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Optimization of CMOS Image Sensor Utilizing Variable Temporal Multi-Sampling Partial Transfer Technique to Achieve Full-frame High Dynamic Range with Superior Low Light and Stop Motion Capability

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Abstract
Differential Binary Pixel Technology is a threshold-based timing, readout and image reconstruction method that utilizes sub-frame partial charge transfer technique in a standard four-transistor (4T) pixel CMOS Image sensor (CIS) to achieve HDR video with Stop Motion. This technology improves low light signal-to-noise ratio (SNR) by up to 21dB. The method is verified in silicon using a TSMC 65nm 1.1µm pixel technology 1 megapixel (MP) test chip array and is compared with a traditional 4× oversampling technique using full charge transfer. The test chip is also compared with the iPhone 6s rear view camera to show superior HDR video capability.

1. Introduction

The past 15 years displayed a remarkable transformation in the Imaging industry driven by the rapid growth of the mobile phone market and scaling advancements in CMOS technology. Scaling advancement allowed pixels to scale down to 1.0µm available in production today [1].

The reduction in physical size of the pixel reduces the number of photons that can be accumulated in that pixel, thus limiting the full well (FW) and hence the dynamic range (DR) of the sensor. Other drawbacks include low light sensitivity. To reverse these limitations, many companies are reverting back to larger pixel sizes for higher dynamic range and improved low light sensitivity [2] [3].

For the mobile and consumer markets, the goal is to match the Dynamic Range of the human eye, which is around 85dB given a wide dynamic range scene. A typical small pixel image sensor yields DR of only 65dB, causing a gap in DR when compared with the human eye. This gap can be eliminated by applying a High Dynamic Range (HDR) method without increasing pixel size. HDR methods allow an image sensor to capture details in both the high light and low light region of a high dynamic range scene. This is illustrated in Figure 1a and 1b.

Figure 1a below is and image capture using conventional CMOS imaging techniques, affecting the level of detail in the sky as well as the shadows.

Figure 1b is an image capture using an HDR technique. This technique allows capture of the full dynamic range of the scene, including details in the sky and the shadows.

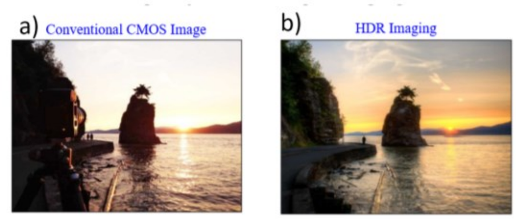


Figure 1a. *Conventional CMOS Image Sensor Capture*
Figure 1b. *Image Capture Using High Dynamic Range*

Previous work on HDR method mostly focuses on automotive and surveillance applications which require 130dB of dynamic range due to safety reasons, using large pixels of 3µm to 6µm. A comparison of large pixel HDR methods can be found in Section 8, Reference [4]. This work describes an HDR method that is geared towards mobile phone imaging market, a short technology review in this market is outlined below.

2. Mobile HDR Image Capture Methods

For mobile sensors, interline-HDR (I-HDR) and multi-capture methods are prevalent [1-3].

This section describes the following HDR image capture methods:

- Interline HDR capture method
- Multi-capture HDR method
- Partial transfer HDR method

Interline High Dynamic Range (HDR) Method

The Interline-HDR method uses a high resolution sensor, where even lines have one exposure and odd lines have a different exposure, in order to include both exposures. This method allows the sensor to capture video without sacrificing video speed and reduces the level of ghost artifacts due to the overlapping exposure of odd and even lines. However, the resolution of the image is sacrificed and a large dip in the SNR vs light level curve occurs if the difference in the 2 exposure times is large. Also, possible artifact can occur due to the risk of increased electron overflow from long exposure rows to short exposure rows.

Multi-Capture High Dynamic Range Method

The multi-capture HDR method combines two sequential captures at different exposures. This allows for a full resolution HDR image. However, since the exposures are taken at two different time instances with very different exposure times, there would be a large dip in the SNR curve when switching from high exposure to low exposure frames. This may require customized tuning to remove artifacts when the captures are combined [4].

Partial Transfer High Dynamic Range Method

Another HDR method is a partial transfer technique where a knee point is set when the charge is partially transferred by setting the transfer gate voltage at a mid-level. However, this method is prone to threshold voltage changes, causing a change in transfer voltage and dark current [4].

3. Differential Binary Pixel Overview

The method presented here is named Differential Binary Pixel (DBP). It is an extension of Binary Pixel, which is presented in [5-8]. The prior work in implementation demanded a change in the pixel architecture, which in turn required a redesign of the pixel. This is not desirable from a design and fabrication process perspective.

DBP uses a standard four-transistor (4T) pixel, CMOS Image sensor (CIS) in a standard existing fabrication process without having to change the pixel array itself, making it a much more desirable technology for adoption in the already competitive mobile market.

The remainder of this document is organized as follows:

- Section 4 describes detailed implementation of the DBP methodology.
- Section 5 shows the Rambus sensor implementation details from pixel architecture to sensor readout scheme.
- Section 6 shows the characterization results and correlates these results with real-world image and video while comparing with state of the art mobile technology.
- Section 7 summarizes the results.
- Section 8 provides a list of references referred to throughout the document.

4. Differential Binary Pixel Operations

DBP uses 4× oversampling in one frame, where the first sample interval is long and the three consecutive ones are short. The four sub-frames are categorized into two types:

- *Full Charge Transfer (F)*
- *Partial Charge Transfer (P)*

Figure 2 shows a DBP frame operation with long and short sub-frames and transfer techniques in each sub-frame operating at 30 frames per second with a frame time of 33 miliseconds. 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 2. These transfer techniques are described below.

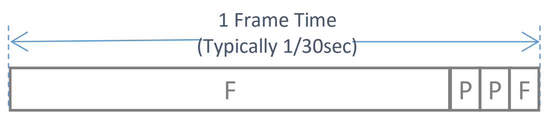


***Figure 2.** Differential Binary Pixel (DBP) Frame Operation with four sub-frames for 4x oversampling*

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). Figure 3a below shows a full charge transfer when all charges are transferred from the photodiode (PD) to floating diffusion (FD).

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. Figure 3b shows a partial charger (P) transfer when only part of the PD charge is transferred to the FD.

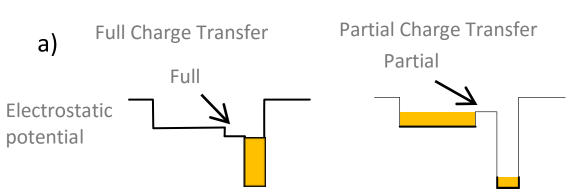


***Figure 3a.** Full Charge Transfer (F)*
***Figure 3b.** Partial Charge transfer (P)*

These methods are used to fully capture both the high light and the low light portion of a high DR image as such:

In the bright region of the high dynamic range scene, where the pixels would saturate, the differential read will 'spill' out a portion of the PD charge to identify bright areas of the image based on such corresponding pixels using P shown in Figure 3b. The pixel would have an F read at the end, but in case that is saturated the "spill" data will provide unsaturated usable signal. This process is illustrated in Figure 4.

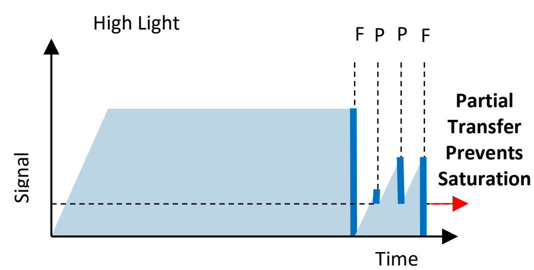


***Figure 4.** DBP sub-frame response in High Light*

In a dark region of the high dynamic range, no charge is spilled during a Differential Read sampling time because the amount of charge accumulation in the PD is less than the barrier of the partially turned on transfer gate. Since there are three short sub-frames, the accumulation of charge can lead to up to 3x the short sub-frame exposure time, the Signal to Noise Ratio (SNR) would improve by $\sqrt{3}$ compared to adding up three separate short sub-frames together [10]. This is modeled and illustrated in Figure 5.

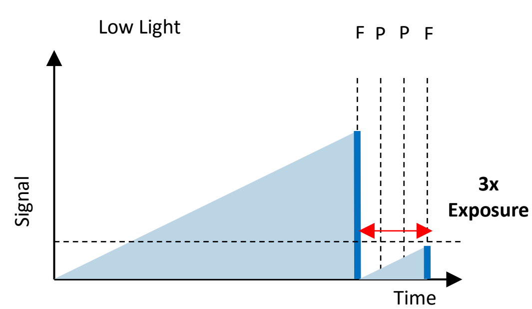


***Figure 5.** DBP sub-frame response in Low Light*

The partial transfer voltage determines the dynamic range of the image as well as the signal-to-noise ratio of the short dark frame. For high DR performance, a higher P ‘ON’ voltage is required. On the other hand, for higher low-light SNR, a lower P ‘ON’ voltage is required. A signal output vs. transfer voltage is outlined in the Results section. Such optimization is further discussed in the Results section 6.3 for achieving the best of both high dynamic range and superior low light performance in a stable usable manner.

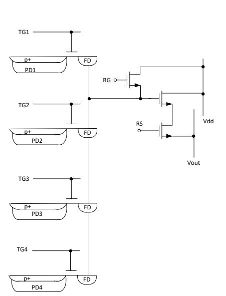
5. Rambus Sensor Implementation

The differential binary pixel methodology was implemented in Taiwan Semiconductor Manufacturing Company’s (TSMC’s) 65nm 1.1µm pixel photodiode process technology. Pixel size was increased to 1.4µm to accommodate extra transistors for earlier Binary Pixel work [9]. DBP uses a reference pixel where extra transistors were disconnected and shorted to the supply voltage rail, VDD.

The pixel architecture is a 1.4µm 4T with 4-way shared 1x4 Transistor. The PD and TG are best on a first generation TSMC 1.1µm pixel but was modified from a 2x2 shared to a 1x4 shared for high speed readout.

Figure 6a shows a schematic of the 4T shared 1x4 architecture. Figure 6b shows a micrograph of the test chip.

a)



b)

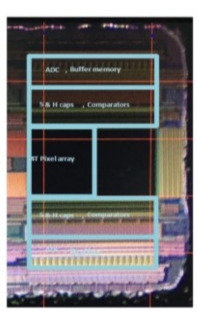


Figure 6a. *Schematic of 4T 1x4 Pixel Architecture*
Figure 6b. *Micrograph of the Test Chip Array*

The pixel array is a 1 megapixel array, 966 x 1084.

The test chip included programmable timing, enabling optimization for best high dynamic range image quality.

The pixel source follower has a width of 0.28µm and a length of 0.7µm. The reset select transistor has a width of 0.28µm and a length of 0.29µm.

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.

The PGA has a selectable gain of 1×, 2×, 4× or 8×. One column output line is connected to an analog output buffer to view the pixel output waveform. An injection point was included at the input of the PGA to determine the electrons per Data Number (DN) of the readout path.

The Source Follower (SF) Ibias current is programmable by an external master current and on-chip current mirror.

The sensor readout timing and control is implemented on a Field Programmable Gate Array (FPGA) external to the sensor.

The pixel output lines have a total resistance of 1261Ω and capacitance of 906 femtoFarads (fF).

The sample and hold capacitors are ~400 fF. The total capacitance (Cpixout) of the column readout is ~1.3 pF (400 fF + 906 fF).

The pixel output bandwidth is limited by the transconductance (gm) of the pixel source follower which is 12 to 55µS depending on the SF bias current used in this experiment. The dominant time constant due to gm (τD = Cpixout/gm), is ~22ns at the baseline SF Ibias condition of 8µA. The conversion gain of the 1 × 4 pixel is 75.6 µV/e−.

Figure 7 schematic illustrates the analog signal chain.

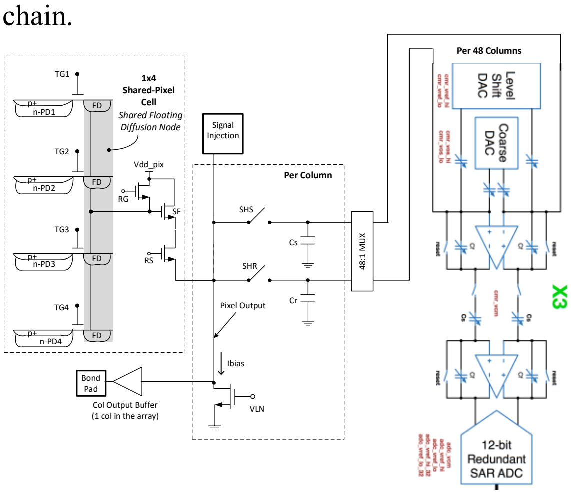


Figure 7. *Test Chip Analog Signal Chain Schematic*

The voltages used for pixel operation are summarized in Table 1.

Pixel Operating Voltages	
TRANSFER_GATE_ON	**3.3 V**
TRANSFER_GATE_OFF	**-1.5 V**
TRANSFER_GATE_PAR-TIAL	**0.56 V**
RESET_GATE_ON	**2.0 V**
RESET_GATE_OFF	**0 V**
RESET_GATE_DRAIN	**1.8 V**
TRANS-FER_GATE_PULSE	**-1.15 V**

Table 1: *Pixel Operating Voltages*

In the 1.1µm PD pixel technology using a 65nm TSMC node, a negative voltage were used to fully turn off the transfer gate. However, TG was pulsed during readout to prevent blooming, which shows up as artifact in the saturated region of an image in HDR mode.

The negative voltages were supplied using an on-chip voltage booster. There were two boosters, one to provide F (full transfer) negative voltage and one to provide P (partial transfer) negative voltage.

6. Results

The results are organized into the following sections:

- Section 6.1 outlines the general pixel characterization data.
- Section 6.2 outlines sensor characterization data comparison between full-transfer 4× over-sampling HDR method using the F versus P
- Section 6.3 provides details of data driven P voltage optimization.
- Section 6.4 compares the two methods after optimizing P voltage.
- Section 6.5 compares the two methods after final image reconstruction
- Section 6.6 compares the DBP test chip with the iPhone 6s rear view (main) camera.

6.1 General Pixel Characterization

The linear full-well is 4200 photo-electrons with read-noise of 20e- at 1× gain and 8e- at 8× gain. The Photo Response Non-Uniformity (PRNU) is less than 1% at 50% of the signal. The SNR max is 36 dB. These are all summarized in Table 2.

In most sensor data sheets on the market, the Dynamic Range (DR) is defined as the linear full-well (LFW) at minimum gain divided by the read noise (RN) at maximum gain. The typical dynamic range result is 56 dB using LFW at a 1x gain and a RN at 8x gain. However, the effective range is 46dB at 1× gain as shown in the following table. The responsivity is 3180 e/lux.s.

General Pixel Characterization Summary	
Linear Full Well	4276e-
Read Noise (1x gain)	20e-
Read Noise (8x gain)	8e-
SNR Max	36 dB
Dynamic Range (at 1x)	46 dB
Dynamic Range (at 8x)	54 dB
Responsivity (530nm)	3180 e-/lux.s

Table 2: *General Pixel Characterization Summary*

Figures 8a through 8c illustrate all the summarized results. Figure 8a shows the signal vs exposure time curve to outline the Linear Full Well (LFW) of the pixel.

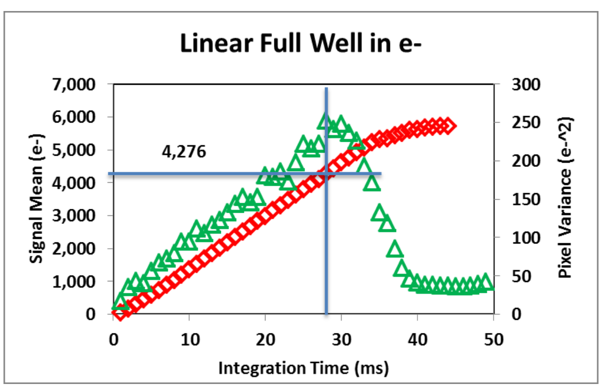


Figure 8a. *Response and Variance vs. Exposure Curve showing LFW*

Figure 8b illustrates the read noise vs. gain for gains 1×, 2×, 4× and 8×.

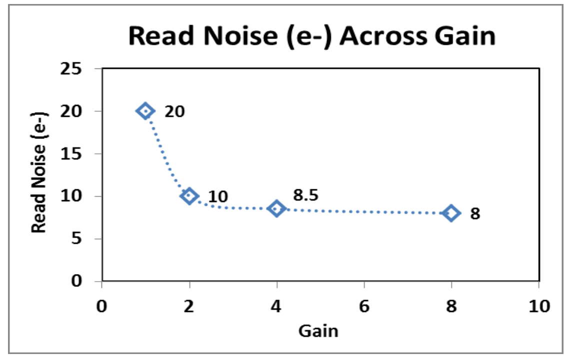


Figure 8b. *Read Noise versus Gains 1x, 2x, 4x and 8x*

Figure 8c illustrates the SNR at 1× gain highlighting the read noise and shot noise dominant region.

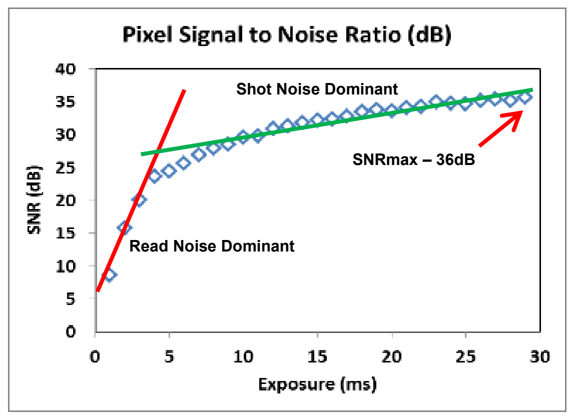


Figure 8c. *SNR vs Exposure Curve*

6.2 Equal Sub-Frame Operations

The equal sub-frame operations are shown in Figures 9a and 9b. The Figure 9a sub-frame policy (how the sub-frames are divided into a frame and the relative duration of each sub-frame) is not used for our HDR system implementation but demonstrated here solely for the purpose of explaining signal to exposure sweep per sub-frame for all four sub-frames.

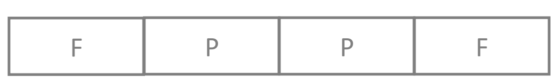


Figure 9a. *Equal division of 4 sub-frame in one frame with F and P Transfer Techniques*

Figure 9b shows four sub-frame signal versus exposure curves.

- The sub-frame 1 signal-to-exposure curve matches the behavior of a typical conventional CMOS image sensor.
- The sub-frame 2 signal to exposure curve has the same slope as sub-frame 1, but is horizontally shifted at a later exposure time. This late start in signal response is due to the P technique of sub-frame 2.
  Before the signal starts increasing after time zero, the charge gets accumulated within the partial transfer barrier. Once the signal accumulation exceeds beyond the P voltage barrier, the signal spills over into the FD and allows to be sampled for read out with the same responsivity of sub-frame 1.
- In sub-frame 3, the accumulation time observed is half of sub-frame 2. This is because sub-frame 3 has charge pre-accumulated from sub-frame 2 and passed on to sub-frame 3, halving the accumulation time required to spill over the P voltage barrier. Between sub-frame 3 start time and sub-frame 2 start time, the slope of the sub-frame 3 signal response is twice that of sub-frame 1 and 2.
  The increase in slope is due to the floating diffusion sampling charge accumulated in both sub-frame 2 as well as the spillover charge from sub-frame 3 providing the FD with twice the amount of charge compared to a single sub-frame, causing the effective sensitivity to double.
- Similarly for sub-frame 4, due to the earlier accumulation from sub-frames 2 and 3, the effective sensitivity becomes three times of a single short sub-frame.

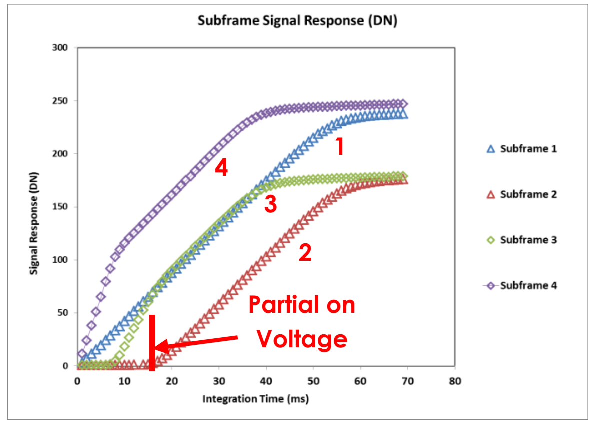


Figure 9b. *Exposure curve of each sub-frame of the total 4 sub-frames*

6.3 Partial Transfer (P) Voltage Optimization

The differential binary pixel requires optimization of the P gate voltage. The goals of this optimization are as follows:

1. In low light, have a long enough short sub-frame to obtain improved SNR for the three combined sub-frames.
2. Provide enough dynamic range in three of the short sub-frames to prevent a signal-to-noise ratio valley.
3. Set a Partial Transfer Gate Voltage that provides a stable output signal for partial transfer and is above the noise floor.

To address goal #1 above, the P Voltage cannot be equal to F Voltage as some of the charge must be held back during sub-frames 2 and 3 for sub-frame 4 low light boost.

To address goal #2, the partial transfer gate voltage cannot be close to off or fully off such that majority of the charge is held back during sub-frames 2 and 3 as shown in Figures 10a and 10b.

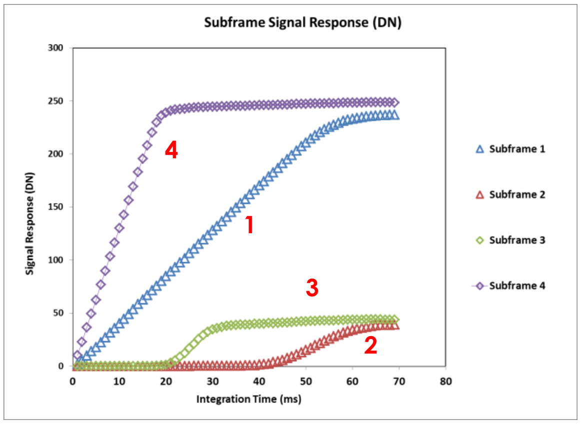


Figure 10a. *Four sub-frame Exposure Curve; P= 0.42V*

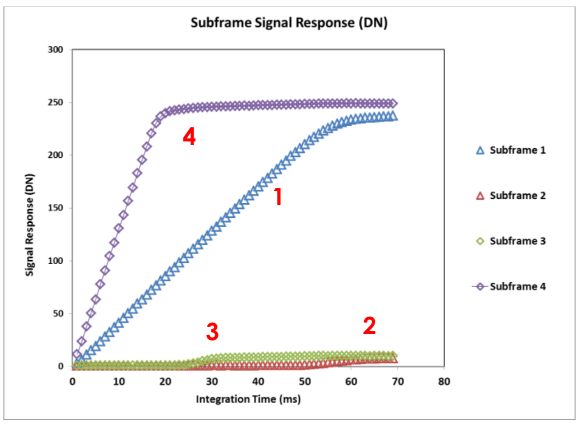


Figure 10b. *Four sub-frame Exposure Curve; P= 0.42V*

To address goal #3, a transfer curve of the partial transfer was taken and the voltage was set to 0.56V as shown in Figure 11a, which show that only over 63% of total signal region was usable.

To understand the extent of usable partial transfer voltage, the following experiment was conducted. First, the partial transfer voltage was set to 0.45V to have only 25% of the full PD signal to be transferred in sub-frames 2 and 3 as shown in Figure 10a. To mimic variability, the voltage is shifted by 0.03V to 0.42V. This resulted in a drop of the entire signal as shown in Figure 10b. Hence, this voltage is considered not optimal for real world use.

Thus, to address such variability independence, the voltage is set to 0.56V. This yields 75% of the full PD signal as the value 192 in Digital Numbers (DN) shown in Figure 11b.

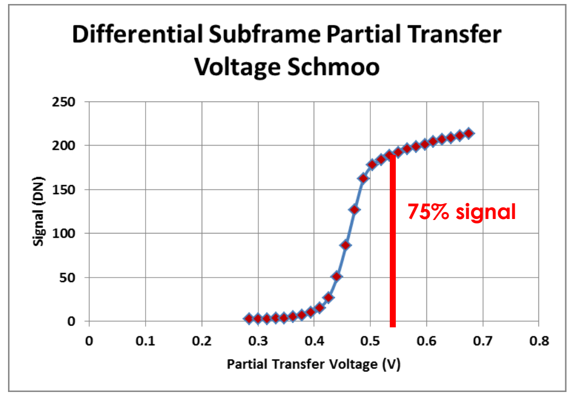


Figure 11a. *Sensor Output vs. Transfer Gate Voltage.*

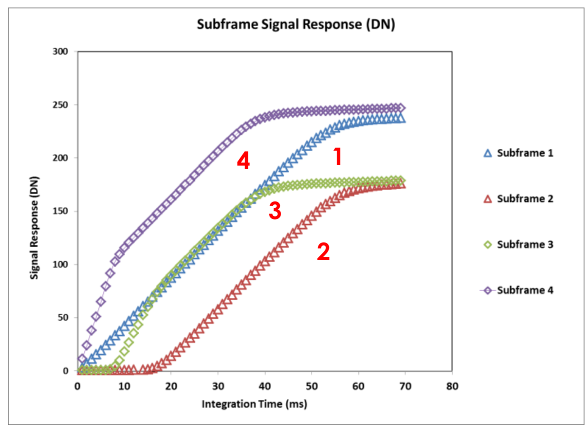


Figure 11b. *Four sub-frame Exposure Curve; P = 0.56V*

6.4 Results after Full Optimization

Figures 12a shows the 4× oversampling HDR method single frame composition using F and 12b shows the single frame composition using P as implemented in DBP.

a)

Figure 12a. *Frame Composition using Full transfer 4x over-sampling Full Transfer Technique*

b)

Figure 12b. *Frame composition in HDR mode using the Partial Transfer Technique*

Full transfer 4× oversampling HDR signal vs. exposure curve is shown in Figure 12c, where sub-frames 2, 3, and 4 are overlapping on top of each other representing the short sub-frame, whereas sub-frame 1 shows saturation at an early exposure time representing the long sub-frame. The policy used here was 13-1-1-1 where 13 is the long sub-frame and 1 represents the three short sub-frames.

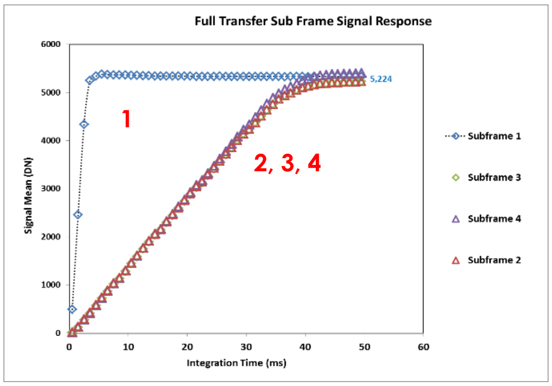


Figure 12c. Exposure Curves – Full Transfer Technique

Compared to this, the DBP signal vs. exposure curve is represented in Figure 12d showing four distinct responses for each of the sub-frames 1 through 4. Sub-frame 1 here is also the long sub-frame, but the 2, 3, and 4 sub-frames are short. Sub-frame 1 and 4 uses F. Sub-frame two and three use P. The policy used here was 54-4-3-3 to ensure DR is not lost significantly even when using 75% of the full signal range in sub-frames 2 and 3.

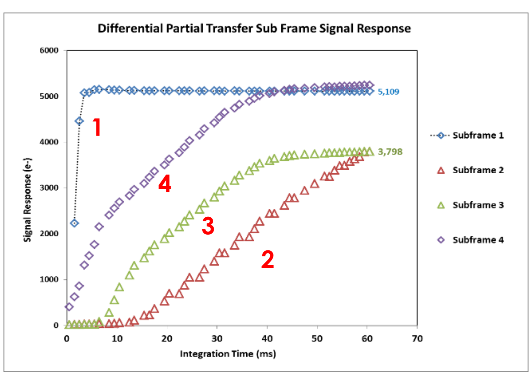


Figure 12d. Exposure Curves – Partial Transfer Technique

Figure 13a shows the signal vs. exposure curve of sub-frame 4 from both conventional HDR and DBP HDR. Notice that the slope of the DBP curve in low light is significantly higher, effectively more sensitive than the full transfer 4× oversampling HDR short exposure frame.

Due to this effective increase in sensitivity, the SNR in the fourth sub-frame is increased by 21dB as shown in Figure 13b.

This is expected as the signal output moves away from read noise dominant region to shot noise dominant region, the SNR increases dramatically.

Our read noise at 1× gain to be 20e-. If a state of the art signal chain is provided with optimized read noise, the improvement may not be as dramatic. A state of the art signal chain read noise is expected to be at 2 e- [4].

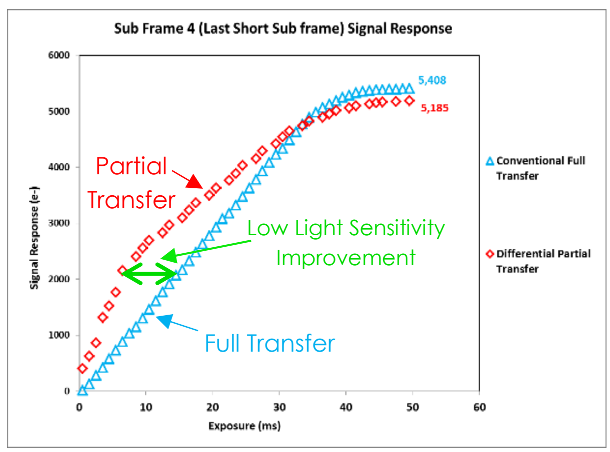


Figure 13a. Exposure curve of the 4th sub-frame to high light Low Light Sensitivity improvement when using Partial Transfer Technique over a Full Transfer Technique

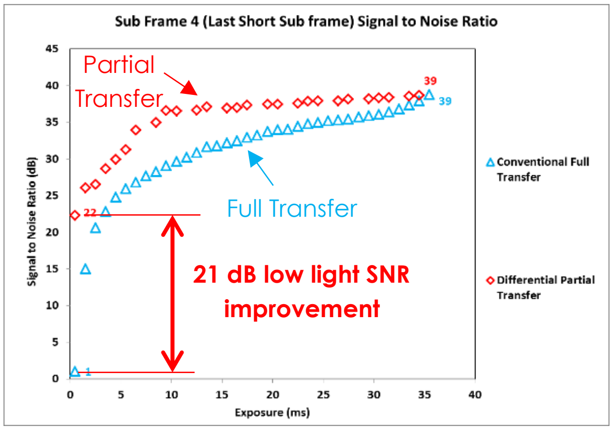


Figure 13b. Signal to Noise curve of the 4th sub-frame to high light Low Light Sensitivity improvement when using Partial Transfer technique over a Full Transfer Technique

6.5 HDR Reconstructed Image Characterization Results

The sub-frames explained in the previous sections are all taken and reconstructed in a single high dynamic range image. In this study, both DBP, as well as full transfer 4× oversampling HDR, were measured from the same test chip to demonstrate the superiority of DBP.

To represent full transfer 4× oversampling HDR, 4× oversampling was used with a 13-1-1-1 policy where the HDR ratio would be 16:1 with all four sub frames as F. For Differential, 4× oversampling was used with 54-4-3-3 policy where the HDR ratio will also be 16:1 ratio when taking into consideration P saturation level to be at 75% of the full signal range of the pixel.

Figure 14 shows the final reconstructed exposure curve with signal in electrons of both DBP as well as full transfer 4× oversampling. This outlines the signal linearity of both curves.

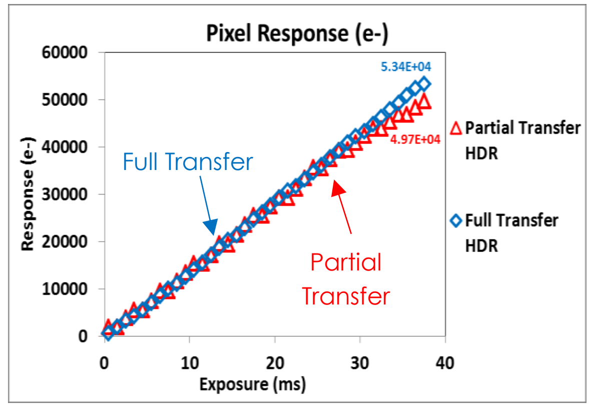


Figure 14. Signal vs. Expsoure Curve of HDR Reconstructed Frame for both Partial and Full Transfer Techniques

Figure 15 SNR vs exposure curve shows the 7dB improvement provide by DBP over 4× oversampling using F.

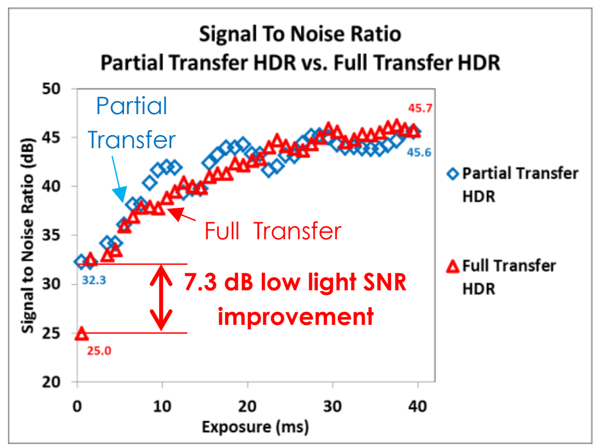


Figure 15. Signal to Noise Ratio (SNR) vs. Exposure Curve Highlighting Low Light SNR Improvement using P Technique over F Technique

The DR of DBP is 1dB less than full transfer 4× oversampling HDR mode, which is visually negligible in images. Note that theoretically both methods are designed to have the same DR. However, this 1 dB difference is due to measurement accuracy.

Although the effective DR of this test chip is 66dB 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-. This is summarized in Table 3.

	Full Transfer	Partial Transfer
Policy Condition	FFFF	FPPF
Policy Duration	13-1-1-1	54-4-3-3
Max Signal	53,400 e-	49,700 e-
SNR Max	45.7 dB	45.6 dB
Low Light SNR	25.0 dB	32.3 dB
Dynamic Range (RN at 1x Gain)	69 dB	68 dB
Dynamic Range (RN at 8x Gain)	76 dB	75 dB
Dynamic Range (Theoretical RN of 2e-)	88 dB	87 dB

***Table 3:** Comparison of P and F Transfer Techniques*

6.6 Real World Images and Videos

The DBP test chip was directly compared with a state-of-the-art iPhone 6s rearview camera using a Greyworld ITHDR-36 chart made for automotive applications with a spec of 130dB for being able to identify all the patches of gray shades. Table 4 compares both camera specifications. Both cameras use still image capture mode.

	IPhone 6s Rear-view Camera	Rambus Differential Binary Pixel
Pixel Size	1.22 um	1.1 um
Array Size	4032x3024	966x1084
Optical Format	1/3"	~1/7"
Sensor Fab	SONY	TSMC
Resolution	12 megapixels	1 megapixels

***Table 4:** iPhone 6s Rearview camera and Rambus Differential Binary Pixel (DBP) Test Chip Specifications*

Figure 16 shows images taken of a Greyworld ITHDR-36 chart. As shown in the left most image, the iPhone 6s in conventional mode is not able to identify patch #26, which is required to have 68dB. However, both the iPhone 6s camera in HDR capture mode and the DBP test chip image of the gray chart were able to identify up to patch #26, yielding a dynamic range of 68dB, matching our measured results .Figure 16 shows three image captures of Greywood ITHDR-36 chart. The center image shows the iPhone 6s rear view camera in HDR mode. The right image shows the DBP in HDR mode.

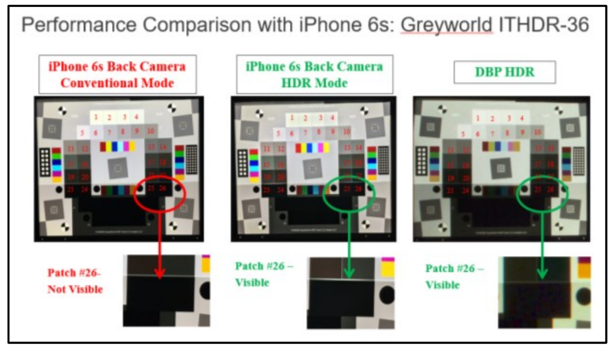


***Figure 16**a. iPhone 6s rear camera in conventional mode*
***Figure 16b.** iPhone 6s rearview camera in HDR mode*
***Figure 16c.** DBP in HDR mode*

Moving on to video capture mode, Figure 17 illustrates how, in a high DR scene, the iPhone 6s is not able to capture the entire image as shown in the two left stills from the video, while the DBP was able to capture all of the details. This is because the iPhone 6s, as well as iPhone 7 does not have HDR video capability. DBP technology can certainly enable that.

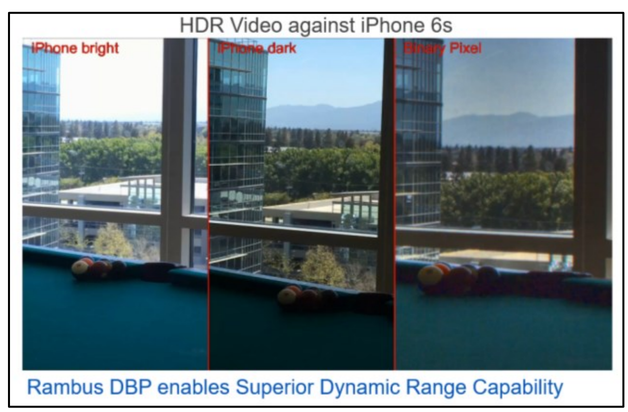


***Figure 17a.** iPhone 6s with auto-exposure adjusted*
***Figure 17b.** Auto exposure adjusted on the background sky*
***Figure 17c.** DBP capture in HDR mode video*

7. Summary and Conclusion

This paper introduces the Rambus Differential Binary Pixel technology and compares it against conventional image capture methods currently on the market.

An overview of image capture methods using conventional CMOS vs. High Dynamic Range (HDR) is presented. Common mobile HDR capture methods are defined and contrasted against the DBP method.

A discussion of the Rambus sensor implementation using DBP describes the design implementation for the sensor, and lists the various parameters of the sensor that make up the full architecture.

Results include general pixel characterization data, 4× oversampling sub-frame characterization data, P voltage optimization, and HDR reconstructed characterization data. Finally, the DBP test chip was compared to that of an iPhone 6s rear view camera.

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