Inverse doping profile extraction for predictive SPAD modeling

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Abstract—**Predictive models are pivotal tools for the development of new SPADs. To verify the effectiveness of such models, the generated results must be compared with experimental data on large set of SPADs. In doing so, a precise knowledge of the doping profile along the detector active region is mandatory, being physical processes involved in SPADs' operation generally strongly dependent on the electric field. Unfortunately, widely-adopted profiling techniques do not provide an accuracy sufficient for predictive SPAD modeling. To cope with this limitation, we developed an inverse method that, by means of electrical simulations and capacitance-voltage measurements, is able to refine approximated doping profiles. We used this method to calculate the breakdown voltages of multiple SPADs. Simulated results closely matching the experimental data provide us a convincing validation of the proposed technique.**

Index Terms—**Breakdown voltage simulation, Doping profile extraction, Inverse modeling, Single Photon Avalanche Diode (SPAD), SPAD modeling**

I. Introduction

Single Photon Avalanche Diodes (SPADs) are solid-state devices able to detect the arrival of a single photon. While different semiconductor materials can be used to fabricate SPADs, silicon is still the material of choice for operating in the visible and near-infrared (up to 1000 nm). Impressive improvements in the main silicon SPAD metrics (like detection efficiency, dark count rate, timing jitter, etc.) have been achieved in the last decade thanks to the adoption of innovative structures and clever designs; however, applications like quantum information processing, non-line-of-sight imaging, or single molecule spectroscopy demand for additional advancements.

In the evolution of SPAD technology an important role is played by the availability of models able to accurately predict detectors performance. To develop models which are ever more reliable, extensive comparisons of simulated results against experimental data are necessary. To this aim, the electric field along the measured SPADs must be calculated starting from the doping profile. Unfortunately, widely-adopted doping-profiling techniques are not accurate enough to cope with the exponential-like dependence of SPAD properties on the electric field.

In this paper we will present an inverse modeling technique aimed at overcoming this limitation. Through to the combined use of device simulations and capacitance-vs-voltage (C-V) measurements, the technique allows us to refine the approximated doping profiles obtained by conventional extraction methods to a level sufficient to accurately predict SPADs properties.

II. Conventional doping profiling techniques

In this section we will briefly discuss the solutions which are usually adopted to attain the doping profile along a silicon device and we will outline the main reasons why they are not sufficient for SPAD modeling.

A first option is to use a process simulator, i.e. a software that simulates the device fabrication flow. This solution is relatively fast and cheap, but is affected by the limited accuracy of simulation models and by non-idealities and non-uniformities that characterize real fabrication processes. Therefore, process simulation must be complemented with other techniques.

The gold standard for measuring doing profiles in semiconductor devices is Secondary Ion Mass Spectroscopy (SIMS). This technique presents numerous advantages, including high depth resolution and an excellent dynamic range. However, its limited sensitivity at medium-low doping concentrations, typical of the multiplication regions, makes SIMS not completely suitable for SPAD modeling. Moreover, SIMS is destructive and expensive, which makes extensive characterization activity challenging.

An affordable and non-destructive alternative is capacitance-vs-voltage (C-V) profiling. Given its sensitivity to medium-low doping concentrations, C-V profiling represents an ideal candidate to refine the results obtained with either SIMS or process
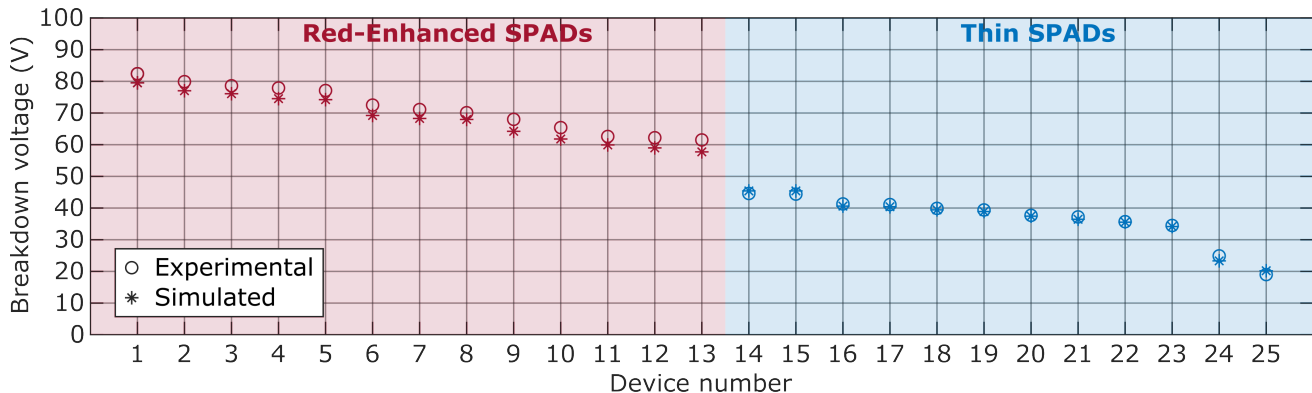
Fig. 1: Comparison between experimental and simulated breakdown voltage for multiple thin and red-enhanced SPADs with different doping profiles.

simulations. However, C-V profiling has its own limitations. For example, the method returns the doping concentration as a function of the space charge width rather than as a function of the distance from the silicon surface; this requires a shift of the results of an amount which is not precisely known. Also, doping profiles significantly different from the actual ones could be extracted if certain hypotheses are not satisfied. Some of such hypotheses, like negligible edge effects and a Debye length much smaller than the desired spatial resolution, are generally not satisfied in real SPADs structures. For these reasons, C-V profiling is potentially very interesting, but it can be rarely used to directly extract the doping profile in a SPAD.

III. Inverse doping profiling

We developed an inverse modeling scheme which allows us to benefit of the advantages of C-V profiling while overcoming its limitations.

Using a commercial TCAD software we build a numerical model of the detector under test. The initial, approximate, doping profile is obtained either from process simulations or SIMS analyses. Then, using the same TCAD software, we simulate the C-V curve of such a device and we compare it with its experimental counterpart. Assuming that any difference between the two curves indicates a mismatch between the doping profile in the model and in the real device, we iteratively adjust the first profile until the simulated C-V curve matches the experimental data. Notably, such an inverse approach is not affected by the limitations of the direct C-V extraction because non-idealities, such as edge effects and carriers diffusion, are fully accounted for in the TCAD simulator.

IV. Validation

To provide a validation of the proposed extraction technique, we applied the method to a large variety of SPADs with different internal structures and different doping profiles. Then, we used the extracted doping profiles to calculate the breakdown voltages of the measured devices. In particular, we resorted to McIntyre relations [1] and Okuto Crowell non-local ionization

coefficients [2], as outlined in [3]. Fig. 1 reports a comparison between the experimental and simulated results.

Despite the large span of considered breakdown voltages ($\approx$ 18 - 84 V), a close matching between simulated and experimental data was obtained for both the categories of SPADs examined, i.e. thin [4] and red-enhanced SPADs [5]. Remarkably, such a good agreement have been attained using the original ionization coefficients proposed by Okuto and Crowell, with no need of additional parameters tuning.

Given the strong sensitivity of the breakdown voltage to the electric field, these results represent a convincing validation of the proposed method. By improving the accuracy of the extracted doping profile, we believe that this technique can enable the development of better SPAD models and eventually lead to the design of detectors with higher performance.

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