Over 2 Million Frames per Second 128×128 Macropixel 3D-Stacked Burst SPAD-Based Image Sensor

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Abstract—**Ultra high-speed imaging enables the detailed recording of fast phenomena with extremely short exposure times. Readout noise becomes significant in conventional image sensors due to limited photon numbers. We present a zero-readout-noise 2.18 Mfps SPAD-based burst imager with 128×128 macropixels and applying 3D-stacked technology for high efficiency. Experimental results confirm solely photon-shot-noise-limited performance, reduced dark noise at higher framerates, and successful capture of transient events.**

I. INTRODUCTION

Ultra high-speed imaging has enabled the ability to capture and analyze transient phenomena occurring at extremely short timescales previously unattainable. With framerates exceeding one million frames per second, high-speed imaging techniques facilitate detailed visualization of ultra-fast events in scientific and industrial fields. It provides an essential solution for fields such as biomedical imaging, aerospace engineering, and nuclear reaction studies [1], where transient interactions must be resolved with high temporal and spatial precision.

Challenges of developing ultra high-speed imaging include the requirement for extremely short exposure times, which significantly limits the number of photons available to the detector. In conventional low-speed imaging, a longer exposure accumulates more photons, leading to improved signal-to-noise ratios (SNR). However, as exposure times shrink to microseconds or even nanoseconds in high-speed imaging, photon count per frame is drastically reduced, exacerbating the impact of noise and making reliable image acquisition a major challenge, while intense or unnatural scene lighting conditions may be required to enhance the low SNR.

Currently, the most widely used sensor technology for high-speed imaging is based on CMOS image sensors (CIS). Even CIS technology has advanced significantly in recent years, it remains constrained by various sources of electronic noise. Thermal noise, flicker noise, and random telegraph signal (RTS) noise arise from the fundamental design of CIS, which relies on analogue readout circuits [2]. These noise sources collectively contribute to readout noise levels ranging from a few to tens of electrons [3]–[5]. Such performance is acceptable in many conventional low-speed imaging applications, however, it presents significant limitations for high-speed imaging, particularly in photon-starved conditions.

To overcome the challenge, single-photon avalanche diode (SPAD) sensors have emerged as a promising alternative for ultra high-speed imaging. Unlike CIS, SPADs operate digitally, detecting individual photons through avalanche multiplication with zero readout noise. This fundamental advantage enables SPAD-based imaging to achieve an SNR limited only by photon shot noise, offering superior performance in extremely low-light conditions. By integrating SPAD technology into high-speed imaging systems, it has the potential to unlock new possibilities for capturing ultra-fast processes with unprecedented sensitivity and spatial and temporal resolution.

In this paper, we present a SPAD-based burst imager capable of 2.18 million frames per second (Mfps), featuring a 128×128 macropixel array and leveraging advanced 3D-stacked technology fabricated using STMicroelectronics' state-of-the-art 3D40SPAD process. The camera architecture, including detailed pixel design, is introduced. A photon transfer curve analysis confirms that shot noise is the sole limitation of the system, with no readout noise contribution. To demonstrate the imager's capability in capturing transient events, experiments involving a fast-blinking LED and a high-speed rotating fan are conducted as proof of concept.

II. PROPOSED STRUCTURE

The SPAD sensor utilizes a shift register as in-pixel memory for frame storage. Although this structure was originally designed for Diffuse Correlation Spectroscopy (DCS) [6], it also enables the capture of 31 consecutive frames at a rate exceeding two million frames per second. The stored frames are read out sequentially before the next burst of 31 frames begins. In this mode, each frame has a depth of 5 bits for photon counting.

Fig.1 shows the image sensor and diagram of the image capturing system. Fig.1 (a) is the SPAD sensor bonded to a PCB board which is further connected to an FPGA for sensor control and data readout. A camera diagram is shown in Fig. 1 (b). Fig.1 (c) is the cross-section of the pixel structure. It achieves 55% peak Photon Detection Efficiency (PDE) [7] by applying the microlens, dedicated BSI top tier process and detection efficiency enhancement structure. Fig.1 (d) is the 4×4 RC-coupled SPAD subarray. Fig.1 (e) is the pixel frontend, combinational logic, and shift register. At every rising edge of a driving clock, a new frame is stored in the first shift register stage and all previously stored frames are moved one stage forward. After 32 clock periods the burst of frames is read out of the pixel.
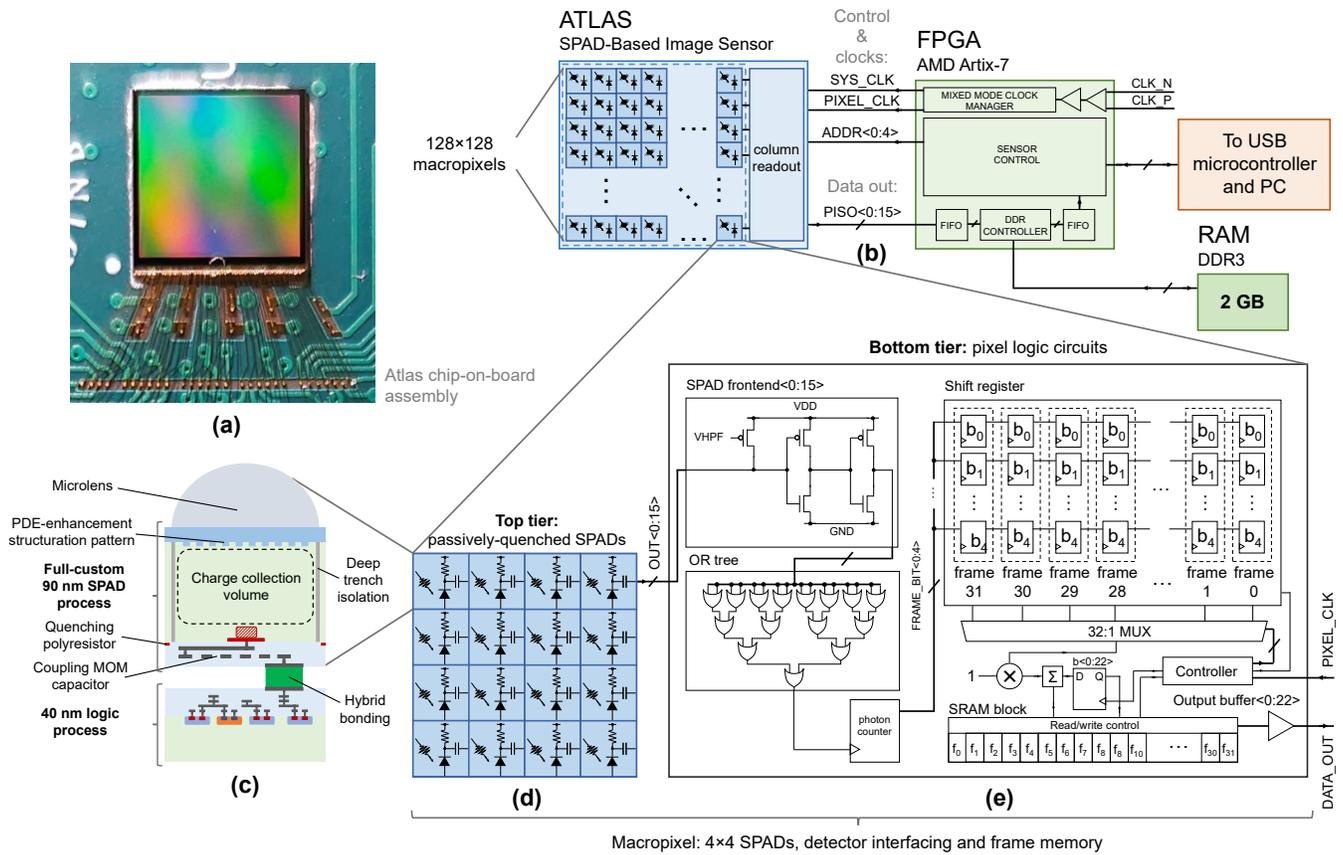
Fig. 1. Diagram of the camera system using a 3D-stacked SPAD-based burst imager. (a) The SPAD sensor bonded to a PCB board. (b) Camera diagram. (c) Cross-section of the Pixel Structure. (d) 4x4 SPAD subarray. (e) Memory structure storing 32 frames.
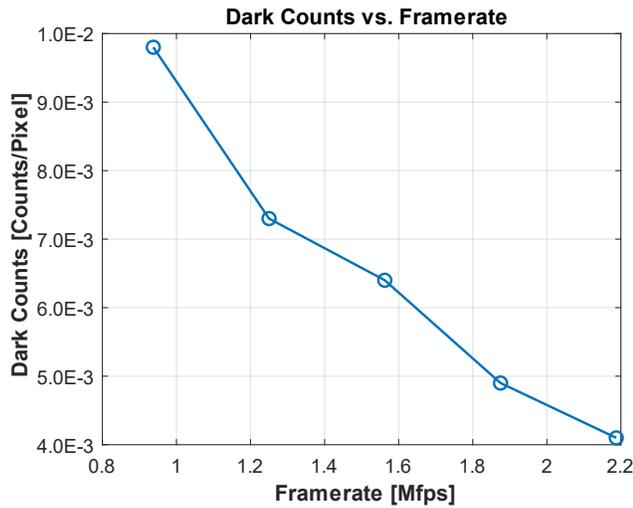

Fig. 2. Average dark count decreases as framerate increases. Each point is calculated at room temperature from 100 frames averaged over 1,638,400 pixels.
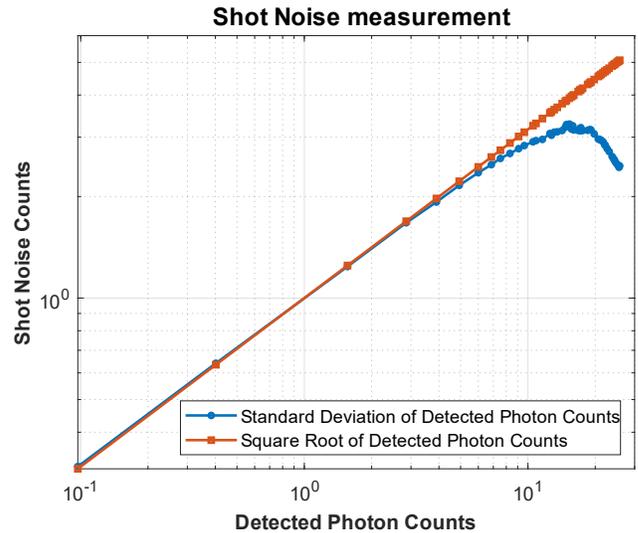

Fig. 3. Photon transfer curve captured at 2.18 Mfps. Each point is calculated from 20 frames, which is 327,680 pixels. Light is collimated using two convex lenses. Shot noise increases as the light illumination is increased and starts to decrease at around 17 photon counts due to the pixels becoming saturated. No slope-zero regime is observed at the beginning of the curve meaning no readout noise from the SPAD sensor, outperforming CMOS/CCD sensor at this point.

III. MEASUREMENT RESULTS

Measurements were conducted to evaluate the performance of the proposed design. These include the relationship between
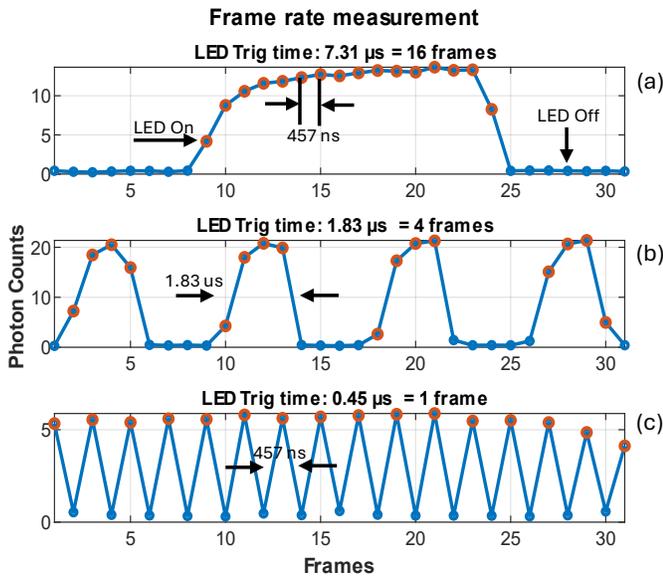
Fig. 4. Experiment proving the framerate 2.18Mfps. Waveforms of different frequency driving the LED are observed by the sensor. Photon counts are calculated from an average of 100 pixels where the LED is focused on the sensor. (a) LED blinking frequency is 68 kHz. (b) LED blinking frequency is 273KHz. (c) LED blinking frequency is 1090 kHz.

Fig. 6. Fragment of a burst of 32 frames captured at 2.18 Mfps. According to the size of the fan in the compressed air blaster and its declared speed 150,000rpm, the theoretical linear movement is around 3.6 mm in 31 frames using the frame rate of 2.18 Mfps. In our measurement, the actual movement is around 2.5 mm and corresponding rotating speed is around 102,000 rpm. The pink arrow points to the original position of a blade in frame 1 and the blade shows a rotation angle of 8° in the last frame. The lower rotating speed than the declared specification of the fan to our knowledge may be caused by the unstable power supply from the battery while current draw is significantly high at this speed.
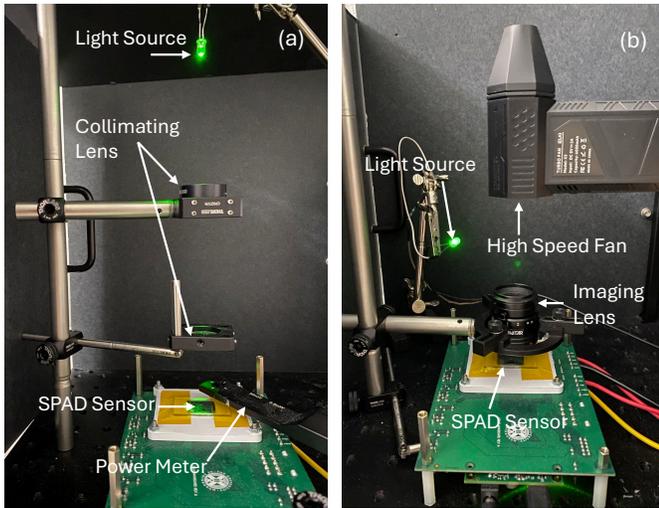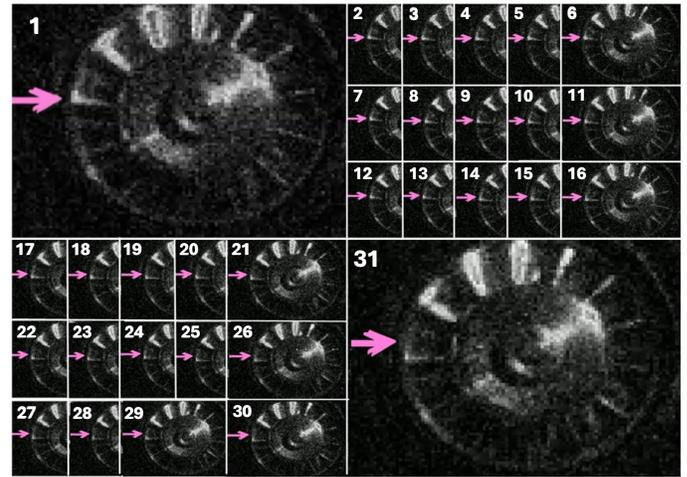

Fig. 5. Experimental setups. (a) LED with different levels of constant power supply applied for tests in Fig. 3 and with pulsed trigger for the test in Fig. 4. (b) High speed imaging test using the fan from EUKI X3 compressed air blaster with the declared speed of 150,000 rpm.

frame rate and dark counts, the photon transfer curve, an experiment using a high-frequency blinking LED to validate frame rate capabilities, and a high-speed fan experiment to simulate transient event imaging.

Fig. 2 shows that as framerate increases from 0.93 Mfps to 2.18 Mfps, the dark noise decreases from 0.0098 to 0.0041 counts per pixel, indicating a reduction in dark count noise at higher frame rates. Fig. 3 shows the photon transfer curve of the macropixel at the frame rate of 2.18 Mfps. Standard deviation follows the square root of the mean signal, indicating the sensor is operating in a photon-shot-noise-limited regime. For the signal levels close to the depth of the counter, the signal variance starts to deviate from the Poisson distribution as the signal fluctuations are constrained by the pixel full well. Fig 4. shows the photon counts registered by the sensor observing an LED driven by waveforms with frequency 68 kHz, 273 kHz, 1090 kHz. The y-axis photon counts are calculated from 100 pixels where the LED image is projected onto the sensor. The red and blue dots replicate the waveform of the LED driving clock, with red dots representing the LED in the on or half-on state, and blue dots indicating when the LED is off. Experimental setups are shown in Fig. 5. Fig. 5(a) shows the LED setup, where the LED is either powered by a constant supply for measurements in Fig. 3 or driven by pulsed triggers for measurements in Fig. 4. The illuminated LED passes through a collimating lens, forming an image on the SPAD sensor. A power meter is used to enable controlled linear power increments for measurements in Fig. 3. Fig. 5(b) is the experimental setup for measurements in Fig. 6, where a EUKI X3 compressed air blaster was used to generate a sample transient event. Fig. 6 captures the fan spinning at over 100,000 rpm in a sequence of frames recorded at 2.18 Mfps. A fragment of a burst of 31 frames at this frame rate is shown. Based on the declared fan speed of 150,000 rpm and its size, the theoretical linear movement over 31 frames at 2.18 Mfps is approximately 3.6 mm. However, our measurement shows an actual displacement of around 2.5 mm, corresponding to a rotational speed of approximately 102,000 rpm. The pink arrow in the images indicates the original blade position in frame 1, with the blade exhibiting an 8° rotation in the last frame. The observed lower rotation speed compared to the

TABLE I
STATE OF THE ART COMPARISON

Parameter	This work	S. Shigetoshi [3]	S. Manabu [8]	V. Dao [9]	D. V. Blerkom [5]
Technology	3-D-stacked 90 nm BSI / 40 nm	180 nm	180 nm	BSI	110 nm BSI
Imaging device	SPAD	Pinned photodiode	Pinned photodiode	CCD	Partially-pinned photodiode
Maximum framerate (burst) [fps]	2.18M	20M	100M	25M	N/A
Maximum framerate (continuous) [fps]	3k	7.8k	N/A	N/A	80k
Readout noise [e- RMS]	0	5	N/A	N/A	23
Photon detection efficiency/ Quantum efficiency (peak) [%]	55	N/A	N/A	N/A	N/A
Resolution	128×128	400×250	50×108	32×32	1280×832
Data rate (burst) [pix/s]	3.6E+10	2.0E+12	5.4E+11	2.6E+10	N/A
Data rate (continuous) [pix/s]	4.9E+07	7.8E+08	N/A	N/A	8.5E+10
Architecture	In-pixel memory	Column memory	In-pixel memory	In-pixel memory	Parallel readout
Memory type	Shift register	N/A	Trench capacitor	CCD gate	N/A
Burst length [frames]	32	256	368	1220	N/A
Pixel size [μm²]	40.68×40.68	32×32	70×35	72.56×72.56	18.54×18.54
Fill factor [%]	~100	63	24	~100	N/A
Full well [e-]	31	10k	N/A	3k	9k
Power consumption [W]	1	10	N/A	N/A	<40

declared specification is likely due to power supply instability, as the battery struggles to meet the high current demand at such speeds. Table I presents a comparison with state-of-the-art high-speed image sensors. Our 2.18 Mfps, 3D-stacked SPAD-based burst imager, featuring a 40.68 μm macropixel pitch, offers unique advantages, including zero readout noise, high detection efficiency, and an approximately 100% fill factor. Additionally, the sensor operates at a power consumption of 1 W at its maximum frame rate.

IV. DISCUSSION AND CONCLUSION

This SPAD image sensor implements a 31-step shift register, allowing storage of only 31 frames at a speed of 2.18 Mfps. Meanwhile, each pixel has a 5-bit depth, limiting the maximum photon count to 32, constraining the dynamic range of the imaging. This work shows the feasibility of a single-photon-counting ultra high-speed image sensor. Future improvements are expected to enhance both high-speed frames and photon counts to be more adaptable to different application requirements.

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