Extending the Dynamic Range of Oversampled Binary SPAD Image Sensors

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Abstract— **High dynamic range (HDR) in spatio-temporally oversampled single photon counting image sensors, such as the Quanta Image Sensor (QIS), is achieved by combining different pixel exposures. In this paper, the HDR techniques applicable to QIS are described. A SPAD-based QIS is employed, with dual global shutters and in-pixel memories, as the first proof of principle demonstrating extended or high dynamic range in a QIS.**

I. INTRODUCTION

Single photon avalanche diode (SPAD) image sensors [1] – [4] offer a look-ahead to the behaviour and operation of the 'Digital Integration Sensor' (DIS), small in-pixel full-well with oversampling frame store, and the oversampled binary 'Quanta Image Sensor' (QIS) [5]. Both the DIS and QIS have severely limited in-pixel dynamic range (DR), alleviated by the bit depth or "full well" of the frame store which creates the image.

However, as in CMOS image sensors (CIS) with limited DR, if the frame store dynamic range is limited then due to the single in-pixel storage of QIS and DIS pixels, two or more back to back exposures with different integration times are required for extended or high dynamic range (HDR). The disadvantages are the motion artefacts between the constituent exposures and decreased frame rate. Multiple in-pixel memories (or storage) with independent shuttering brings the benefit of being able to capture and create oversampled images with extended DR simultaneously with reduced motion artefacts at native frame rate (for example for suppression of LED or indoor lighting flicker). This paper explores extending the dynamic range of SPAD-based QIS by employing multiple in-pixel memories and shows the first demonstration of the extended or high dynamic range in a QIS. Furthermore the paper projects the trends of CIS technology and pixel shrink for SPAD-based image sensors and HDR QIS.

HDR Technique	Single In-pixel Memory and Sequential HDR[7]	Multiple In-Pixel Memories and Interleaved Simultaneous HDR [11]
Electrical Sensitivity Modulation	√	X
Physical Sensitivity Attenuation	√ *	√ *
Shuttering or Integration Time Modulation	√	√ *(This Work)*
HDR Effects		
Spatial Effects (e.g.Aliasing, reduced MTF)	√ *	√ *
Suppression of Motion Artifacts and Lighting Flicker	X	√
Frame Rate	$\frac{Native}{Sequential\ Frames}$	Native
Frame(s) Store Required	√	*Depends on Application*

Table 1. Comparison table of HDR techniques appropriate for Quanta binary image sensors and effects of single and multiple in-pixel memories or storage. *Spatial effects only due to physical attenuation filter pattern.

II. DYNAMIC RANGE EXTENSION IN OVERSAMPLED IMAGERS

Dynamic range enhancement for CIS is well known for 20 years [6]-[8], Fossum more recently proposed oversampled HDR for QIS in a modelling and theoretical paper [5] using linear summation of multiple exposures where the QIS dynamic range is defined as the signal reaching 99% of saturation (which has an single exposure fundamental maximum DR of ~73dB regardless of frame store dynamic range, but improved by multi-exposure HDR of >100dB). Table 1 presents the different known HDR techniques that can be implemented for QIS and their applicability to single in-pixel memory (sequential frames) or multiple in-pixel memories (single frame with interleaved exposures). The photo-sensitivity of an imager can be globally electrically modulated in certain technologies for example modulating the applied bias of organic photo-conductive film (OPF), the reverse bias in an avalanche photo diode (APD), or the excess reverse bias above breakdown in a SPAD. In a similar manner the photo-sensitivity of any imaging technology can be attenuated by on-die filtering or metal apertures/shielding applied in an interleaved pattern across the imaging array. The downside to this approach is the spatial aliasing or MTF reduction that will occur. Single in-pixel memory will have reduced frame rate by the number of sequential frames needed to produce the HDR output image with the significant addition of a frame store. Here we apply the

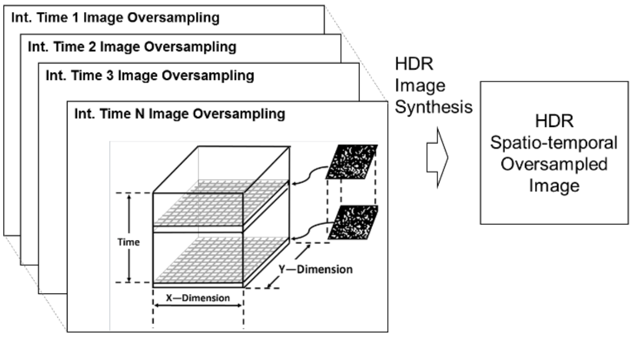


Fig. 1. Extended or High DR oversampled image formation through parallelised oversampling. In this work using 2 integration times with 2 in-pixel global shutters.

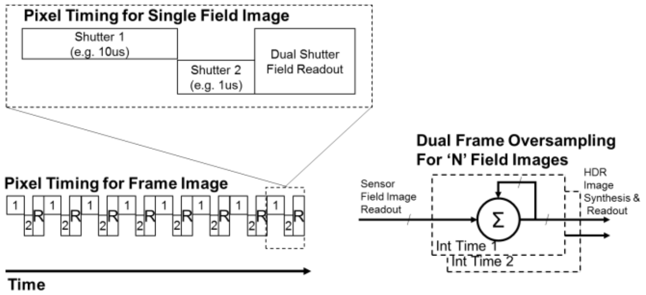


Fig. 2. Implemented interleaved pixel timing and block diagram of 'N' field images oversampled in parallel.

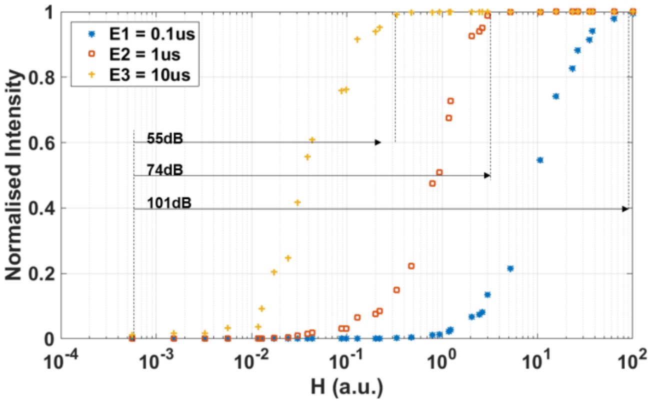


Fig. 3. Measured normalised intensity (D or 'Bit Density') to normalised exposure (H) for 3 integration times (100ns, 1μs and 10μs) and the extension of dynamic range from 55dB to 101dB.

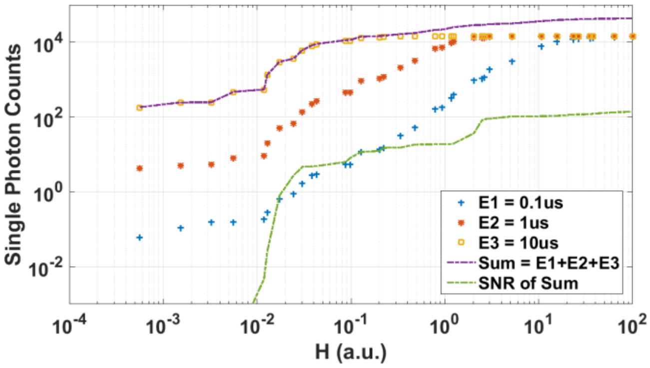


Fig. 4. Measured intensity data plotted alongside the extended dynamic range linearly summed data (top line) and SNR (bottom line).

	Frames @ 500FPS	Measured DR
Single Exposure	1	55dB
Dual Exposures	1	74dB
Three Exposures	2	101dB

Table 2. Measured dynamic range extension.

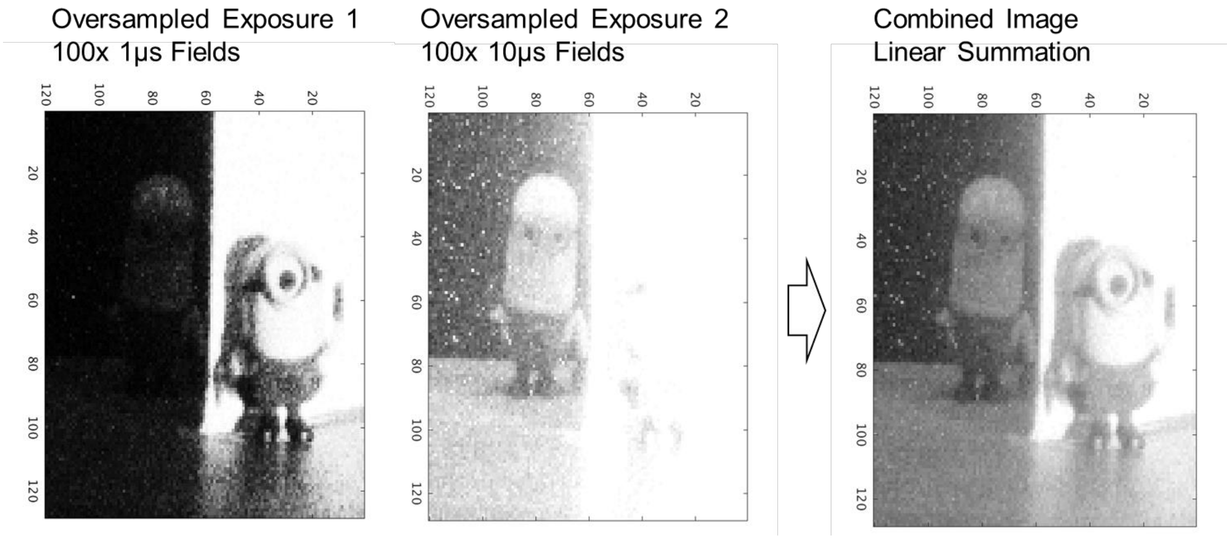
technique of different integration times to achieve extended dynamic range oversampled binary imaging, with the significant benefit of noiseless oversampling through operation wholly in the digital domain as illustrated in Fig. 1.

III. MEASUREMENT RESULTS

A SPAD image sensor [1] is employed with two independent global shutters and two multi-bit ripple counters in-pixel that are truncated to single bit in post-processing, indicating 0 or ≥1 photon to emulate the single-bit QIS. The implemented pixel timing is shown in Fig.2, where 'N' field images are read out and oversampled in two frame stores to create the dual frame images. Ideally the two frames are overlapping for optimal motion artifact suppression but in the employed SPAD imager, the two global shutters are contiguous and non-overlapping due to the gating circuit in the pixel. The short field image exposure is set for 1μs and the long field image exposure for 10μs. As a proof of principle of extended DR, the measured signal to exposure for the dual shutters is shown in Fig. 3, with the dynamic range of 55dB for a single oversampled exposure (the non-linear compression typical to QIS is apparent) extended to 74dB in extended DR oversampled mode with 10:1 ratio between field integration times. Fig 4 shows the "flat" SNR curve expected with QIS but the SNR bump between H=1 and H=10 indicates future optimisation of integration times is required. Greater than 100dB HDR becomes possible with ≥3 different exposures with frame rate trade-offs, shown in Table 2. Fig. 5 displays two oversampled frame images (noiseless summation of 100 binary field images), on the left hand side, captured of a high dynamic range scene. The right hand side shows the extended DR synthesised image.

IV. FUTURE PROJECTIONS FOR QUANTA IMAGE SENSORS

The pitch of SPADs is decreasing from 5μm [9] to latest state of the art 3μm [10], and the pitch of SPAD image sensor pixels is decreasing below 8μm [1]. Predicting this trend further, Table 3 illustrates a projection for SPAD pixels for megapixel QIS arrays in monolithic 2D CMOS and 3D stacked technology. They are compared using a reference design of an all-digital ripple counter architecture. In order to achieve pixel shrink two conclusions are apparent: the need for 3D stacking technology, and the resulting digital counter depth reduction which forces the system to incorporate one or more oversampling frame stores. It indicates that sub-1μm pitch will require 3D stacked CMOS and employing technology nodes below 16nm for the pixel logic tier of stacked SPAD image


Oversampled Exposure 1
100x 1µs Fields

Oversampled Exposure 2
100x 10µs Fields

Combined Image
Linear Summation

Fig. 5. 100 binary oversampled field images, captured simultaneously at two different exposures. Linearly summed to create extended DR combined image. No filtering has been applied.

	CMOS Tech. Node (nm)	Pixel Pitch (µm)	2D	3D	Single Exposure		HDR Dual Exposure	
					Full Well	Ripple Counter Bit Depth	Full Well	Ripple Counter Bit Depth
State of the Art	40	~8	2D	3D	≤4095	≤12	≤63	≤6
Future Projected Trends	40	6			127	7	7	3
	32	6			16383	14	127	7
	32	3			7	3	1	1
	22	3	▨		127	7	7	3
	22	1.5			1	1		
	16	1.5			7	3	1	1
	16	1			1	1		
	11	1			7	3	**1**	**1**
	11	**0.75**			**1**	**1**		

Pixel Pitch Decrease

Toward 3D Stacked QIS

Toward HDR QIS

Table 3. Projected trends, of 2D monolithic and 3D-stacked SPAD pixels based on an all-digital ripple counter architecture, towards 3D-stacked Quanta Image Sensors. Cells marked in red indicate where spatio-temporal oversampling is assumed to be required for in-pixel full well less than 255 photons.

sensors able to be able to get to large mega-pixel arrays for single exposure and dual exposure HDR QIS.

V. CONCLUSION

The first practical demonstration of extended and high dynamic range in oversampled binary imaging is shown using a SPAD image sensor in a QIS mode. A dynamic range of 74dB is measured in a single frame using dual in-pixel storage elements to capture two frames, and 101dB is measured using three frames. The future technology scaling for SPAD image sensors is discussed for both monolithic and stacked implementations indicating the requirement for oversampling.

VI. REFERENCES

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