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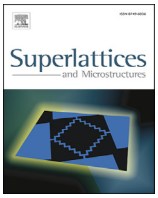

An accurate behavioral model for single-photon avalanche diode statistical performance simulation

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ABSTRACT

An accurate behavioral model is presented to simulate important statistical performance of single-photon avalanche diodes (SPADs), such as dark count and after-pulsing noise. The derived simulation model takes into account all important generation mechanisms of the two kinds of noise. For the first time, thermal agitation, trap-assisted tunneling and band-to-band tunneling mechanisms are simultaneously incorporated in the simulation model to evaluate dark count behavior of SPADs fabricated in deep sub-micron CMOS technology. Meanwhile, a complete carrier trapping and de-trapping process is considered in after-pulsing model and a simple analytical expression is derived to estimate after-pulsing probability. In particular, the key model parameters of avalanche triggering probability and electric field dependence of excess bias voltage are extracted from Geiger-mode TCAD simulation and this behavioral simulation model doesn't include any empirical parameters. The developed SPAD model is implemented in Verilog-A behavioral hardware description language and successfully operated on commercial Cadence Spectre simulator, showing good universality and compatibility. The model simulation results are in a good accordance with the test data, validating high simulation accuracy.

1. Introduction

In the past two decades, single-photon avalanche diode (SPAD) detectors have been attracted in diverse application areas, for instance high-resolution 3D imaging, molecular imaging and spectroscopy, quantum information processing and so on [1,2]. Presently, the SPAD detectors are highly developing towards monolithic integrated high-density imagers fabricated in standard deep sub-micron (DSM) CMOS technology with high resolution, small size and low cost [2–4]. Geiger-mode SPADs operating at reverse excess biases have a high electric field in the avalanche multiplication region, thus only a carrier generation due to photon absorption or thermal and tunneling excitation may trigger a self-sustaining avalanche pulse. Subsequently, the avalanche current must be quickly quenched and the SPAD device needs return to excess bias state for successive single photon detection. Therefore, the on-chip integrated front-end electronics including quench, recharging, readout and interface electrical circuits, are needed in SPAD detectors [5–8]. In order to accurately emulate the avalanche

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quenching and recharging process in circuit design stage, a SPAD simulation model is needed to describe its behaviors. Note that besides basic static and dynamic properties, SPADs also suffer from dark count and after-pulsing noise, which seriously affect the performance of SPAD detectors. Accordingly, the statistical phenomenon of dark counts and after-pulsing should be also included in the SPAD simulation model.

The early simple SPAD simulation models cannot provide sufficient simulation precision. Afterwards, F. Zappa et al. presented an accurate SPICE simulation model, which can emulate fast avalanche current build-up, self-sustaining charge-multiplication and self-quenching process [9,10]. At the same time, Mita R et al. applied Verilog-A hardware description language (HDL) to describe the static and dynamic behaviors of SPADs, avoiding convergence problem in SPICE model [11]. But these presented models cannot simulate important statistical behaviors like dark count and after-pulsing noise. For this purpose, G. Giustolisi et al. put forward a behavioral model to predict the statistical events of turn-off probability, dark-count and after-pulsing [12]. Nevertheless, this simulation model only considers thermal dependence of dark counts, and the influence of electric field related tunneling effect is ignored. Lately, a comprehensive and accurate SPAD simulation model was proposed [13]. The band-to-band tunneling effect and temporal dependence of after-pulsing probability are considered in this model. However, the trap-assisted tunneling mechanism cannot be taken into account although it has become the most common origin of dark counts for DSM CMOS SPADs. On the other hand, in the secondary dark noise (afterpulsing) modeling, the carrier capture and release process are not fully considered and more artificially defined parameters are introduced. Particularly, the used key parameters, for instance avalanche triggering probability comes from empirical formula, which may lower the accuracy of model simulation.

This paper presents an accurate behavioral simulation model to emulate key statistical noise of dark counts and after-pulsing for DSM CMOS SPADs. Various generation mechanisms are completely included in this simulation model and the analytical equations are derived to accurately predict dark count and after-pulsing noise. Most importantly, the key model parameters such as avalanche triggering probability and electric field are directly extracted from Geiger-mode TCAD simulation. As a result, the model simulation accuracy is significantly improved. The simulation model is implemented in Verilog-A codes, featuring good universality and compatibility. Thus, it is very suitable for designers to perform SPAD circuit simulation and optimization.

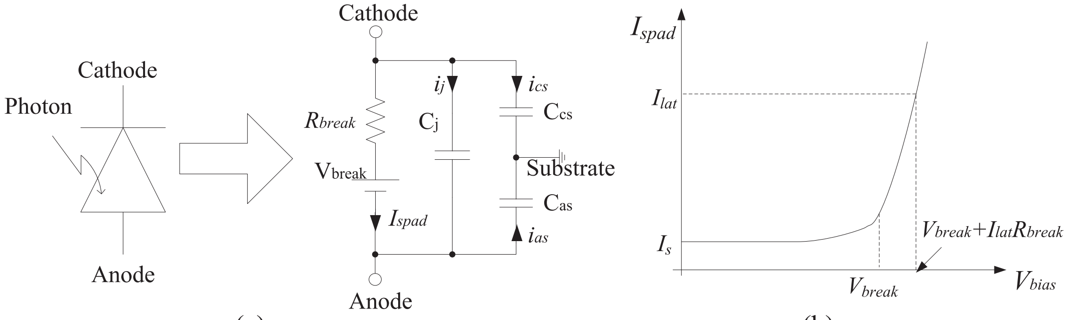
2. Behavioral modeling of statistical performance

2.1. Basic model structure

Fig. 1(a) shows a basic structure of SPAD simulation model, consisting of a static DC branch and a dynamic AC branch [11–13]. When the SPAD device is reversely biased above breakdown voltage (V_{break}) and a photon is accident on the SPAD depletion region at this moment, a large avalanche current (I_{SPAD}) may flow through the SPAD depletion region and then the SPAD can quickly turn on with series resistance R_{break}. Two capacitive effects are used for AC behavior modeling, including two constant stray capacitances C_{cs} and C_{as}, and a voltage dependence of depletion region capacitance C_j.

The static DC I–V characteristic is shown in Fig. 1(b), which is represented by an approximate linear piecewise function. It is worth noting that, when the reverse bias voltage across the diode is close to V_{break}, it is difficult to converge in the DC simulation. Therefore, a fully differentiable pseudo-min/max function is applied to solve this converge problem. The DC avalanche current is established as following [11–13].

$$I_{spad} = I_s + \frac{V_n}{R_{break}} \ln\left(1 + e^{\frac{V_{ex}}{V_n}}\right). \tag{1}$$



(a) (b)

Fig. 1. SPAD model: (a) basic model structure; (b) *I-V* curve.

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