Silicon PhotoMultiplier SPICE Modeling and Circuits

Federica Villa, Orazio Pennisi, Giovanni Montagnani, Yu Zou, Rudi Lussana, Alberto Tosi, and Franco Zappa

Politecnico di Milano, Diprtimento Elettronica, Informazione e Bioingegneria, P. Leonardo da Vinci 32, I-20133 Milano, Italy

federica.villa@polimi.it

We present a comprehensive electrical SPICE model for Silicon Photomultipliers (SiPMs) based on a microcell able to accurately simulate avalanche current build-up and self-quenching within this Single-Photon Avalanche Diode (SPAD) "pixel" [1] with its own series-connected quenching resistor. The entire SiPM is modelled either as an array of many microcells, each one individually triggered by independent incoming photons, or as two macrocells, one with all microcells firing concurrently while the other one with all quiescent microcells; the most suitable approach depends on the light excitation conditions and on the dimension (i.e. number of microcells) of the overall SiPM. We validated both models by studying the behaviour of various SiPMs in different operating conditions, in order to investigate the effect of photons pile-up, the deterministic and statistical mismatches between microcells, the impact of the number of firing microcells vs. the total one, and the role of different microcell parameters on the overall SiPM performance. We also designed and characterized different SiPM front-end circuits for photon-counting and photon-timing applications.

Fig. 1 (left) shows the perfect match between the measured signal of a 20 × 20 Excelitas SiPM (1 mm^2) connected to a transimpedance Current Feedback Amplifier (CFA) and the SPICE simulation with our SiPM model. The fast rising edge is due to the stray capacitance in parallel to the quenching resistance [2], which introduces a zero in the transfer function, but it is smoothed by the 30 MHz CFA bandwidth (note that the theoretical peak value is not reached because of the low-pass filtering effect of the CFA). The falling edge is characterized by a fast decay theoretically given by $\tau_f \approx (C_D+C_Q)\cdot R_D$ = 376 ps, but still limited by the CFA and a slow tail dominated by the SiPM time constant $\tau_s \approx (C_D+C_Q)\cdot R_Q$ = 81.6 ns (the figure doesn't show the entire decay), where C_D = 50 fF (detector capacitance), C_Q = 18 fF (quenching capacitance), R_D = 400 Ω (detector resistance) and R_Q = 1.2 MΩ (quenching resistance). Fig. 1 (centre) shows the photoelectron spectrum of the same 20 × 20 Excelitas SiPM and transimpedance CFA, acquired after a fast peak-stretcher through the Analog-to-Digital Converter (ADC) of a microcontroller (STM32 by STMicroelectronics). The simulated photoelectron spectrum matches the measured one, when considering 2% tolerance on the quenching resistances and 0.5% on breakdown voltages of the SiPM microcells. Finally Fig. 1 (right) shows the Single Photon Time Resolution (SPTR) of the 20 × 20 Excelitas SiPM connected to a Time-to-Digital Converter (TDC) timing board [3]; at 7 V excess bias the SPTR is as low as 160 ps Full Width at Half Maximum (FWHM), thanks to the presence of the quenching capacitance in the SiPM and to the low jitter front-end circuit and low-threshold comparator.

The proposed models can benefit both SiPM application users, for designing the best readout electronics, and also SiPM device designers, for assessing the impact of each parameter on the overall detection performance and electrical behaviour. Eventually, we developed a compact board that integrates all the SiPM circuitry for sensing, counting, and timing photons and an user interface manages all system parameters (SiPM excess bias, transimpedance amplifier gain, comparator threshold, etc.). This system allows to measure the SiPM photoelectron spectrum, to obtain a SPTR even better than 160 ps, and can be used as a versatile demo-board for characterization and comparison of different SiPMs at different operating conditions.

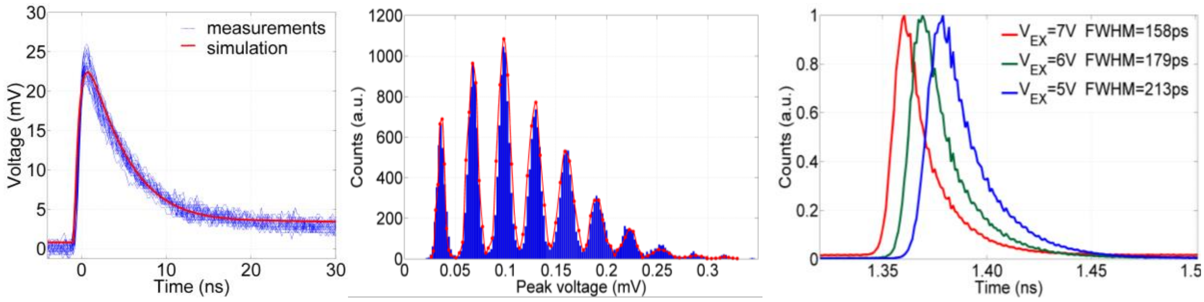

Fig. 1. Measured and simulated single-photon response (left) and photoelectron spectrum at an average flux of 3 photons per pulse (centre) of a 20 × 20 Excelitas SiPM connected to a trans-impedance CFA and its single photon time resolution (right).

References

[1] F. Zappa, A. Tosi, A, Dalla Mora, S. Tisa, "SPICE modeling of single photon avalanche diodes", *Sensors and Actuators A Physical*, Vol. 153, no. 2, pp. 197-204, 2009.

[2] F. Acerbi, M. Cazzanelli, A. Ferri, A. Gola, et al., "High Detection Efficiency and Time Resolution Integrated-Passive-Quenched Single-Photon Avalanche Diodes," *IEEE Journal of Selected Topics in Quantum Electronics*, vol.20, no.6, pp. 268-275, 2014.

[3] D. Tamborini, D. Portaluppi, F. Villa, S. Tisa, A. Tosi, "Multichannel low power time-to-digital converter card with 21 ps precision and full scale range up to 10 µs," *Review of Scientific Instruments*, Vol. 85, no. 11, 114703, 2014.