700 frames/s 2 MPixel global shutter image sensor with 2 Me- full well charge and 12 µm pixel pitch

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ABSTRACT

We report on a global shutter image sensor with high full well, designed for Full-Field Optical Coherence Tomography (FF-OCT). This application benefits from a large full well charge of 2 Me- in order to reach sufficient dynamic range in the final OCT image. Further specific requirements are a high frame rate (730 fps), needed to create real-time live 60 fps FF-OCT images, and a resolution of 2 MPixel on 12 µm pixel pitch.

1. INTRODUCTION AND IMAGE SENSOR REQUIREMENTS

Full field Optical Coherence Tomography is an imaging technique where images from a reference beam and a sample are combined in an interferometry setup, using an incoherent light source. Thanks to the low coherence length of the light source, interference will only occur when the optical path lengths are identical for both light beams. The resulting image projected on the sensor represents a 2D cross-section of a layer of about 1 µm thick of the illuminated specimen. In a microscopic setup, a 3D image cube can be reconstructed with a field-of-view of 1.3 x 1.3 mm^2 with a lateral resolution of 1.5 x 1.5 μm^2 and an axial resolution of 1 µm. This can replace traditional medical pathology procedures where biopsy tissues need to be frozen and sliced, before being imaged with traditional microscopy. The same setup can be made in a rigid endoscope, which can allow non-invasive real-time diagnostic information during surgery procedures. Both solutions are being pursued in the frame of the EU FP7 funded "Careioca" project [1].

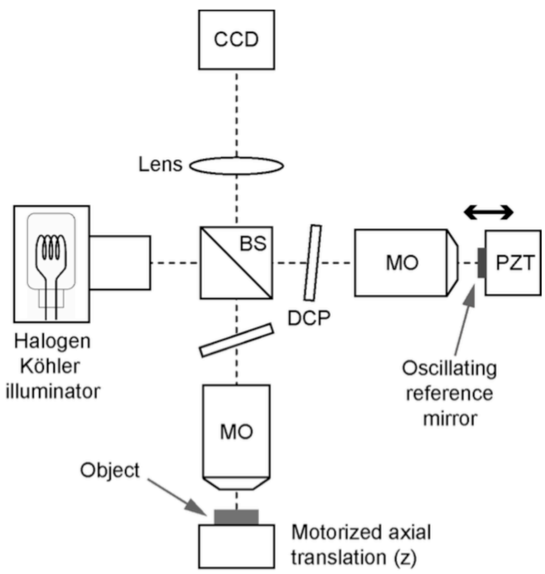

Figure 1: FF-OCT system (from [2]): BS=beam splitter; MO=Microscope objective; PZT: piezoelectric element

The requirements of such system directly translate into image sensor specifications. The OCT image is formed from the difference between two images with slightly different optical path length, realized by actuating the reference mirror with a piezoelectric element. The differential image of the two images is calculated to reconstruct the OCT cross-section image. To achieve a satisfactory signal-to-noise ratio (SNR) in the final OCT image, it is essential that SNR of the two images is sufficiently large. Since shot noise is inherently present in both images, this can only be achieved by a large full well charge (FWC). A FWC of 2 Me- is targeted for this purpose. The lateral resolution and the optical field requirements of the rigid endoscope and the microscope specify the resolution of 1400 x 1400 pixels and the pixel size of 12 µm. The requirement for handheld distortion-free endoscopy operation with final OCT frame rate of 60 fps results in a frame rate of > 700 fps for the image sensor. Global shutter operation is required for fast OCT image calculations. Some specifications are more relaxed than usual. Dark fixed pattern noise is not critical due to the operation on differential images. Dark read noise is not as critical, since low-light pixels would not reveal OCT information in any case, because of their low SNR due to shot noise. In fact, the lowest part of the response curve will typically be clipped. Dark current is not critical because of the large frame rate. The system operates with red and infrared incoherent light sources. All these requirements have been taken into account in the development of a CIS for this application.

2. IMAGE SENSOR ARCHITECTURE

Figure 2 shows a block diagram of the image sensor. The sensor is designed in a 0.18 µm 5V/1.8V 4 layers metal CIS process. To achieve the required frame rate of >700 fps, several measures are taken:

1) The sensor is read out at both sides of the pixel array
2) 2 rows are read out concurrently at each side of the pixel array
3) Column amplifiers and column ADC are designed on half of the pixel pitch.

In this way, 4 rows are read out in one AD conversion cycle. With the nominal frame rate of 730 fps, this means that this quadruplet of 4 rows must be sampled and converted in 3.8 µs. Pre-amplification and AD conversion are pipelined through an intermediate sampling stage. A 10 bit single-slope counting ramp ADC with 2 counters per ADC [3] converts the signal in 2.7 µs. Actually, in the available row time, the signal can be converted to 1440 codes (10.5 bit operation). The sensor uses 36 pairs of LVDS output channels operating at 700 MBPS, and supporting clock and status output channels.

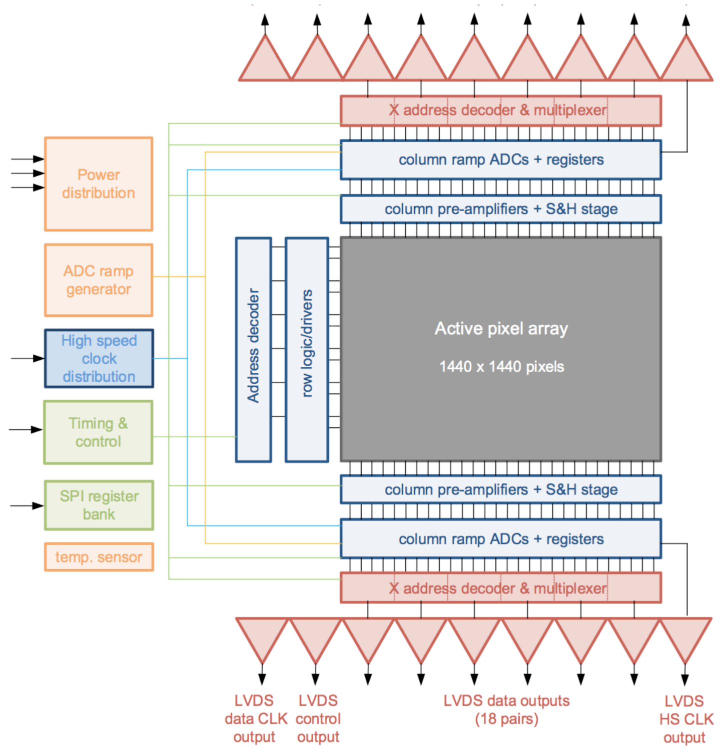

Figure 2: image sensor architecture

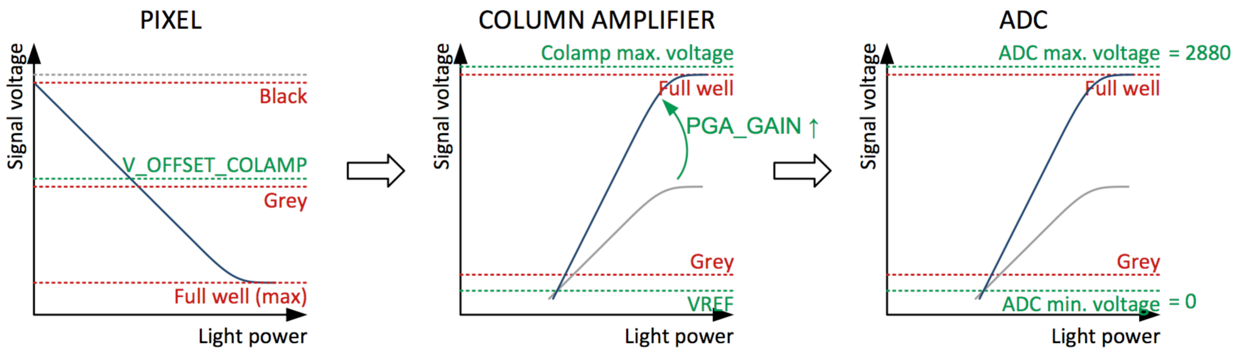

Figure 3: left: pixel output signal; center: clipping of the response curve and increasing analog gain; right: matching PGA output to ADC range

It was explained that for OCT imaging, only the signal levels with sufficient SNR are useful. In practice the range between 1 Me- and 2Me- is typically used. The sensor allows subtracting a fixed offset from the signal before AD conversion and map the remaining range on the full 10.5 bit ADC scale (1440 codes), as shown in fig. 3. This ensures that the sensor is operated in shot-noise limited regime over the entire used signal range. And it allows limiting the ADC resolution, which relaxes the clock frequency requirements for this counting ramp ADC.

3. PIXEL STRUCTURE

The pixel must combine global shutter operation with a large full well charge on a relatively limited pixel area of 12 x 12 μm^2. Fixed pattern noise and temporal noise requirements are less critical. These parameters resulted in the pixel topology shown in figure 4. A number of choices were made to reach the required performance:

1) 5V CMOS process: The use of thicker gate oxide allows increasing the signal swing on the sense node and the in-pixel capacitance. This benefits the full well charge requirement.
2) No pinned photodiode: The use of a pinned photodiode would demand for a charge handling capacity of 2 Me- on the photodiode as well as on the floating diffusion, which is hard to achieve in the available pixel pitch. The benefits of lower dark current and lower read noise are not essential for the OCT application. A

regular n/p-epi junction can be used as photodiode, with a parallel gate capacitor added to the photodiode to reach the required FWC.

3) In-pixel sampling stage, sampling the sense node voltage after a first source follower: Storage of a charge packet of 2 Me- in a charge storage stage with sufficient charge density for this pixel size is not possible. Therefore the signal is sampled on a 100 fF in-pixel storage capacitor. kTC noise of this sampling stage contributes to the pixel noise. Area and dynamic range optimization of sample stage and photodiode sense node result in equal capacitances for both capacitors.
4) No CDS: a second sampling stage would allow CDS but would take considerable area of the pixel

This results in a pixel with a 6 x 6 µm photodiode of 19 fF, centrally located in the 12x12 µm pixel, and to which a parallel NMOS gate capacitor of 87 fF is added. This brings the sense node to 106 fF in total. The sample stage is 100 fF. With 3 V swing on the photodiode, this results in the required FWC of 2 Me- and a pixel noise contribution of 303 e- RMS.

At the output of the pixel, a swing of 2.24 V is reached.

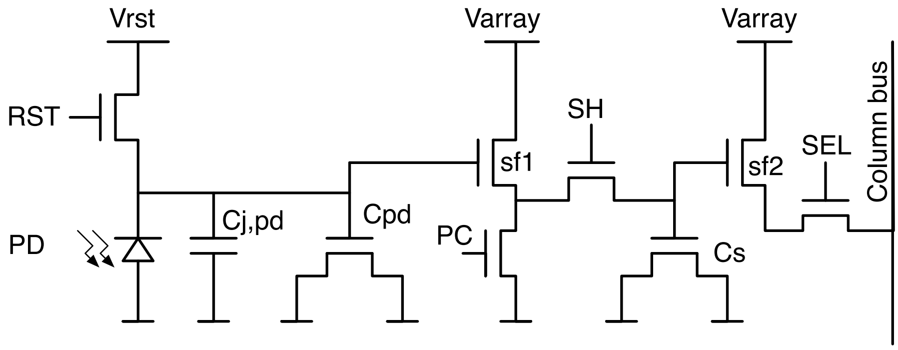

Figure 4: pixel schematic

4. Measurement Results

Table 1 lists the measured performance parameters. Read noise at unity gain, which maps the 10.5 bit scale on the 2 Me- range, results in a read noise of 969 e- RMS and is limited by quantization noise. At 2.35x gain, a read noise of 450 e- RMS is reached. It is demonstrated that with PGA dark offset subtraction, hereby mapping the 10 bit ADC scale to the range between 1Me- and 2Me-, allows to operate in shot-noise limited conditions over the entire range used in the OCT application, as intended.

Table 1: measured pixel performance parameters

Parameter	Value	Comment
Full well charge	2 Me-	(to full saturation)
Linearity	< 2% up to 90% of FWC	Deviation from linear fit
Dynamic range	66 dB	Intra-scene, unity gain
Dark read noise	969 e- RMS at unity gain	Quantization noise limited at unity gain
	450 e- RMS at 2.35x gain	
Dark current	3799 e-/s at 20ºC	
QE at 750 nm	34%	Wavelength used in OCT system
PRNU	0.32% RMS (local)	
	0.68% RMS (full image)	
FPN	9150 e- RMS (local)	High but not critical for the OCT application (differential imaging)
	12418 e- RMS (full image)	
Resolution	1400 x 1400 pixels	
Frame rate	730 fps	
Output	36 LVDS channels at 700 mbps	
Power supply	5V / 1.8V	
Power	2.1 W	At 730 fps
Package	Ceramic 173 PGA	

5. OCT DEMONSTRATION AND CONCLUSIONS

A high frame rate high full well CIS optimized for FF-OCT has been developed. This sensor has been demonstrated in its final application. Figure 5 compares an OCT image acquired through this sensor with an image acquired with a conventional sensor with 90 Ke- FWC. Significantly more contrast and detail is revealed with the new image sensor. In the frame of the EU FP7 Careioca project, pathologists compare images of the OCT system against conventional histological images. During this process, the pathologists try to identify morphological features included in the image and search for evidence to reject or support the diagnostic. The pathologists' training has resulted in the identification of different diagnosis criteria whose final relevance will be evaluated during the data analysis of the complete correlation study.

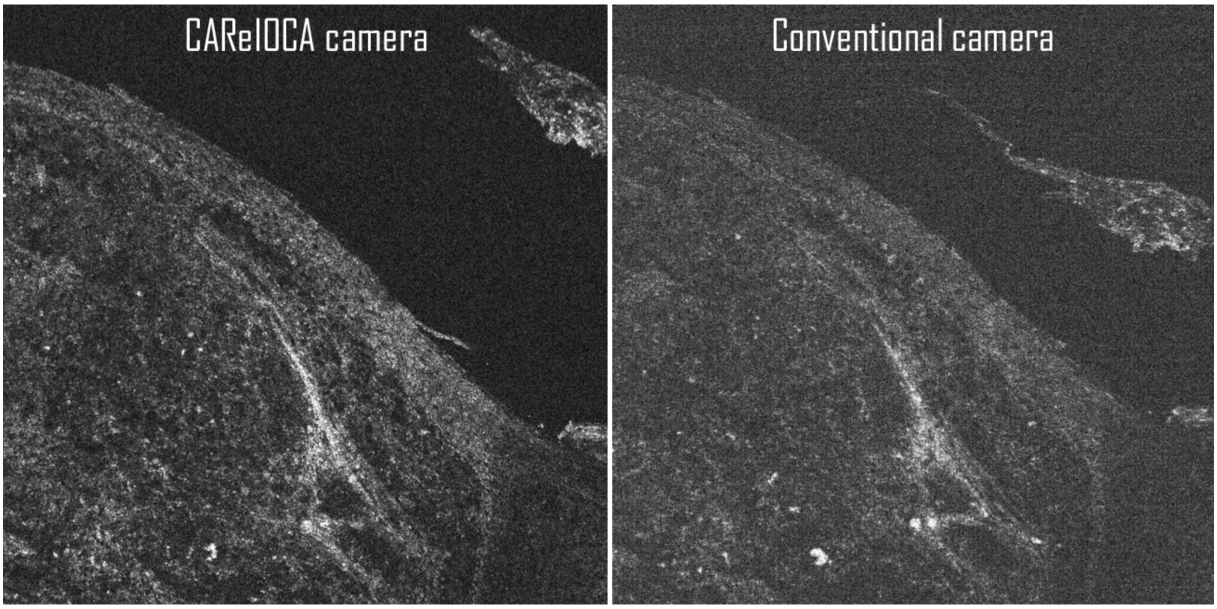

Figure 5: OCT picture acquired with the high full well sensor (left) compared to an OCT picture acquired with a conventional image sensor with a FWC of 90 Ke- (right) (from LL Tech)

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