Integrated Simulator for Single Photon Avalanche Diodes

Michele Anti, Fabio Acerbi, Alberto Tosi, Franco Zappa
Dipartimento di Elettronica e Informazione - Politecnico di Milano
Piazza Leonardo Da Vinci 32, Milano, Italy
anti@elet.polimi.it

Abstract—**We present a new mono-dimensional device simulator optimized for the behavioral inspection and design of single-photon avalanche diodes (SPAD). The particular operating conditions in which these pn junctions are used, reverse biased above the breakdown voltage, lead to a non-univocal I-V characteristic and a non-stationary behavior, which is difficult to simulate with commercial products. For this reason we developed a complete integrated simulation environment for investigating SPAD performances. At present we have included simulations of electric field, breakdown, Dark Count Rate and afterpulsing, while the modularity of the simulator can ensure great expandability.**

Keywords- SPAD; CAD; Device simulator; Photodetectors; FEM

I. INTRODUCTION

Simulation of semiconductor devices is a fundamental step during both the design process and the test phase of new devices. Many device simulators are commercially available, but they are not suitable for SPADs because they can make only two types of electrical simulations, (quasi-)stationary and transient simulations, which are not efficient for SPAD analysis.

SPADs are pn junctions reverse biased above breakdown, thus triggering an avalanche pulse with a finite probability every time a carrier is generated, either by the absorption of a photon or by noise (either thermal or field assisted generation). After the avalanche pulse is detected by the front-end electronics, the avalanche is quenched by biasing the SPAD below breakdown. After a hold-off T_{OFF} period (necessary to limit the afterpulsing effect) the front end electronics reset the SPAD by biasing again the device above breakdown. Since the device changes completely the operating conditions (from ON to OFF), its response is time-dependent and stationary simulations cannot be used to analyze it. Signal and noise in SPADs are represented by the number of avalanches triggered respectively by absorbed photons or by other generation processes. However, only carriers generated within the high-field volume (i.e. the active area volume) contribute to Dark Count Rate, while carriers generated outside the active area give the peripheral leakage currents because they do not trigger any avalanche. It is important to separate these contributions by calculating the trigger efficiency, which is usually not included in commercial tools, in order to calculate important SPAD parameters such as Dark Count Rate, afterpulsing probability and detection efficiency. To this aim we include in the proposed SPAD simulator models of breakdown, detection efficiency and noise described in literature with new afterpulsing models in a single mono-dimensional integrated simulation environment, which we believe is a valuable tool to evaluate SPAD performances and to design new devices.

II. WORKING PRINCIPLE

Figure 1 shows the complete I-V characteristic of a SPAD. The current-voltage relation is divided into three branches, which we respectively modeled with three independent states of a state machine. This approach allows to apply stationary equations to each one of the states, and to performe time-invariant simulations of SPAD performances. Furthermore, equations can be tailored for every state, saving computational effort.

The three states are called ‘ON’, ‘AV’, ’OFF’. The ON state models the device when it is biased above breakdown before the generation of any carrier. When a carrier is generated inside the active volume, it can either trigger or not an avalanche pulse. If it does, the state machine moves to AV (meaning “avalanche”), otherwise it remains in the ON state. From the AV state, the quenching electronics forces the device to the OFF state, while a reset electronics biases again the SPAD above breakdown in the ON state after a period T_{OFF} from the quenching time. Intensity of the avalanche pulse and timings of the last two states depends on operating conditions and can be settled inside our simulator.

We implemented the simulator in MATLAB using a graphical user interface (GUI) and the finite element method (FEM). The GUI is composed by three main parts. In the first, it is possible to setup the device structure, selecting different materials, geometries and dopings. In the second one, it is possible to setup some physical parameters (such as ionization coefficients or deep energy levels decay times) and to run different simulations. Finally, the third part includes a plot where results are shown.

At the beginning of every simulation, the software creates the vector of elements that composes the device and assigns to each of them the values of the physical parameters required by the particular simulation. Drift-diffusion equations are solved over the simulation domain in order to compute electric fields. Thereafter it is possible to simulate different quantities, such as trigger efficiency, Dark Count Rate and others.

978-1-61284-878-5/11/$26.00 ©2011 IEEE

To ensure the maximum compatibility of the software with virtually every material used to fabricate the SPAD, we included the possibility to define physical parameters of new materials in addition basic ones, such as Silicon, InGaAs and InP.

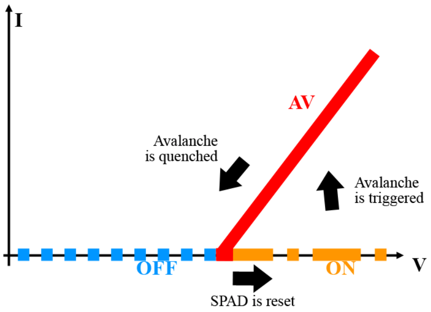

Figure 1 Complete current-voltage characteristic of a reverse-biased pn junction. The knee is at the breakdown voltage.

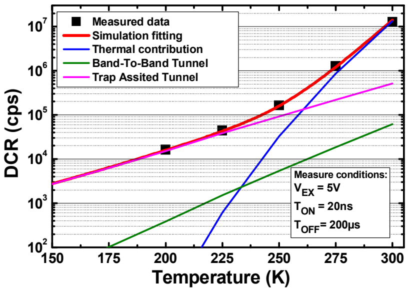

Figure 2 Measured and simulated primary Dark Count Rates of a commercial device. It is possible to separate tunnel contributions from thermal contributions.

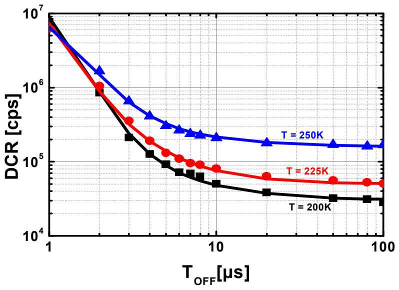

Figure 3 DCR enhancement due to afterpulsing at low T_{OFF}. Symbols are measured data, lines are fittings.

III. MODELS AND SIMULATIONS

Breakdown voltage is calculated evaluating the ionization integral [1] and ionization coefficients are used also to compute the trigger efficiency [2]. Absorption efficiency is modeled calculating the absorption coefficient of every element and integrating the results over the whole device. Noise carrier generation is simulated as the sum of different contributions such as thermal generation [3] and tunnel generation, which is composed by both direct band-to-band tunneling [1] and tunneling through defect states in the bandgap (also called trap-assisted tunneling) [4]. The Dark Count Rate is calculated multiplying the noise carrier generation by the trigger efficiency, which depends on the position inside the active volume. The measured total DCR can be increased by the so-called afterpulsing effect, which model [5] implement different types of operating conditions, both free-running and gated-mode operations.

We used the SPAD simulator to fit measurements acquired on a commercial InGaAs/InP SPAD [6]. Figure 2 reports measured Dark Count Rates at different temperatures and Figure 3 shows the DCR enhancement due to afterpulsing at small hold-off (T_{OFF}) periods. Both figures show also the predictions of the simulator. The agreement is good. In fact, physical parameters extracted from these simulations have been used to compute two different SPAD performance indicators, reported in Figure 4, such as DCR and minimum T_{OFF} to keep afterpulsing below 1% at different multiplication region thicknesses as an example of different simulations that can be performed with our software.

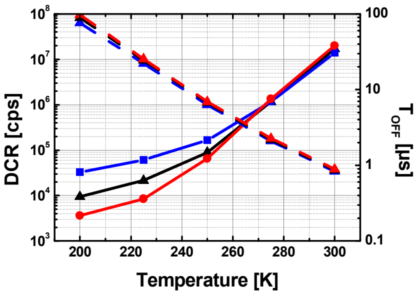

Figure 4 A simulation of primary DCR (solid lines) and minimum T_{OFF} (dashed lines) to keep afterpulsing below 1% for three different multiplication layer thicknesses in InGaAs/InP SPAD.

IV. CONCLUSIONS

The reported Single-Photon Avalanche Diode integrated simulator has been designed to be highly modular and expandable. Using a FEM approach, we are able to implement every partial differential equation and compute SPAD performances like breakdown, detection efficiency, noise etc. and their dependencies on parameters like temperature, excess bias, T_{ON}, T_{OFF}, etc. When possible, we also compared results of our tool with commercial simulators and we verified the reliability of our software.

REFERENCES

[1] S. M. Sze, Physics of Semiconductor Devices, New York: Wiley, 1969.

[2] W. G. Oldham, R. R. Samuelson, P. Antognetti, "Triggering phenomena in Avalanche Diodes", IEEE Transactions on electron devices, vol. 19 no. 9, pp. 1056–1060, September 1972.

[3] W. Shockley, W.T. Read Jr., "Statistics of the recombination of Holes and Electrons", Physical Review, vol. 87 no. 5, pp. 835-842, September 1952.

[4] N. Tabatabaie, G.E. Stillman, R. Chin, P.D. Dapkus, "Tunneling in the reverse dark current of GaAlAsSb avalanche photodiodes", Appl. Phys. Lett., vol. 40, no. 5, pp 415-417, March 1982.

[5] M. Anti, A. Tosi, F. Acerbi, F. Zappa, "Modeling of afterpulsing in Single-Photon Avalanche Diodes", Proceedings of SPIE PW2011, in press.

[6] M. A. Itzler, R. Ben-Michael, C. F. HSU, K. Slomkowski, A. Tosi, et al., "Single Photon Avalanche Diodes (SPADs) for 1.5 μm photon counting applications. Journal of Modern Optics vo. 54 n. 2, 2007