A High QE, Fast Shuttered CMOS Image Sensor with a Vertical Overflow Drain Shutter Mechanism

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***Abstract*— This paper presents a prototype CMOS image sensor with a fast global shutter based on the Vertical Overflow Drain (VOD) shutter mechanism. The imager presents several novel features: First, the adaptation of the VOD shutter mechanism previously used exclusively in CCDs into a 0.18-µm CMOS image sensor process. Second, the application of the VOD shutter for purposes of fast gating with several nanosecond pulse widths. Measurement results of the novel imager show fast shutter efficiency of 1:100 which is equivalent to an unprecedented measured modulation contrast (MC) of 98%. The measured rise and fall times of 2ns and minimal measured shutter width of 5ns are in line with the state of the art for indirect Time-of-Flight (TOF) image sensors. These fast gating times, equivalent to modulation frequency higher than 100MHz, can be reached without reduction in the modulation contrast due to the novel shutter mechanism. The prototype pixel was designed and fabricated with special emphasis on high IR QE, featuring a deep photodiode with simulated internal QE of up to 19% for 850nm illumination. In this work the device structure and special mode of operation, that enables fast shutter operation, are studied through TCAD simulations and experimental results. Important design features that influence the pixel performance are illustrated in detail.**

I. Introduction

In indirect pulsed TOF imaging an illumination pulse train is sent by the camera in synchronization with fast modulation of the pixel response. By truncating a light pulse returning from the scene, a correlation is produced between the number of integrated photons and the distance to the target, as described in Figure 1. The quality of depth inference is therefore derived from the quality of the fast electronic shutter that modulates the pixel response [1]. Naturally, a global shutter mechanism is required in order to simultaneously modulate the entire pixel array in sync with an external illumination source. This shutter mechanism must have fast (ns-scale) rise and fall times in order to create strong correlation between the pixel response and the target distance. Shutter uniformity is important so different pixels across the array will have the same transient response. The shutter contrast ratio, i.e. the ratio between the response of a pixel with a closed and open shutter, affects performance by defining the ability to modulate the incoming light. It affects both the depth resolution and the ambient light rejection ratio.

The need for nanosecond-scale modulation time often dictates a nonstandard pixel design that is not always in agreement with modern trends. While almost all standard modern image sensors are based on the pinned photodiode structure [2], many TOF imagers are using different specialized methods in order to achieve the required modulation characteristics [3]–[5]. Some TOF imagers do use the PPD structure, but require either a specialized

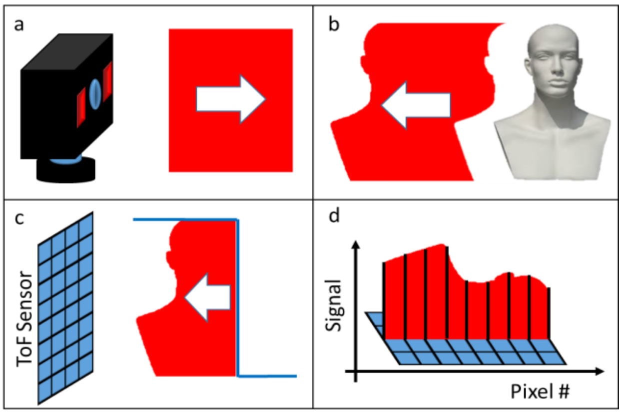

Figure 1 – The basic principles of pulsed Time of Flight imaging: (a) A pulse (or a sequence of pulses) of illumination is sent by the camera. (b) The pulse is reflected back from the scene. (c) The returning pulse is truncated by the sensor's fast shutter, therefore - (d) A correlation exists between the amount of integrated signal and the target distance.

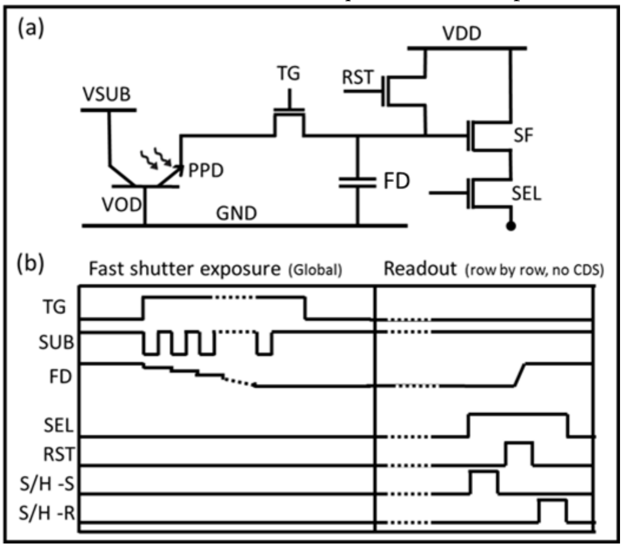

Figure 2 – (a) A schematic representation of a 4-T PPD pixel with a VOD shutter mechanism, represented by an NPN transistor in punch-through mode. (b) Essential timing diagram of the pixel in fast-shutter exposure and readout.

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transfer gate (TG) design or a special photodiode layout [6], [7]. Recently, we have shown that it is possible to exploit the Vertical Overflow Drain (VOD) mechanism, implemented in an off-the-shelf CCD image sensor, in order to produce a fast (ns-scale) and uniform global shutter [8].

In this paper we present a CMOS image sensor for Pulsed TOF and transient imaging applications utilizing the VOD shutter mechanism. While common in Interline-Transfer (IT) CCDs, this mechanism is applied here to CMOS image sensor pixels, and is operated in a unique way to allow for fast gating.

The sensor presented in the text is a 2nd generation prototype with an improved pixel and shutter design. It offers a significant improvement in IR quantum efficiency and better shutter performance compared to the first generation. A detailed report of the first pixel generation was accepted to the 2015 Special Issue of IEEE-ED on Solid-State Image Sensors, and is expected to be published on January 2016 [14].

II. Fast VOD Shutter in CMOS

The VOD structure was originally designed as a blooming suppression mechanism for IT-CCDs [9], [10]. In these devices the photodiode is formed in a lightly doped p-well on top of an n-substrate [11]. When the photodiode saturates, excess electrons cross the barrier formed by the p-type region and drain to the substrate instead of diffusing to adjacent photodiode. It was later recognized that this mechanism can also be used as an electronic global shutter in pinned photodiode pixels [12], [13]. The shutter is activated by increasing the substrate voltage so that the barrier formed by the p-well is depleted and a punch-through current drains the electrons from the photodiode to the substrate. Standard operation of a pixel with a VOD shutter starts with a substrate pulse to apply a global PD reset. The reset pulse starts the integration, which ends with a global transfer pulse.

However, global operation of the transfer gates with nanosecond scale rise/fall times and uniformity, is difficult due to its high impedance of the signal route. Instead, we purpose the following method to achieve fast gating, which is applicable to CCDs as well as to CMOS sensors with a VOD shutter: The transfer gate remains open during the entire integration period, while only the substrate bias is modulated. Electrons that are generated while the substrate voltage is high will be drained to the substrate, while electrons that are generated while the substrate voltage is low will immediately drift to the floating diffusion. This operation is enabled by the strong fields created by the VOD shutter, that quickly and effectively sweep all the photoelectrons from the photodiode even though the transfer gate is open. Rapid and uniform toggling of the substrate is easily achieved using an off-chip driver due to the fast propagation in the thick silicon bulk. In addition, the total capacitance of the VOD shutter is relatively low due to the width of the lower depletion region, allowing fast rise and fall times. A schematic circuit of a 4-T CMOS pixel with a VOD shutter that was used in this experiment is presented in Figure 2(a). The principal timing diagram used for the pixel's fast operation is presented in Figure 2(b).

The implementation of a VOD shutter mechanism in CMOS image sensor technology requires switching to an

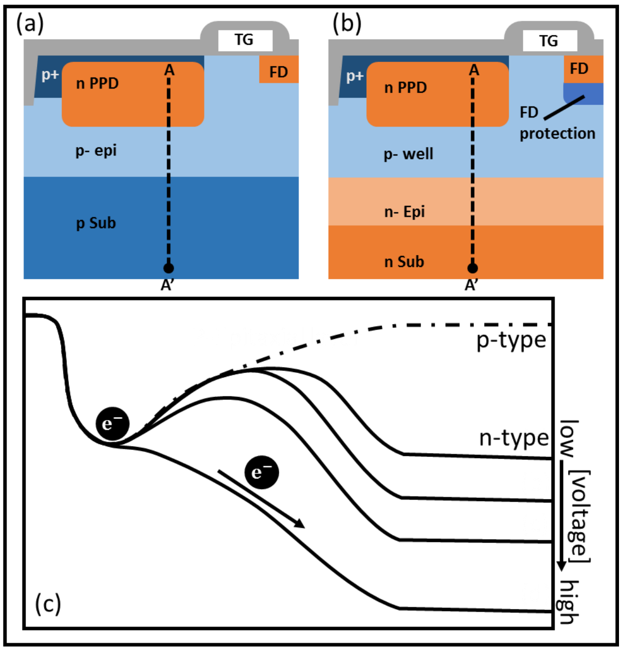

Figure 3 – (a) The essential structure of a standard CMOS PPD pixel. (b) The essential structure of a CMOS PPD pixel with a fast VOD shutter. (c) Electrostatic potential cross sections (A-A') in a standard CMOS pixel (dash-dot) and in a pixel with VOD shutter, at different substrate bias voltages (solid).

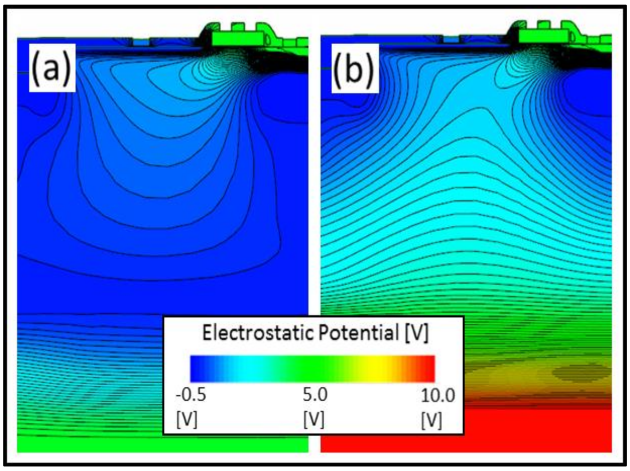

Figure 4 – Results of TCAD device simulations showing the electrostatic potential map with (a) low substrate bias – 'shutter open', (b) high substrate bias – 'shutter closed'.

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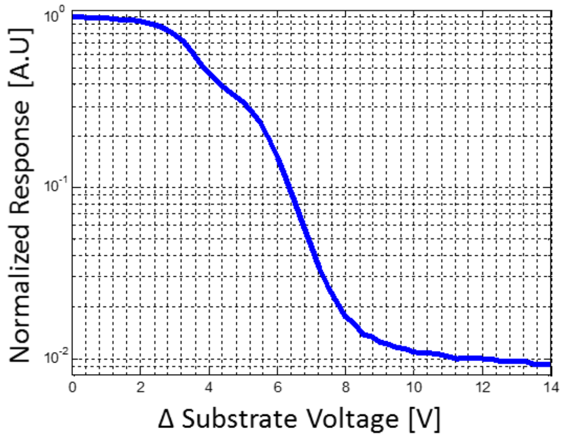

Figure 5 – Pixel response versus substrate voltage bias.

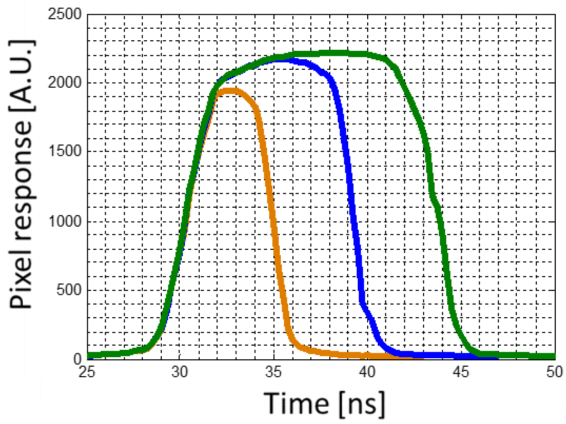

Figure 6 – Pixel response versus time for shutter widths of 5, 10, & 15ns.

n-type epi on n+ substrate starting material, similar to the one, usually used in IT-CCDs. Some special modules were introduced into the Tower-Jazz 0.18um CIS process in order to allow this change. A 4-T pixel with 5.6um pitch was used as a benchmark for development and was adapted to operate on the n-type starting material, and new design rules were created in order to support the design of the periphery circuits. Special p-wells were added in order to form the VOD barrier as well as to protect the FD and standard CMOS transistors from the substrate bias. The major process changes, administered to the pixel array area in order to add a VOD shutter mechanism to a standard CMOS PPD, are detailed in Figure 3 (a, b). A conceptual drawing of the electrostatic potential at the center of the photodiode in a standard device compared to one with a VOD shutter at different bias voltages is presented in Figure 3 (c).

III. PIXEL DESIGN AND SIMULATION RESULTS

The pixel development, described in this work, was aimed for high IR QE and improved shutter behavior over the first generation design. The high IR QE is apparent in the electrostatic potential maps that were extracted from the pixel TCAD simulations and are presented in Figure 4. In a photodiode with a VOD barrier the QE for long wavelengths is defined by the depth of the VOD barrier, since every electron that is generated deeper than the barrier will be drained to the substrate. The VOD barrier crest in the simulation is located in a depth of about 4μm, yielding a theoretical internal QE of up to 19% at 850nm. It is enabled by a deep Boron implant that forms the VOD barrier.

IV. EXPERIMENTAL RESULTS

A special characterization system was developed in order to study the fast shutter characteristics of the prototype imager [8]. This system can sync to the camera shutter driver and produce an illumination pulse train with 100ps pulse width and arbitrary delay with 250ps step resolution. The exact pulse time stamp is sampled by a fast photodiode and stored in pair with the image sensor

Table 1 – Summary of pixel parameters

Parameter	Value
Pixel size	5.4μm x 5.4μm
Pixel Type	4-T with VOD global shutter
Pixel Conversion Gain	40μV/e^-
Full Well Capacity	15000 e^-
Readout noise	17 e^- [no CDS]
Shutter Contrast Ratio	1:100 (@ 850nm)
Equivalent Modulation Contrast	98% (@ 850nm)
Shutter rise/fall time	2ns (10%-90%)
Minimal tested shutter width	5ns
Equivalent Modulation frequency	>100 MHz
Simulated internal IR QE	19% (@ 850nm)

reading. Using this system it is possible to scan and reproduce the accurate per-pixel shutter shape and to extract important parameters such as the pixel modulated optical response.

The first experiment that was performed in order to study the prototype CMOS chip was a sweep of the substrate voltage effect on the pixel response. This experiment studies the basic performance of the VOD shutter mechanism and its results are presented in Figure 5. It can be observed that the pixel response drops to ~1% of its value due to ~10V change of the substrate bias. This results represent a contrast ratio of 1:100, or a modulation contrast (MC) of 98%, which is an unprecedented result in CMOS TOF sensors.

An additional experiment was scan of the temporal response of the pixel, which yields the shutter shape. The results of shutter shape characterization for pulse widths (FWHM) of 5, 10, and 15 ns are presented in Figure 6. The shutter shape reveals shutter rise/fall times (10%-90%) of about 2ns. While such a short modulation period can be achieved by the most advanced TOF sensors in the market, none of them simultaneously show such a high modulation contrast and high quantum efficiency for 850nm illumination. An additional improvement in rise/fall times

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is expected with improvement in chip packaging that will allow lower impedance of the substrate signal.
Additional measurements of the pixel readout noise, full well capacity, and conversion gain were performed. These measurements and their results are common and therefore will not be discussed here in detail. The results are detailed in Table 1, alongside a summary of all pixel properties that were discussed in the body of the text.

V. Conclusions

In this work we have presented a prototype CMOS image sensor chip with a fast global shutter based on the VOD mechanism. Two major accomplishments of the chip are the successful import of the VOD shutter structure into a standard CMOS image sensor process, and its operation in high shutter speeds, appropriate for pulsed TOF and other time-resolved imaging applications. This second generation prototype also presents higher IR QE and improved shutter performance in comparison to the first prototype, achieved by improvements in the pixel design, as well as by a significantly larger photodiode depth.

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