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A Small Pixel High Performance Full Frame HDR Sensor

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Abstract

This paper presents a test chip sensor that achieves full frame HDR video with Stop Motion at 30 fps by employing Differential Binary Pixel (DBP) technology. DBP is a threshold-based timing, readout and image reconstruction method that utilizes sub-frame partial charge transfer technique in a standard four-transistor (4T) 1.1um pixel, TSMC 65nm process, CMOS Image Sensor (CIS) technology. A side by side comparison with a non-threshold based oversampling HDR mode is presented. Results show 7.3dB low light signal-to-noise ratio (SNR) improvement without sacrificing dynamic range (DR) performance. Further technology verification was performed against the iPhone 6s rear view camera to show superior HDR video capability.

I. Introduction

Capturing the dynamic range that matches the eye with high resolution images and videos is crucial for consumer applications such as mobile and action cameras. This is challenging for scaled pixels of sub 2um pixel size. Multi-frame HDR technology has been used for image capture, but it is challenging to use for video due to motion artifacts. This paper presents an HDR technology with stop motion for small pixel high resolution image sensors. Section II provides the technology operation details. Section III provides implementation description of the technology. Section IV provides the results and discussion.

II. Technology Operations

DBP uses 4× oversampling in one frame, where the first sample interval (sub-frame) is long and is followed by three consecutive short sub-frames as shown in Figure 1. The four sub-frames are categorized into two types: Full Charge Transfer (F) and Partial Charge Transfer (P). A Full Transfer, or F, is defined as when the pixel transfer gate is fully turned on to completely transfer all of the photodiode (PD) charge to the floating diffusion (FD) as illustrated in Figure 2a. A Partial Transfer, or P, is defined as when the pixel transfer gate is partially turned on. With the gate partially turned on, only a portion of the full PD charge collected is transferred to the FD, whereas some of the charge will be held back in the PD as illustrated in Figure 2b. Of the four sample intervals, the first and last sample intervals are Full Charge Transfer samples, whereas the second and third are Partial Charge Transfer samples as illustrated in Figure 1. The total frame time is 33ms, allowing the HDR operation to take place at 30 frames per second.

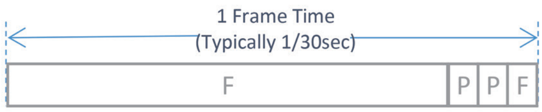

Figure 1. *DBP Frame Operation with four sub-frames for 4x oversampling*

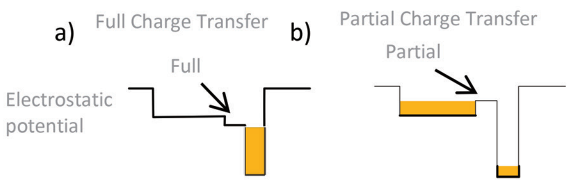

Figure 2a. *Full Charge Transfer (F)*
Figure 2b. *Partial Charge transfer (P)*

Using this technique, an image sensor can fully capture both the high light and the low light portion of a high DR scene while enabling stop motion capability

First, in the bright region where the bright pixels would saturate, the partial read will 'spill' out a portion of the PD charge to retrieve unsaturated useful information as illustrated in Figure 3.

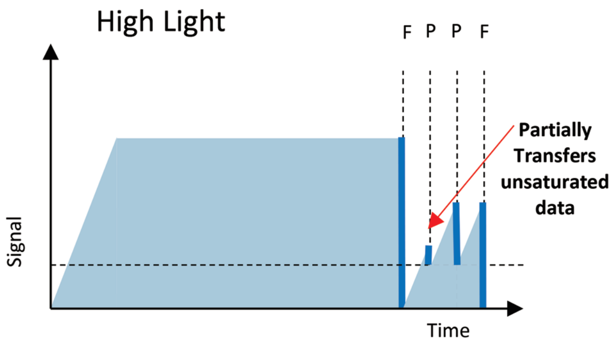

Figure 3. DBP sub-frame response in High Light

Secondly, in a dark region of the scene, generally the long exposure region would be chosen to get the best Signal-to-Noise Ratio (SNR). This is problematic for motion videos since the long exposure time creates a motion blur artifact. Hence the short exposure time interval needs to be used but better SNR is required. The DBP method provides a 3x increase of the short exposure time for low light capture as shown in Figure 4. During low light operation, no charge is spilled during a partial transfer time because the amount of charge accumulation in the PD is less than the barrier of the partially turned on transfer gate. Accumulation over 3 short sub-frames allows 3x the short sub-frame exposure time, and a SNR improvement by $\sqrt{3}$ compared to adding up three separate short sub-frames together [1]. With an improved SNR short sub-frame, stop motion can be enabled by capturing moving objects without blur.

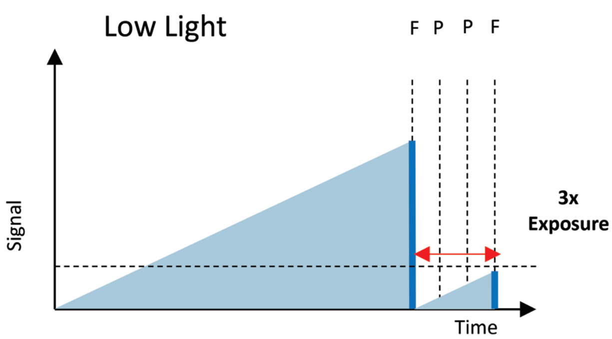

Figure 4. DBP sub-frame response in Low Light

III. Sensor Implementation

The differential binary pixel methodology was implemented using Taiwan Semiconductor Manufacturing Company's (TSMC's) 65nm CIS process technology. The pixel architecture is a 4T with 4-way shared 1x4 Transistor as shown in Figure 5a. The PD and TG layout is based on a first generation TSMC 1.1μm pixel but was modified from a 2x2 shared to a 1x4 shared for high speed readout [2]. Figure 5b shows a micrograph of the test chip. The pixel array is a 1 megapixel array, 966 x 1084.

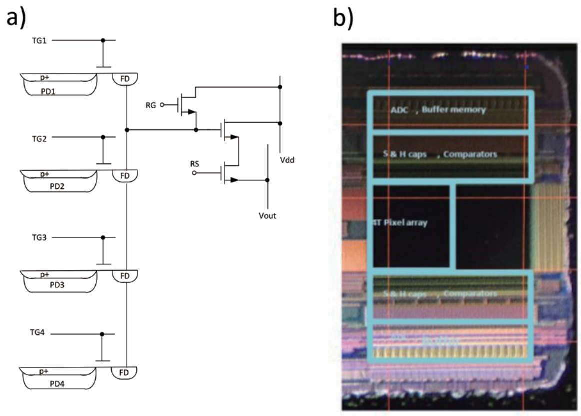

Figure 5a. Schematic of 4T 1x4 Pixel Architecture
Figure 5b. Micrograph of the Test Chip Array

Per-column sample and hold capacitors are used to store the reset and transfer signal levels for a Correlated Double Sampling (CDS) readout. A switched capacitor programmable gain amplifier (PGA) and 12 bit SAR ADC are shared by 48 columns. The PGA and ADC layout is split into two banks, one at the top and one at the bottom of the array. Adjacent groups of four columns are routed to the top and bottom ADC banks. This architecture was chosen for fast readout [2]. Figure 6 schematic illustrates the analog signal chain.

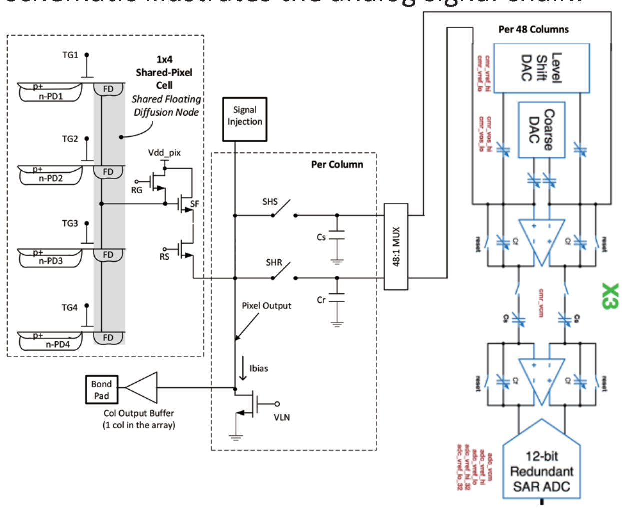

Figure 6. Analog Signal Chain Schematic

IV. Results

The linear full-well is 4200 photo-electrons as shown in Figure 7a. The read-noise of 20e- at 1× gain and 8e- at 8× gain as shown in Figure 7b. The Photo Response Non-Uniformity (PRNU) is less than 1% at 50% of the signal. The SNR max is 36 dB. The responsivity is 3180 e/lux.s. These are all summarized in Table 1. The partial transfer voltage is optimized to 75% of the 'ON' voltage to ensure that the partial transfer voltage is robust against TG Vt shifts due to process variation.

Pixel Parameter	units	
Linear Full Well	e-	4200
Read Noise (1x gain)	e-	20
Read Noise (8x gain)	e-	8
SNR Max	dB	36
Dynamic Range (at 1x RN)	dB	46
Dynamic Range (at 8x RN)	dB	54
Responsivity (530 nm)	e-/lux.s	3180

Table 1: *General Pixel Characterization Summary*

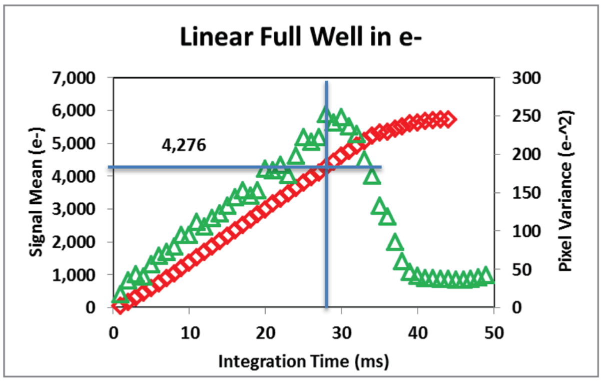

Figure 7a*. Response and Variance vs. Exposure Curve showing Linear Full Well*

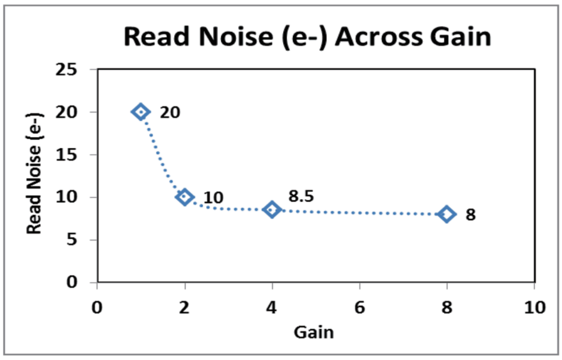

Figure 7b*. Read Noise versus Gains 1x, 2x, 4x, 8x*

F transfer for all sub-frames was compared to the DBP method. For F transfer mode, 4× oversampling was used with a 13-1-1-1 sub-frame interval policy where the policy describes the relative duration of each sub-frame. The HDR ratio would be 16:1 using full transfer for all sub-frames. For DBP, 4× oversampling was used with 54-4-3-3 interval policy where the HDR ratio will also be 16:1 ratio when taking into consideration partial saturation level to be at 75% of the full signal range of the pixel.

Figure 8 SNR vs exposure curve shows the 7dB improvement provided by DBP over 4× oversampling using a full transfer in each sub-frame. The DR of DBP is 1dB less than full transfer 4× oversampling HDR mode, which is visually negligible in images and videos.

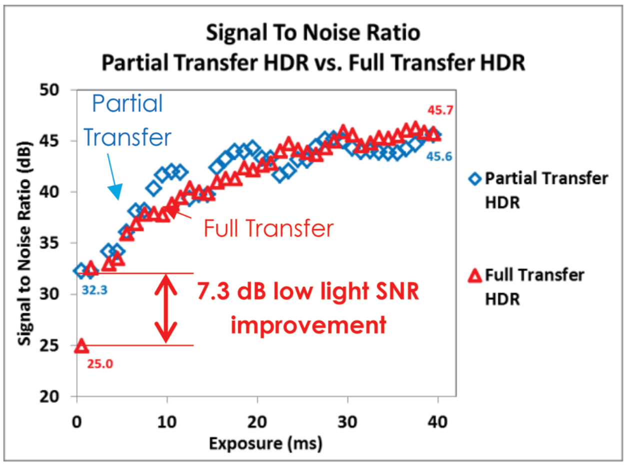

Figure 8. *SNR vs. Exposure Curve Highlighting Low Light SNR Improvement using P Technique over F Technique*

Although the effective DR of this test chip is 68dB with read-noise of 20e-, given a state of the art pixel and signal chain, a DR of 87-88 dB can be reached with a read-noise of 2e as shown in Table 2. The DR measurement of 68dB is further verified via image capture of Greyworld ITHDR-36 chart [3].

HDR Conditions	Full Transfer	Partial Transfer
Policy Condition	FFFF	FPPF
Interval Durations	13-1-1-1	54-4-3-3
Max signal	53400 e-	49700 e-
SNR Max	45.7 dB	45.6 dB

Low Light SNR	25 dB	32 dB
Dynamic Range	69 dB	68 dB
DR (RN of 2e-)	88 dB	87 dB

Table 2: *Comparison of P and F Transfer Techniques*

Video captures were compared to iPhone 6s. Figure 9 illustrates how, in a high DR scene, the iPhone 6s is not able to capture the entire scene DR as shown in the two left frames from the video, while the DBP was able to capture all of the details from both the dark foreground and the bright background. The iPhone 6s, as well as iPhone 7 do not have HDR video capability. DBP readout and image reconstruction methods provide HDR video without motion artifacts.

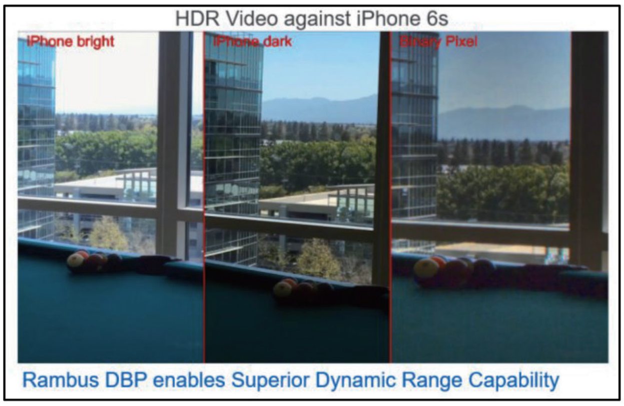

Figure 9a. *iPhone 6s with auto-exposure adjusted to the pool table in the foreground*
Figure 9b. *6s Auto exposure adjusted on the background blue sky*
Figure 9c. *DBP in HDR video mode adjusted to capture both foreground and background*

Figure 10 shows a side by side comparison of long sub-frame and short sub-frame usage in dark foreground for the HDR reconstructed video to study motion artifacts. Figure 10a shows that if the darker foreground uses the long sub-frame, a moving object such as the rolling ball would create an artifact due to the motion blur. To mitigate the motion blur artifact, the shorter sub-frame is used, as shown in Figure 10b, to remove the motion blur artifact enabling stop motion. The short sub-frame SNR here is increased by $\sqrt{3}$ using DBP partial transfer technique to create a visibly better image quality of the moving ball in dark foreground.

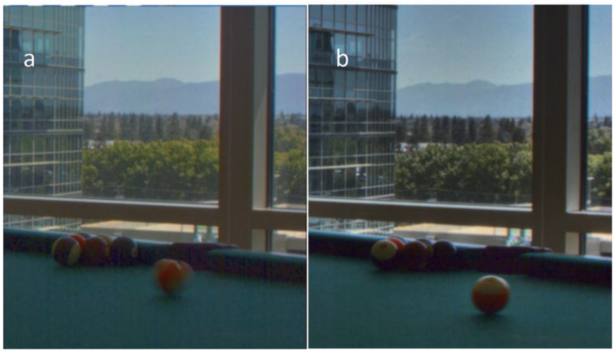

Figure 10a. *HDR image reconstruction using long sub-frame for the dark foreground causing motion artifact*
Figure 10b. *HDR image reconstruction using short sub-frame for the dark foreground to remove motion artifact and enable stop motion*

In Summary, this paper outlined an implementation of a 4x oversampling, threshold based HDR method in 1.1um TSMC 65nm pixel technology to enable HDR video with stop motion at 30 frames per second using conventional 4 Transistor pixel architecture that is capable of achieving 87dB Dynamic Range to match the human eye in consumer applications.

V. Acknowledgement

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VI. References

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