2024 International SPAD Sensor Workshop (ISSW2024)

Avalanche build-up field and its impact on the SPAD pulse width and inter-pulse-time distributions.

D. Rideau, R. Helleboid, G. Mugny, I. Nicholson*, A. Bianchi, D. Golanski, B. Mamdy, J-B. Kammerer**, S. Rink** C. Lallement**, B. Rae*, W. Uhring**, S. Pellegrini*, M. Agnew*, E. Lacombe, J.R. Manouvrier, M. Al-Rawhani*.

*STMicroelectronics Crolles, France, *STMicroelectronics Edinburgh, UK, **ICube laboratory, Strasbourg, France.*

***Abstract*— We present an experimental and theoretical study of the simple photon avalanche diode (SPAD), transient, pulse width and inter-pulse-time statistical distributions. We show that both the avalanche build-up (BU) and the incoming light feature statistical behaviors and how they impact the structure of these later figures of merits. Additionally, the avalanche build-up field, inferred from the electrostatic response to the additional impact-ionization charges in the diode junction, can also interfere with the SPAD quench circuit and can be evidenced by means of statistical SPAD 'digital out' measurements and transient on-pixel measurements.**

***Index Terms*— SPAD, Quenching circuit, VerilogA.**

I. INTRODUCTION

The SPAD avalanche is a random dynamical process that affects the overall performance of the pixel, especially in applications with high count rates and low power [1][2]. In [3], we introduced a new technique for measuring on-pixel stochastic transient responses, and using the statistical approach of [2], we modeled the SPAD transient behavior, including the impact of the quench circuit. In this paper, we detail the statistical VerilogA models embedded in [3], the role of the build-up field, as well as the impact of carrier fluctuation in the avalanche region on the main statistical figure of merits (FOM) of the SPAD. Statistical and transient measurements are also presented with a view of supporting the proposed modeling approach.

II. EXPERIMENTAL SETUP

Statistical measurements shown in this paper are obtained using the experimental setup and schematic shown in Figure 1 (and described in [1]), which consists of SPAD pixels connected to a quenching resistance R_Q and capacitance C_Q and a digital output. In a separate, but complementary, series of measurements, we used the direct transient setup transient current and voltage measurement setup described in [3]. Two additional low impedance RF amplifiers are added to allow on-pixel current and voltage transient measurements at the SPAD cathode and anode.

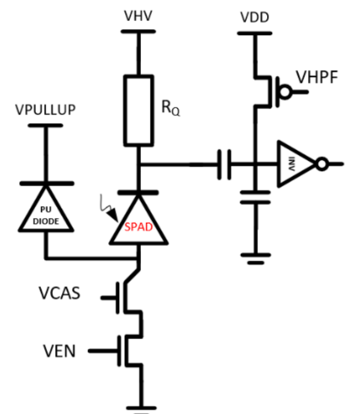

Figure 1: Test Chip of [1] allowing measurements of the digital output of the SPAD. The additional 'VHPF transistor' accelerates the quench dynamics of the transistor.

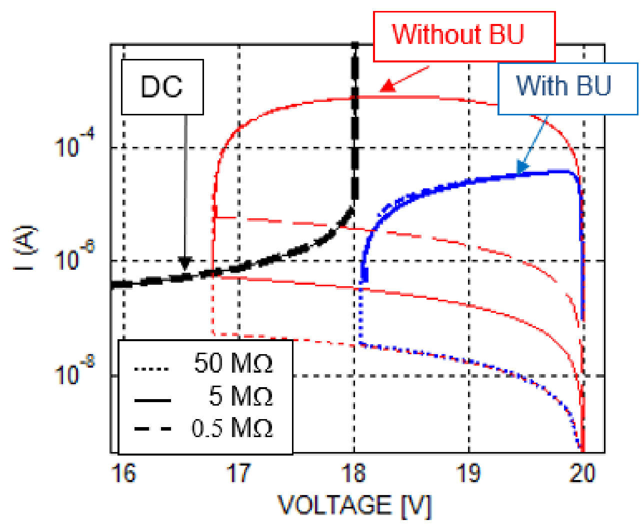

Figure 2: Modeling study of the 'deterministic' transient behaviour of the SPAD for various quench resistors with and without accounting for the internal build-up field correction. Also superimposed, the DC SPAD current (dashed).

III. MODEL

The master equations of the VerilogA model of [2] and [3] are recalled here for convenience. The diode avalanche electrons

* Contact author: Denis Rideau: denis.rideau@st.com

and hole currents I_e and I_h are modeled with two coupled continuity equations:

$\frac{dI_e}{dt} = [M_e.I_e + M_h.I_h - I_e]/\tau_e$, for electrons,

$\frac{dI_h}{dt} = [M_e.I_e + M_h.I_h - I_h]/\tau_h$, for holes. (Eq. 1)

$\tau_{e,h}$ are the transit escape times and $M_{e,h}$ the multiplication factors, where e that stands for electrons and h for holes. The dimensionless coefficients $M_{e,h}$=$\alpha_{e,h}.w_{e,h}$ depend on the effective multiplication width w_e and w_h [2], as well as on the maximum junction field F: $\alpha_{e,h}$=$a_{e,h}$.exp $(-b_{e,h}/F)$. The parameters $a_{e,h}$ and $b_{e,h}$ are taken from the Van Overstraeten-de-Man model [4]. When an electron-hole pair is generated in the SPAD collection area, the electron (or hole) can move towards the avalanche region and produce a Ramo's current $I_0 \stackrel{\text{def}}{=} q.v_s/w$, where v_s is the carriers saturation velocity, q the elementary charge and w an effective width of the depleted region. This can trigger an avalanche and a sudden increase in the total current $I_T(t)$= $I_e(t)$+$I_h(t)$. Eq. 1 is a balance equation between impact ionization carriers $\Delta_{e,h}$= $M_{e,h}.I_{e,h}/I_0$ and number of carriers escaping the depleted region ($n_{e,h} = -I_{e,h}/I_0$) during a time step of $\tau_{e,h}$.

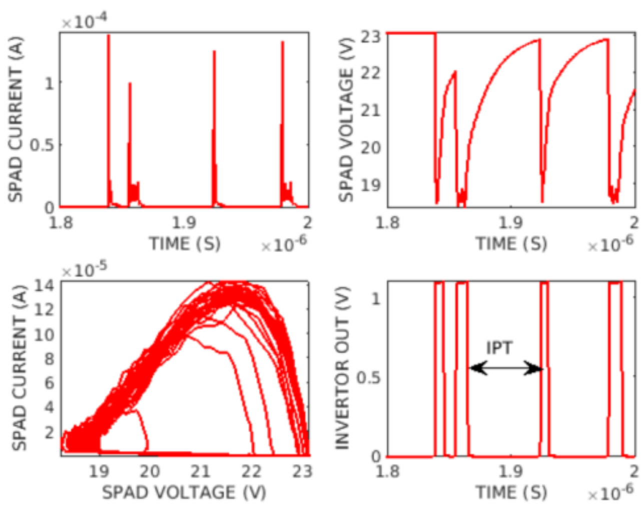

Figure 3: Transient SPAD statistical simulations for a quench resistor of 0.5MΩ. Both intrinsic fluctuation of the impact-ionized carriers and photon arrival time are introduced in the model.

As detailed in [2], F is extracted from well calibrated Technology Computer Assisted Design simulations of the diode biased in reverse regime, with the impact ionization model turned off. The impact of the additional carriers on the junction field is accounted by means of a correction $F \leftarrow F - \gamma n_e$the value of which is adjusted in order to predict as accurately as possible the charge per pulse measurements, the maximum cathode transient swing, but also the overall transient response of the SPAD (see later and in [3]). Figure 2 describes the difference in the diode I-V curves when considering the build-up field correction versus not considering it ($\gamma = 0$). This correction has two effects: a change in the voltage and current swings of the diode, and a potential for non-quenching behavior after an avalanche (in the latter case, only a higher and unrealistic quench resistor would fully recharge the SPAD). As a matter of fact, Eq. 1 alone fails to predict the behavior observed in measurements (the SPAD recharges for quench resistance of 0.5 MΩ). Accounting for the intrinsic stochastic fluctuations [2],[3],[5],[6],[7] of impact-ionization generated carriers in the junction is key. Introducing a small fluctuation of $\Delta_{e,h}$ (using a Poisson distribution) leads to a different behavior as depicted in Figure 3.

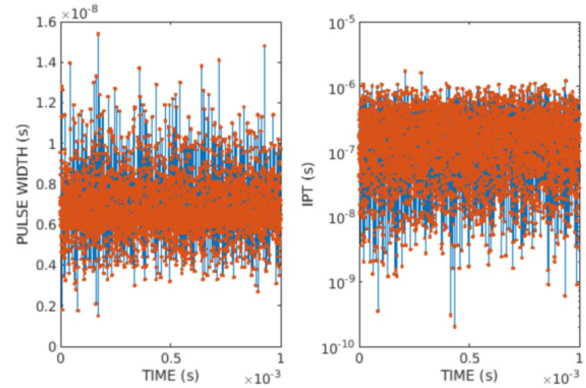

Figure 4: Extracted PW and IPT from a 1ms transient simulation, including SPAD statistical carrier fluctuation as well a laser Poisson photon arrival time.

Current fluctuations are clearly visible as well as slight oscillations of the minimum cathode voltage. As shown later, direct comparison of this behavior is possible with direct transient current and voltage measurement setup described in [3]. Such a direct comparison greatly eases model parameters extraction. In what follows, the strength of the build-up field γ parameter has been adjusted in order to match the model predictions to the observed cathode swings.

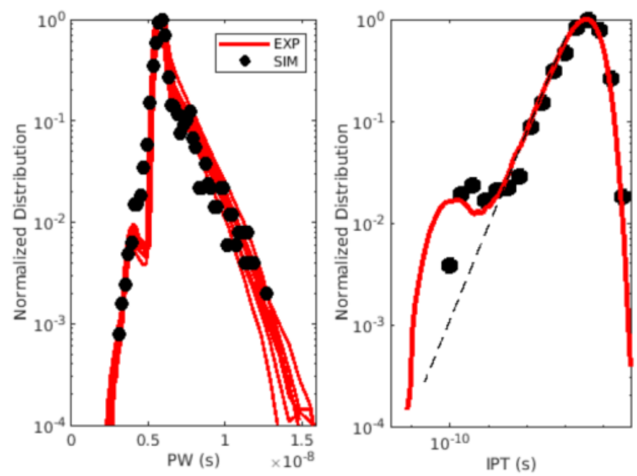

Figure 5: PW (left) and IPT (right) distributions of Figure 4 compared to measurements. Dashed line is a guide for the eyes. Quench resistor of 0.5MΩ.

The avalanche is initiated by a single carrier current I_0, the frequency of which depends on the photon arrival time. To further compare model predictions with measurements, we added a Poisson laser source model. This later model is mandatory for IPT simulations.

III. MEASUREMENTS

The invertor out pulses width (PW) as well as the inter pulse time (IPT) (see Figure 3) are shown in Figure 4 and a significant dispersion is observed. From these quantities, statistical distribution can be extracted and compared to 'digital out' measurements. The PW and IPT statistical distributions compare favorably with the measurements, as testified by Figure 5. The present model prediction are compared to the direct transient measurements form [3]. As can be seen in Figure 7, the model exhibits statistical features that compare favorably with the measured transient cathode voltage swing ones. A similar overall good agreement between model predictions and direct transient measurement is also shown for the I-V curves in Figure 7.

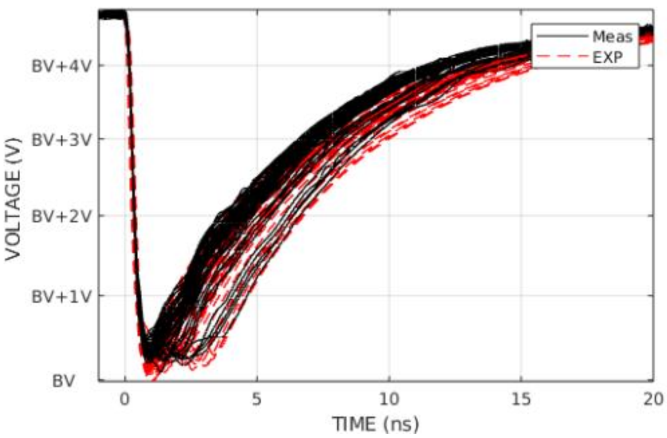

Figure 6: Transient SPAD catode voltage swing with statistical simulations and direct transient measurements. Quench resistor of 0.5MΩ.

CONCLUSION

A photon avalanche diode VerilogA model allowing transient, pulse width and inter-pulse-time statistical simulations is presented. Combining statistical PW and IPT distributions to direct on-pixel current and voltage transient measurements enables comprehensive validation of the present statistical SPAD models. It also significantly eases the model parameters extraction, giving access to extended cross validation between various FOM, e.g PW distribution and transient cathode measurements.

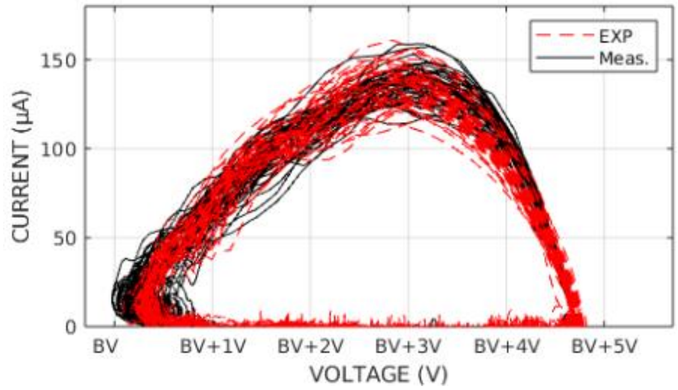

Figure 7: Transient SPAD I-V statistical simulations and direct transient measurements. Quench resistor of 0.5MΩ.

REFERENCES

[1] B. Mamdy, et al, "A high PDE and high maximum count rate and low power consumption 3D-stacked SPAD device for Lidar applications" International Image Sensor Workshop (IISW), 2023.

[2] Y. Oussaiti, et al. "Verilog-A model for avalanche dynamics and quenching in Single-Photon Avalanche Diodes", 2020 International Conference on Simulation of Semiconductor Processes and Devices (SISPAD), 2020.

[3] D. Rideau, et al, "Direct Measurements and Modeling of Avalanche Dynamics and Quenching in SPADs", IEEE 53rd European Solid-State Device Research Conference (ESSDERC), 2023.

[4] R. van Overstraeten and H. de Man, "Measurement of the Ionization Rates in Diffused Silicon p-n Junctions," Solid-State Electronics, vol. 13, no. 1, pp. 583–608, 1970.

[5] D. Rideau, et al. "Single Photon Avalanche Diode with Monte Carlo Simulations: PDE, Jitter and Quench Probability", 2021 International Conference on Simulation of Semiconductor Processes and Devices (SISPAD), 2021.

[6] Rémi Helleboid, et al. "A Fokker–Planck-based Monte Carlo method for electronic transport and avalanche simulation in single-photon avalanche diodes", J. Phys. D: Appl. Phys. 55 505102, 2022.

[7] Sara Pellegrini, et al. "Simulation in action: the application of modelling to SPAD architecture design", IEEE International Electron Devices Meeting (IEDM), 2023.