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Invited Paper
Single-Photon-Capable Detector Arrays in CMOS – Exploring a New Tool for Display Metrology

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Abstract

The technology of CMOS-compatible Single Photon Avalanche Diodes is evolving rapidly and has matured to the point at which it can address the requirements of a range of imaging applications. In this report we consider the current suitability and future potential of CMOS-compatible Single Photon Avalanche Diodes to address the particular application of display metrology.

Author Keywords

Complementary Metal Oxide Semiconductor; CMOS; Single Photon Avalanche Diode; SPAD; Display Metrology; Digital Silicon Photo-Multiplier, dSiPM; Quanta Image Sensor, QIS;

1. Introduction

Adequately measuring the optical performance of advanced electronic display panels and systems is an ongoing challenge as display product specifications continue to grow more stringent and component technologies improve to meet the increased specifications. Examples of increasing device performance include higher contrast to help deliver High Dynamic Range (HDR) and better visibility; and faster switching time to help deliver higher frame rates and better reproduction of rapid motion. Switching times are currently of the order of ~ms for in-plane switching (IPS) Liquid Crystal (LC) [1], ~µs for Ferroelectric LC (FLC) [2], and << µs for Organic Light Emitting Diode (OLED) [3] and microLED (µLED) [4].

A large number of measurement techniques, technologies and instruments have been developed to adequately measure the range of parameters required for comprehensive display specification and characterization. Each has strengths and weaknesses. Several examples are summarized here. Charge-Coupled Device (CCD) technology [5] is well established and offers high photon sensitivity and low dark noise. However, the readout rate may be slow, and may need to sacrifice resolution when high frame rate is required; CMOS based camera [6] offers a faster rate but still suffers from the read noise; Silicon photodiode/avalanche photodiode (APD) [7] is able to take fast measurement as single point sensor; Photomultiplier Tube (PMT) [8], which has a better low light sensitivity over silicon photodiode/APD, however, it is vulnerable to damage at very high luminance.

In this paper, we introduce a relatively new optical detector / image sensor technology - Single Photon Avalanche Diode (SPAD) that is fabrication-compatible with Complementary Metal Oxide Semiconductor (CMOS) technology. We briefly describe the technology, capability and potential of CMOS SPADs and its suitability for display metrology. We have demonstrated the use of CMOS SPAD devices for single point sensing and imaging for electronic display characterization [9].

2. SPAD technology

The Single Photon Avalanche Diode was first reported by McIntyre in 1961 [10]. A SPAD can be considered as a solid-state analog of a conventional PMT. Such avalanche photodiodes are designed to be biased above the breakdown voltage to operate in Geiger-mode allowing for single photon detection. SPAD devices have been reported in a number of technologies, including InGaAs-InP [11], GaN [12] and CMOS [13]. These technologies offer SPADs with a variety of performance criteria to meet the needs of specific applications. The first allows single photon detection at infrared wavelength, the second is for ultraviolet light applications and the third works well across the visible spectrum. The implementation of SPADs in 2D arrays [14] substantiates its potential for image sensor capability. Recently, the design and implementation of SPADs in mainstream CMOS processes has lowered the barrier for research, product development and industrial SPAD applications. In principle, a SPAD device in a CMOS process is not hugely different from a conventional silicon photodiode, so CMOS-SPADs exhibit similar spectral response as conventional CMOS image sensors. Therefore, in spectral sensitivity CMOS SPADs are well suited for the measurement of electronic displays across the spectrum of visible light.

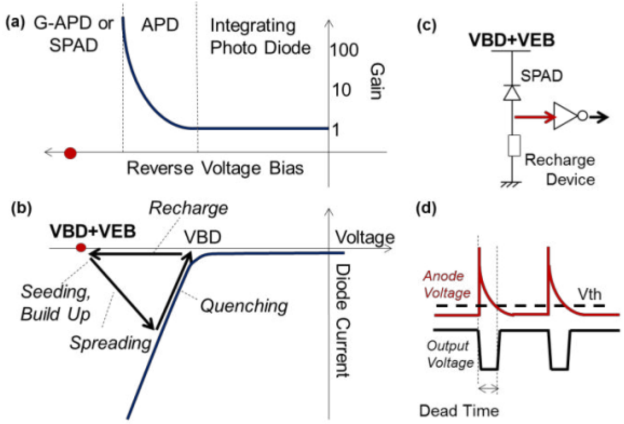

Figure 1. SPAD principle of operation
(a) Photon detection gain versus reverse bias voltage
(b) photo-detector current versus reverse bias voltage
(c) passive recharge circuit with CMOS inverter
(d) timing diagram of anode and inverter output [15]

CMOS SPAD arrays are able to capture optical signals with single photon sensitivity and picosecond time resolution. Reported applications of these devices include time-of-flight three-dimensional (3D) vision [16], fluorescence lifetime imaging microscopy (FLIM) [17] and ultrafast physical processes such as light-in-flight [18]. Thanks to the recent increasing research interest in CMOS SPADs, both high performance SPAD based digital silicon photomultiplier as single point sensor [15, 19], and QVGA CMOS SPAD imager [20] with high Fill-Factor (FF), fast frame rate, small pixel pitch and high Quantum Efficiency (QE) have been developed.

3. CMOS SPAD Principle of Operation

A SPAD is a variation on an APD designed for operation in Geiger mode. Figure 1 (a) shows the gain of APD versus reverse bias voltage. When the applied reverse bias voltage is beyond the breakdown voltage, the SPAD is able to exhibit single photon response. There are five stages of SPAD operation: seeding; current build-up; spreading; avalanche breakdown followed by quenching; and full recharge. The I-V response which shows the sequence of these states is displayed in Figure 1 (b). A typical circuit schematic for SPAD front-end is shown Figure 1 (c), and Figure 1 (d) shows how the quenching and recharge behavior is transformed by a digital inverter into a pulse. The pulse width is in the order of nanoseconds, also known as the "dead time" of the SPAD – the period when no further photon can be detected.

4. SPAD array as "single-point" sensor for electronic display

In this section we report the application of a CMOS-SPAD array as single point sensor for display measurement.

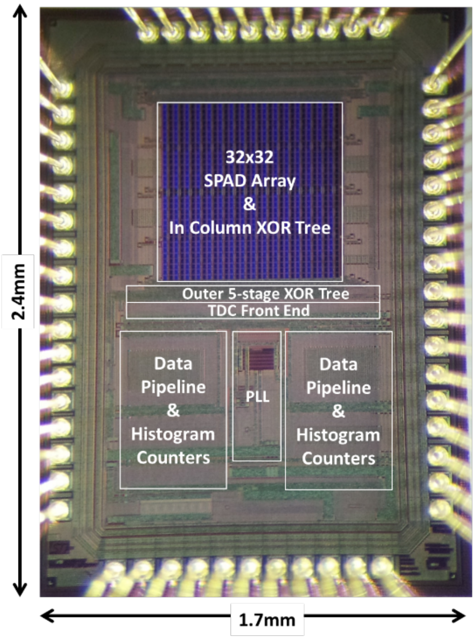

Figure 2. Photomicrograph of FlashTDC chip used in this work [15].

In this work, we employed a CMOS-SPAD device – a digital Silicon Photo-Multiplier (dSiPM) labelled FlashTDC [15]. Figure 2 shows a photomicrograph of the FlashTDC which was designed in STMicroelectronics 130 nm imaging CMOS process. Unlike a conventional analogue silicon PMT which sums the currents of the individual SPADs in an array, FlashTDC combines the individual digital pulses from each SPAD front-end into a single pulse train. The FlashTDC sensor array is formed by 32×32 SPAD pixels, with 21 µm pixel pitch and 43% FF. The output of each SPAD front-end is connected to a toggle flip-flop which encodes photon counts at positive and negative edges. The toggle outputs are then connected to an XOR tree to generate a single output pulse train. The XOR tree is capable of recording photon events with a higher bandwidth than the conventional OR tree architecture. This is illustrated in Figure 3. As shown in Figure 3 (a), the conventional OR tree network cannot record additional SPAD events within the dead time of an initial SPAD firing. The SPAD pulse length can be reduced by combining a pulse-shortening monostable circuit which only outputs a very short pulse, as shown in Figure 3 (b). The XOR tree, shown in Figure 3 (c), can extend the channel bandwidth beyond that of an OR tree due to the dual data rate encoding which is independent of any pulse width [21].

There is an upper limit to XOR detection rate - when two "events" are very close in time (less than a gate delay) and propagate through the same XOR gate, those events will be cancelled out and result in loss of information. For the use of optical display characterization, the sensor uses banks of digital counters sampling the XOR tree output at rates up to 10 MS/s, where the XOR tree bandwidth is 900 Mega Counts per second.

A small array of test-pixels for an OLED microdisplay is used here to demonstrate the measurement capability of CMOS-SPADs. OLED microdisplays are usually viewed under optical magnification in projection or near-to-eye systems. Yet it is a challenge to measure them, as the pixels are extremely small, <10 µm pitch and can be very low intensity. The OLED pixel luminance can vary from very dark (theoretically 0 cd/m^2) to up to 10,000 cd/m^2 [22] or more. And the switching time is sub-microsecond. It is challenging to perform a measurement that is capable of capturing high dynamic range at high speed.

Conventional analog PMT is the technology that was used for low light and high speed display measurement [7, 8]. However, analog PMTs require higher bias voltage, are vulnerable at high-light exposure and can exhibit gain nonlinearity induced by excess noise, compared to dSiPMs. Therefore most of the measurement systems that have employed analog PMT have also featured a photodiode array [7] to extend the dynamic range and give a uniform gain. In addition to the inherent combination of high dynamic range and gain linearity in photon detection, dSiPM is advantageous over PMT in its compatibility with CMOS.

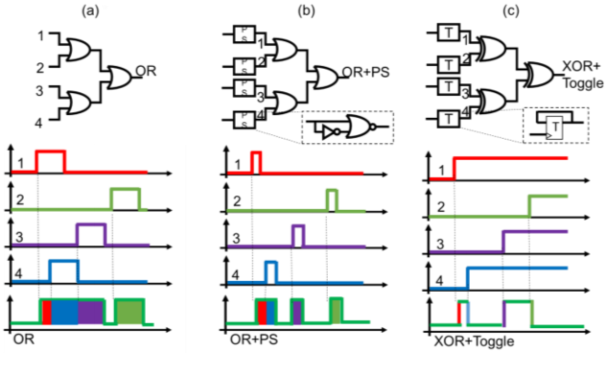

Figure 3. (a) OR Tree (b) OR tree with monostable pulse shaper input (c) XOR Tree with toggle flip-flop input [15].

Figure 4 shows an example optical measurement of OLED pixel flicker with FlashTDC [23]. The measurement is shown as photon counts every 100 µs sampled by the dSiPM. The OLED pixel is implemented as a Source -Follower (SF) structure, as shown in Figure 4 (b). The pixel is addressed at the beginning of a frame, then V_{DATA} is switched to minimum level. The measurement demonstrates that varying the minimum V_{DATA} shows different levels of flicker. A higher minimum V_{DATA} induces less flicker as it reverse biases the SF pixel switch.

Table 1 gives a specification comparison of the dSiPM and a commercially available tool Gray Level Response Time Measurement Kit (based on Hamamatsu H10722-110 PMT) [8].

Table 1. Single point sensor specification comparison between PMT and dSiPM (FlashTDC)

	FlashTDC (this work)	**GLRT [8] (Hamamatsu H10722-110)**
Optical frequency bandwidth	10MS/s (900 M counts/s for XOR tree bandwidth)	DC to 20kHz
Spectral response (nm)	350-900, peak at 480	230-700, peak at 400

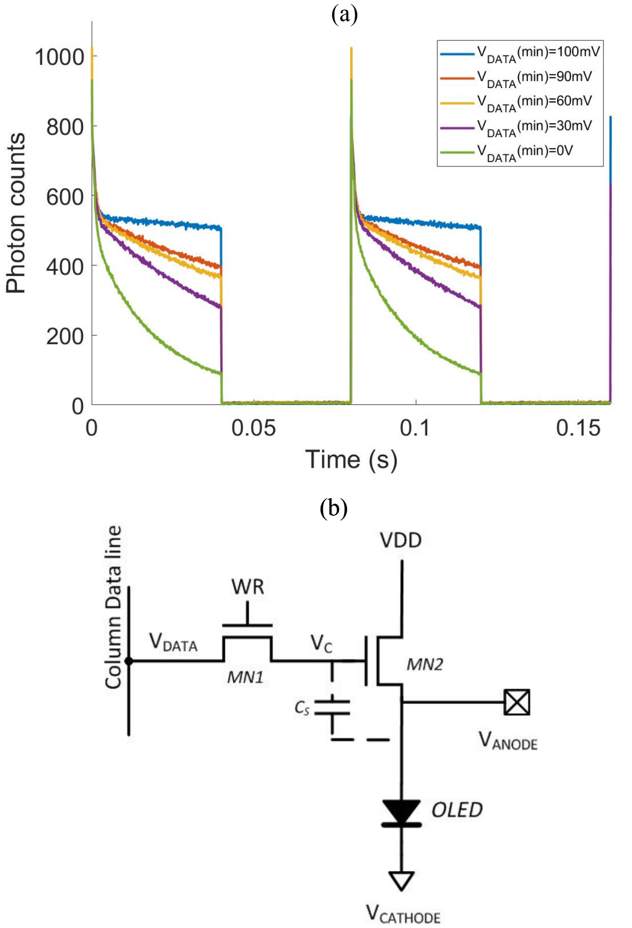

Figure 4. (a) Optical measurement of SF pixel response with FlashTDC with 10 kS/s (b) SF pixel circuit schematic

5. SPAD array as Image sensor

High performance image sensors have been applied for measurements of electronic displays to provide spatial uniformity and temporal motion blur information. CCD, electron multiplying CCD and CMOS are the leading technologies that typically used. The minimum measurement frame time for these traditional technologies is usually in the scale of tens of milliseconds. For displays set at low luminance, there are usually very few photons at millisecond exposure (especially for OLED displays). In this case, the readout noise becomes dominant, degrading the signal to noise ratio. Besides, for measuring electronic displays with digital driving scheme, one display frame is divided into several sub-frames, the pixel is written as 'ON' state or 'OFF' state during each sub-frame. Therefore, the switching behavior in between the sub-frames would affect the display signal level. In this context, a high frame rate camera, operating faster than the minimum display sub-frame time, allows precise detection of the switching behavior.

CMOS SPAD array technology provides a practical solution for electronic display measurement with single photon sensitivity. We employed a binary QVGA SPAD camera (labeled as SPCImager), as an example for display measurement [20]. By optimizing pixel architecture for binary memory and analogue counting, an 8μm pixel pitch and 26.8% filled factor is achieved. With negligible readout noise, single photon sensitivity and high frame rate >10k frame per second for 240 rows, the SPCImager is able to provide accurate measurements at low light intensity. Additionally, the concept of Quanta Image Sensor (QIS), which converts oversampled temporal and/or spatial binary bit-planes into greyscale image frame, would extend the dynamic range of SPCImager [24]. Table 2 gives a specification comparison between existing measurement systems and SPCImager.

Table 2. Image sensor specification comparison SPCImager and existing measurement systems

Measure-ment system	**Image sensor techn-ology**	**Dynamic range**	**Minimum Measure-ment time**
SPCImager	SPAD	4 – 10^7 photon counts/s (approx. 2×10^{-4} – 550 cd/m^2 at 520 nm) for 100ns exposure to 1s exposure, -5C° cooled	5µs including readout for 10×320 of SPAD pixels (10 selected rows)
2-in-1 Imaging Colorimeter [6]	CMOS	0.01 cd/m^2 – 5000 cd/m^2	65 ms at 100 cd/m^2, 330 ms at 1 cd/m^2
Motion Master [5]	CCD	N/A - Detects motion blur (Image difference)	typ. 0.26ms – 0.52ms

6. Summary and Conclusions

We have described in outline the relatively new technology of CMOS SPADS. We have set the capabilities of CMOS SPAD technology in context alongside some existing technologies used in display metrology and concluded that CMOS SPADs can exceed the performance of incumbent technologies in some significant respects such as sampling frequency. We have provided initial demonstrations of CMOS SPAD devices used for both single-point sensing and imaging. We conclude that CMOS SPAD technology can already make a significant contribution to display metrology. Furthermore, there is substantial potential for the contribution of CMOS SPADs to grow in scale and significance through generic improvements in the technology and the custom design of products optimized to address the specific requirements of display metrology.

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