuminator wavelength is 850nm. The modulation contrast of this device is shown as a function of modulation frequency and compared with state-of-the-art ToF imaging devices [3], [4]. This figure is measured at the sensor level, including pixel array response, driver bandwidth and even package inductance effects.

The modulation contrast is one aspect of the ToF performance of the device. The QE or responsivity and fill-factor of the device is also important as it tell us what percentage of the arriving photons are actually turned into detected electrons. The device in this work is fabricated using 18um high-ohmic epitaxial wafers in an FSI 6-metal process, while the DS325 reference devices is fabricated using 23um high-ohmic epitaxial wafers in a FSI 4-metal process. This in part explains the

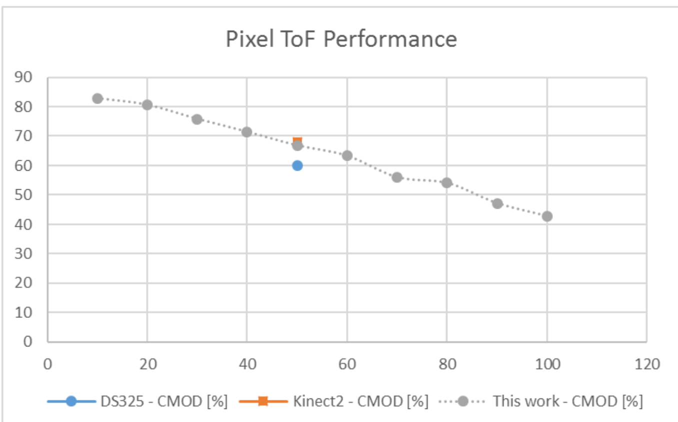

Figure 4 - Modulation contrast (%) versus modulation frequency of this work and reference works.

lower responsivity values obtained in this work. Additionally, we were able to increase the fill-factor of the pixels from 45% for a 15um pixel in 350nm process to 56% for a 10um pixel in 180nm process, thanks to the smaller MOS and metal feature size and the additional metal layers.

Figure 5 summarizes the main ToF metrics determining the device ToF performance, showing state-of-the-art ToF performance for 10um pixel pitch. The table also includes a figure of merit describing the ToF performance not taking into account pixel and system noise floor. First part of the Figure of Merit (FoM) describes how well the device can convert photons into electrons using the Fill-Factor and responsivity values reported around 850nm. The second part of the FoM revolves around the ToF performance of the device, focusing on the modulation contract (MC) at the reported modulation frequency (Fmod). In the active light shot noise limit case, the first part contributes with the square-root to the system performance, while the second ToF part contributes in a linear way, hence the FoM used in this work. For the comparison table, only performance metrics from imagers with QVGA or higher resolution are used.

	DS325	Kinect2	This work
Technology Node	0.35um	0.13um	0.18um
Resolution	320x240	512x424	320x240
Pixel Pitch	15um	10um	10um
Modulation Contrast	60% @ 50MHz	68% @ 50MHz	63% @ 60MHz
Responsivity	0.32 A/W @ 850nm	0.144A/W @ 860nm	0.22 A/W @ 850nm
Pixel Fill factor	45% (native)	60% (w/ uLenses)	56% (native)
FOM = (sqrt(Re*FF)*MC*FMOD) [MHz.A/W]	11.4	10.0	13.3

Figure 5 - Summary table of ToF metrics

The sensor was integrated in a time-of-flight system to verify the behavior and performance. A sample depth image and depth noise performance recorded using this system are shown on figures 7 and 6 respectively.

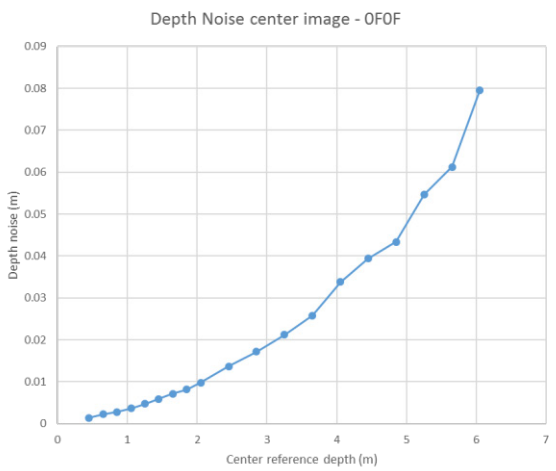

Figure 6 - Module performance, 550mW, 5 depth-fps, 7.5m non-ambiguous range

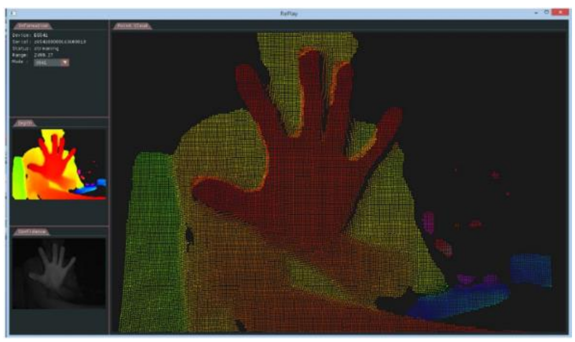

Figure 7 Color coded sample depth image streaming from the ToF module.

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[3] C. S. Bamji et al., “A 0.13μm CMOS System-on-Chip for a 512 × 424 Time-of-Flight Image Sensor With Multi-Frequency Photo-Demodulation up to 130 MHz and 2 GS/s ADCs”, IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL.50, NO.1, JANUARY 2015

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[5] D. Van Nieuwenhove et al., “A 15um CAPD Time-of-Flight pixel with 80% modulation contrast at 100MHz”, IISW 2015.