Reduction of Avalanche-Induced Electro-Optical Crosstalk in Clocked-Recharge SPADs

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***Abstract*— In this work, we analyze the physical mechanisms leading to continuous avalanche in clocked-recharge SPAD pixels and their impact on electro-optical crosstalk. Using a 10 µm-pitch SPAD pixel implemented in a stacked 90/40 nm CMOS process, we demonstrate that photons detected during a 5 ns low-impedance recharge phase can lead to an avalanche that persists over the entire recharge interval, resulting in up to 9× higher avalanche charge and therefore proportionally higher photon emission compared to events detected in the high-impedance phase. We further show how afterpulsing in clocked-recharge SPADs can also trigger avalanche-induced emission. Finally, we experimentally validate an operating mode that reduces electro-optical crosstalk by more than 30%.**

Keywords*— *Clocked recharge. SPAD, Continuous avalanche, continuous avalanche, HDR intensity imaging

I. Introduction

Single-Photon Avalanche Diodes (SPADs) are attracting increasing interest for high-dynamic-range (HDR) imaging, especially for extending the dynamic range at the low-light end [1–2]. For SPAD-based systems, the sensor must cover a wide dynamic range, from very low light to high illumination levels. In time-of-flight (ToF) applications, SPADs are typically operated in passive [3] or active recharge mode to enable the construction of multi-target histograms where multiple SPAD pulses are sampled for a single laser pulse. In contrast, HDR imaging can benefit from operating SPADs in a clocked-recharge scheme, which enables deterministic control of avalanche events and therefore low-power operation.

In bright scenes, a SPAD operated in passive recharge can avalanche and then recharge repeatedly throughout the entire integration window, as illustrated in Fig. 1(a). If a photon is received during the recharge phase, the SPAD can avalanche and quench thanks to a sufficiently high quenching resistor, and so long as the output toggles the event can be detected. In clocked-recharge mode, the overall integration time is divided into a sequence of time windows. At most, one avalanche event is allowed per window, and therefore only one recharge operation occurs in each window. However, a photon detected during the recharge phase may cause the SPAD to enter a continuous avalanche state that lasts for the entire recharge time, as shown in Fig. 1(b). This continuous avalanche leads to a large charge flow and therefore intense hot-carrier–induced photon emission [4]. Furthermore, a persistent avalanche during the recharge phase prevents the SPAD from recharging back to its ready state, causing the SPAD output to remain high preventing photon detection.

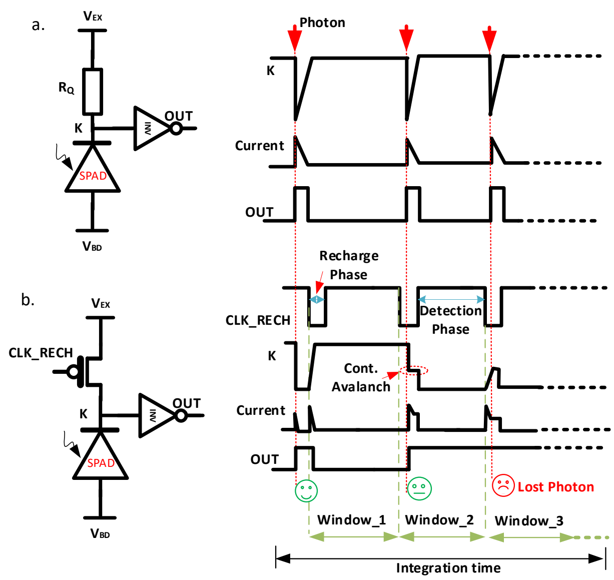

Fig. 1 (a) Passive quenching and recharge operation. (b) Clocked-recharge operation and continuous avalanche

This paper investigates this issue in detail, including: a) the mechanism that leads to continuous avalanche in clocked-recharge SPADs, b) its impact on pixel power consumption and electro-optical crosstalk and c) design and operation strategies that reduce its effects.

II. Clocked-Recharge SPAD Operation and Continuous Avalanche Mechanism

To demonstrate the operation of the clocked-recharge scheme at high ambient light conditions, we designed a mini-array of 4x16 SPAD pixels with deep trench isolation (DTI) in between SPADs to study the effect of continuous avalanche on pixel performance [5]. Fig. 2(a) shows a cross section of one SPAD where its anode is biased at negative high-voltage equal to its breakdown voltage V_{BD}. On the cathode side, the drain of a high-voltage transistor (recharge transistor) is connected, and its source is biased at a variable voltage V_{EX} to provide the required excess bias above its breakdown. The recharge transistor is controlled using a periodic clock signal CLK_RECH, as shown in Fig. 2(b). With a variable pulse width and an amplitude alternating

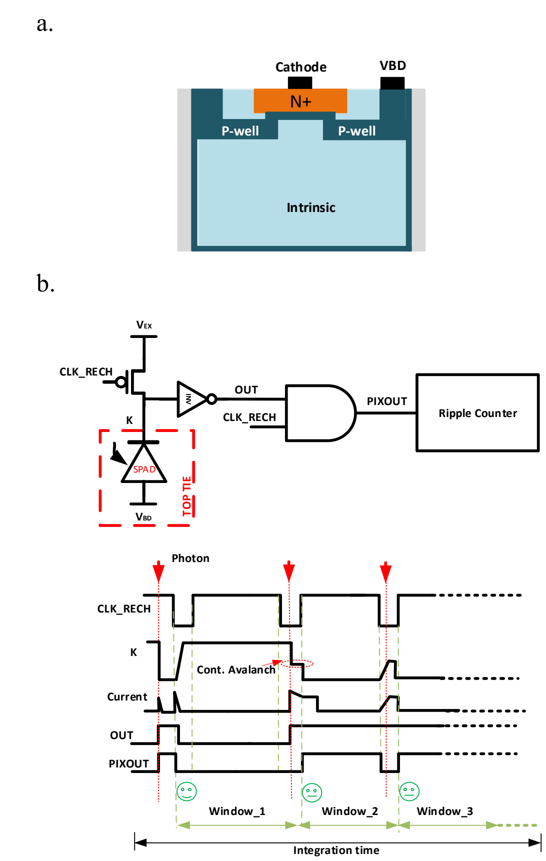

Fig. 2 (a) Cross-section of the pixel. (b) schematic of the 10 µm pitch pixel and its timing diagram

between 0 V and V_{EX}, the SPAD operates in two main phases:

1. **Recharge phase** (CLK_RECH) = Low: The quenching element (high-voltage transistor) presents a low-impedance path. The SPAD recharges from the V_{EX} supply.
2. **Detection phase** (CLK_RECH) = High: The quenching path becomes high impedance. If a photon is detected during this phase, the SPAD junction collapses and the stored charge is discharged through the SPAD to the negative supply V_{BD}. The avalanche is quenched once the charge is removed and the bias falls below breakdown.

Under high illumination, more photons can arrive during the recharge phase. Despite the low-impedance state of the circuit, a photon received during this phase is not lost and can still be detected, but with different behaviour. During the recharge time, the SPAD will not self-quench due to the low-impedance recharge path, leading to continuous avalanche behaviour over the full duration of the recharge pulse. When CLK_RECH goes high, the transistor cuts off the supply and the continuous avalanche discharges the remaining charge, eventually bringing the SPAD below breakdown and quenching the avalanche. If the SPAD cathode is connected to a simple inverter, as in the conventional configuration of Fig. 1, the voltage change at the cathode flips the inverter output to the high state, and a ripple counter increments by one. However, if another photon is received during the next recharge time, the SPAD can again enter continuous avalanche before being fully recharged to ready state and won't have the opportunity to toggle the inverter output. This leads to missed counts in the presence of repeated continuous avalanches. To ensure the digital output toggles whenever a photon is received during the recharge time, an additional logic stage is required. In our implementation, an AND-based scheme is used so that the pixel output toggles reliably whenever a continuous avalanche event occurs during the recharge phase, as illustrated in Fig. 2(b). The only drawback of this implementation is that the effective detection timing is delayed with respect to the avalanche start, which is acceptable for HDR intensity imaging.

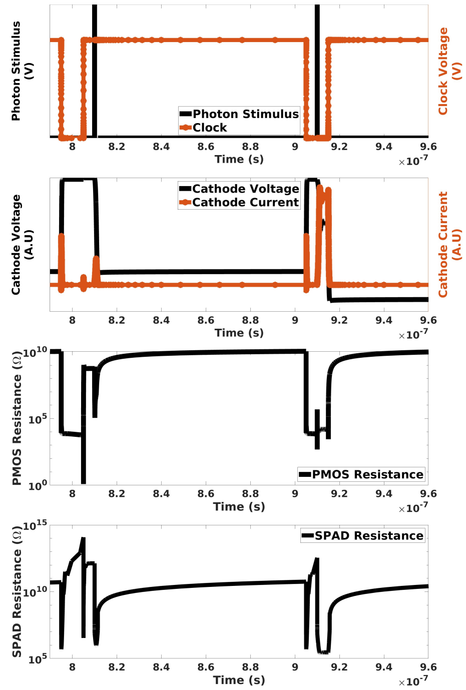

Fig. 3 Simulation results of the circuit under continuous avalanche, illustrating the timing signals, cathode voltage and current, as well as the resistances of the recharge transistor and the SPAD itself.

III. CONTINUOUS AVALANCHE SIMULATIONS

To confirm the transient behaviour of the SPAD when operated in clocked recharge mode, the SPAD is modelled in Verilog-A. This model is designed to match capacitance vs. voltage (C-V) and current vs. voltage (I-V) measured characteristics across a range of temperatures. This ensures a strong correlation between simulation and real-world results. At its core, the model utilizes a standard expression of electric field in a *P-N* junction and uses it to inform Van-Overstraten De Man equations for calculating multiplicative coefficients of the underlying impact ionisation events. These are then iteratively used to solve transient current updates, linking the applied device bias to the current, in conjunction with SPICE-modelled circuitry [6].

Fig. 3 depicts the result of the simulation of a continuous avalanche. As shown, the cathode begins in a low state from a previous cycle and is recharged as CLK_RECH goes low.

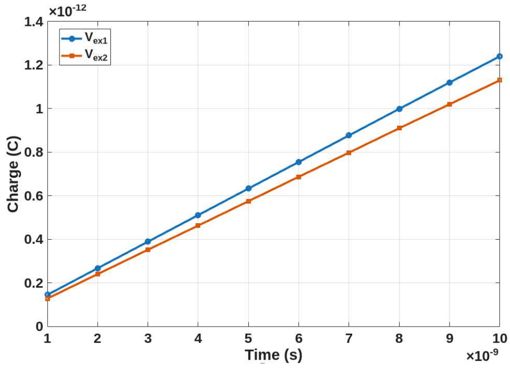

Fig. 4 Extracted charge vs CLK_RECH pulsewidth when a photon is received at the beginning of the recharge phase

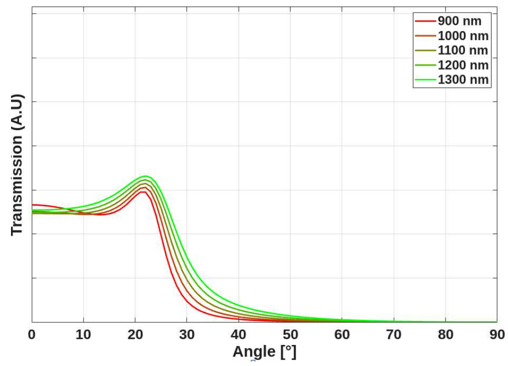

Fig. 5 Simulated transmission through DTI versus incident angle at different wavelengths, illustrating the reduction of direct optical coupling

The SPAD is fully recharged. Later, an incident photon arrives while CLK_RECH is high, discharging the cathode and quenching the SPAD, showcasing normal operation. In the consecutive window, another photon is received but this time when CLK_RECH is low. This leads to the continuous avalanche which can be characterized by the continued high levels of current flowing through the SPAD cathode, only being brought to a halt by CLK_RECH going high allowing the SPAD junction to clear of free carriers. Only once the junction is empty of carriers, can the SPAD undergo a recharge on the following clock cycle, allowing for it to be sensitive to incident photons again. The bottom two graphs explore the effective resistances of both the PMOS as well as the SPAD obtained through implementation of Ohm's Law based on observations of node voltages as well as current flows. Through calculations it is possible to model the intermediate voltage of the cathode during a continuous avalanche by visualizing the circuit as an effective voltage divider, splitting the total applied bias amongst the two resistances, and accurately predicting the node voltage. This result reinforces the idea that following the initial avalanche, the internal SPAD capacitance has collapsed, allowing for the SPAD to be freely modelled as a resistance.

The amount of continuous charge flowing through the SPAD from higher potential supply (V_{EX}) to negative supply (V_{BD}) is quantified as function of recharge time. Fig. 4 shows the simulated extracted avalanche charge as a function of CLK_RECH pulse width when a photon is received at the beginning of the recharge phase. As the pulse width increases, the charge in continuous avalanche mode increases linearly. At a 5 ns recharge time, the total charge is approximately 630 fC, whereas an avalanche occurring during the high-impedance integration time is only about 70 fC at the same excess voltage, i.e. a factor of 9 difference in hot-carrier charge. This ratio can be reduced by decreasing the excess voltage, but at the expense of photon detection efficiency.

IV. Side Effect of Continuous Avalanche

The large amount of continuous avalanche charge per event can be detrimental in terms of power consumption for HDR systems, especially at high illumination levels. Most importantly, a continuous avalanche generates a large number of hot-carriers which significantly increase the probability of photo-emission from the SPAD junction. This enhanced photon emission can induce electro-optical crosstalk in neighbouring SPADs via two main mechanisms: 1) direct optical crosstalk through the silicon bulk, where emitted photons propagate laterally and trigger avalanches in neighbouring pixels and 2) optical crosstalk via reflections and scattering at interfaces, metal layers, or shallow trench isolation, which redirect emitted broadband photon emission in all directions towards adjacent SPADs. As the SPADs are isolated by DTI, the trench structure fully suppresses lateral carrier diffusion and significantly reduces optical coupling, thereby partially mitigating crosstalk. Simulations of DTI transmission show that DTI can reduce direct optical crosstalk for certain angles and wavelengths as illustrated in Fig 5.

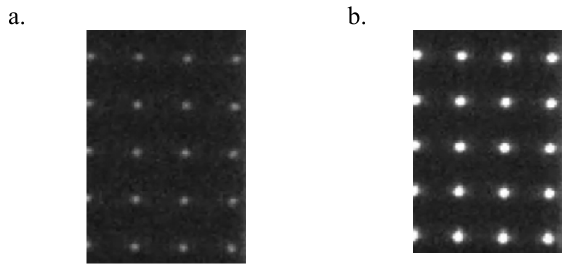

Figure 6 a) Hot-carrier photon emission viewed through a microscope for 2ns recharge pulse duration. b) emission for 15ns recharge pulse duration.

V. Characterization Results

Emission microscopy measurements were performed to assess qualitatively the impact of increasing the recharge duration on hot-carrier photon emission. Fig. 6 shows two NIR pictures of a subset of a SPAD array under operation (clocked at 40 MHz) and stimulated by visible light. Longer recharge duration (15 ns) increases the probability for a photon to hit the SPAD during the low impedance phase and trigger a continuous avalanche, which translates into a more intense photo-emission coming from the SPAD diode.

To further visualize the impact of the photon arrival time with respect to the recharge time, we fired at the SPAD a 70 ps FWHM laser pulse synchronized to the clocked recharge signal (40 MHz, 5 ns pulse width) and varied the delay between both (see Fig. 7). With CLK_RECH running at a 25 ns period, approximately 6.5 ns are used to recharge the SPAD, making the maximum SPAD output pulse width

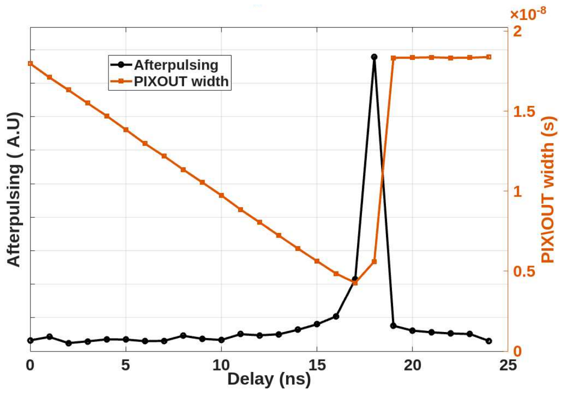

Fig. 7 Afterpulsing probability and average pulse width vs laser pulse synchronization with respect to the recharge cycle (40 MHz, 5 ns recharge)

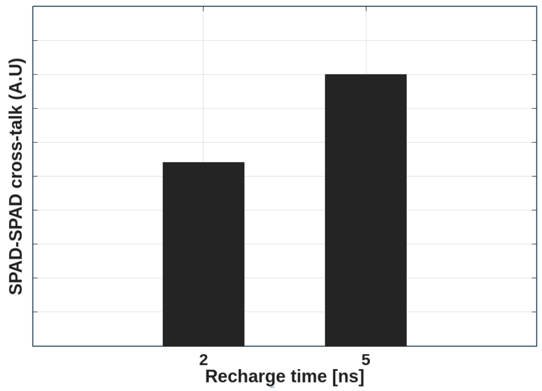

Fig. 8 SPAD-to-SPAD crosstalk probability versus CLK_RECH pulse width

around 18.5 ns. A laser pulse which hits the SPAD during the recharge time and causes a continuous avalanche is detected at the end of the recharge phase when the quench transistor returns to the high impedance state (i.e. with a delay vs the start of the avalanche). All events which occurred during the recharge phase are recorded as pulses with the maximum 18.5 ns duration.

In SPADs operated in clocked-recharge mode, afterpulsing behaves differently compared to SPADs operated in passive recharge. If the laser hits during the recharge or at the beginning of the high-impedance phase, the afterpulsing probability is effectively suppressed to very low levels. Critically, the afterpulsing probability depends strongly on when the photon is received relative to the recharge time. When the laser is synchronized to fire just before the recharge time, the afterpulsing probability increases drastically. In Fig. 7, we see that the afterpulsing probability rises by a large factor when the laser hits the SPAD right before the recharge occurs. In this case, the afterpulse occurs during the subsequent low-impedance phase and triggers a continuous avalanche.

Regardless of the source of the event triggering the continuous avalanche, the enhanced photo-emission tends to increase crosstalk to neighboring pixels. SPAD-to-SPAD crosstalk was quantitatively measured in the SPAD mini-array as a function of recharge pulse duration. When decreasing the recharge pulse duration from 5 ns to 2 ns (out of a 25 ns acquisition period), the measured crosstalk probability decreased by more than 30%, as shown in Fig. 8.

VI. Conclusion

We have analyzed the mechanism of continuous avalanche in clocked-recharge SPAD pixels and its impact on power consumption and electro-optical crosstalk. Using a 10 µm-pitch SPAD implemented in a stacked 90/40 nm CMOS process, we showed through modelling and experiments that photons detected during the low-impedance recharge phase can trigger continuous avalanche events whose duration is set by the recharge pulse width. This leads to a significantly increased avalanche charge and enhanced hot-carrier photon emission. Emission microscopy and array-level measurements further demonstrated that longer recharge durations and unfavorable photon arrival times markedly increase photo-emission, SPAD-to-SPAD crosstalk, and afterpulsing probability. In particular, we showed that afterpulsing becomes significantly more likely when a photon is received close to the recharge edge, where it can trigger a new continuous avalanche during the subsequent low-impedance phase. Finally, we showed that appropriate isolation, together with careful choice of recharge timing, can strongly mitigate these effects. These results are directly relevant to HDR SPAD imagers using clocked-recharge schemes, where minimizing crosstalk and afterpulsing is crucial while preserving high dynamic range and low power consumption.

VII. References

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