Electro-Optical Simulation and Characterization of DCR and secondary emission in SPADs

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***Abstract*—We demonstrate the use of simulations in the modeling and characterization of important aspects of Single Photon Avalanche Detectors (SPADs). Electrically, we discuss the use of drift-diffusion and avalanche triggering probability solvers and results for dark count rate (DCR) and their comparison to measurements. Optically, we discuss the use of full wave electromagnetic solvers to simulate the transmission function for secondary emission photons that cause crosstalk. Combined with optical measurements, we demonstrate how to calculate the avalanche photon production spectrum.**

Keywords—photodiode, photodetector, avalanche, single photon, optoelectronics

I. Introduction

SPADs are photodetectors based on avalanche and biased above breakdown due to which they exhibit large multiplication gains leading to low-level light detection down to a single photon. They can operate at room temperature, and find applications in areas such as medical imaging, terrain mapping, LiDAR, high energy physics experiments, and are considered for quantum photonic computing. Here we present the simulation methodology and results, as well as measurements for both the electrical and optical characteristics of SPADs. Using drift-diffusion and avalanche triggering probability solvers, we simulate DCR including all relevant thermal generation mechanisms and compare it to measurements. Based on full wave electromagnetic simulations, we show how to simulate the transmission function from the secondary photon source inside a SPAD to the microscope objective and combine this with measurements to extract the avalanche photon production spectrum. We then show how to scale the simulated far-field power to obtain the true angle resolved secondary emission.

II. The Electrical Simulation of the DCR

The DCR simulation consists of several steps. First, we need to simulate the internal device electric field using the drift-diffusion solver and the doping profile, Fig. 1. As the next step, we solve the avalanche triggering probability (ATP) equations using the electric field and an impact ionization model, Fig. 2. The drift-diffusion solver also calculates various thermal generation rates, which, when combined with the ATP yields the dark count rate, Fig. 3.

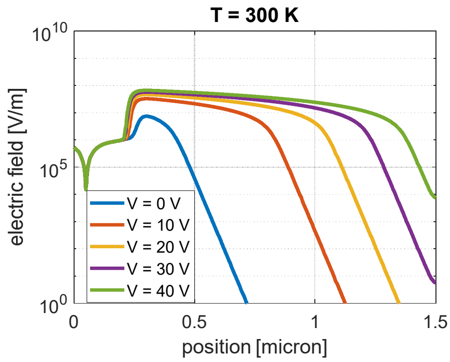

Fig. 1. Electric field along the middle line through the device junction as simulated by CHARGE [1].

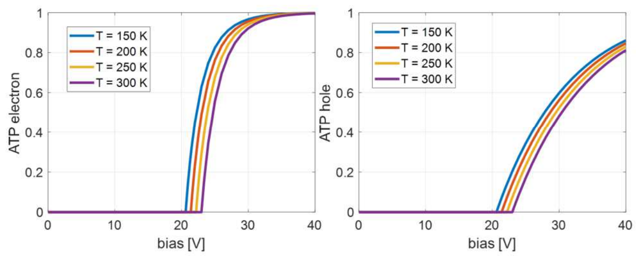

Fig. 2. Avalanche trgierring probabilities along the middle line through the device junction. These are the probabilities that the electron and hole will initiate an avalanche when generated at the far side of the junction.

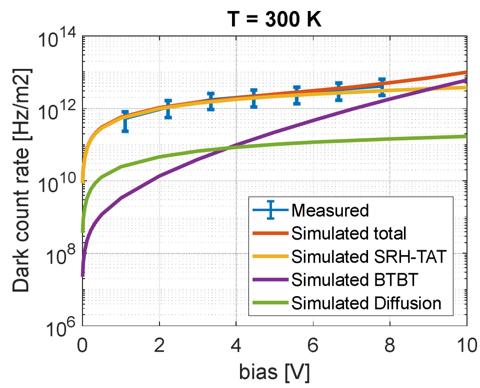

Fig. 3. Dark count rate vs. measurement. This represents the frequency of unwanted detector triggering when no incoming photons are present. Also shown are components of the dark count rate due to the SRH recombination with trap assisted tunneling, the band-to-band tunneling, and the diffusion current from outside the high field region.

Obtaining a good match with the measurements requires fitting a certain number of material and process dependent quantities that control the SRH and band-to-band tunneling models and the surface recombination at the contact-semiconductor interface.

III. The Optical Transmission Function

Fig. 4 shows the approximate optical stack of the proprietary SPAD device in our study (FBK VUV-HD3 [2,5]) consisting of the active Si layer and the SiO2 coating with the estimated thickness in the range 1-1.5 microns. The transmission function from the avalanche source to the far field is affected by absorption in Si and reflections at every interface. The avalanche region location for this SPAD has been estimated in [2].

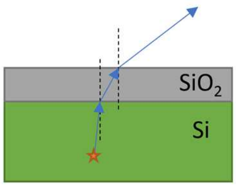

Fig. 4. Approximate structure of the SPAD device. Light emitted from the avalanche point (star) travels through the Si and SiO2 before being emitted into the atmosphere. Reflection occurs at each boundary and absorption occurs in Si. An interference effect is a consequence of a thick SiO_2 layer.

To determine the exact SiO2 thickness we first run a simulation sweep over thickness and wavelength, as shown in Fig. 5, and find the thickness where the discrepancy between the simulated transmission peaks and the measured emission peaks is the smallest. Using this thickness, we can find the final transmission function, as shown in Fig. 6.

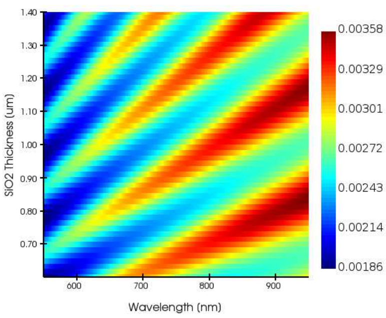

Fig. 5. The change in transmission probability with SiO2 thickness as simulated with STACK [3]. The SiO2 thickness is extracted from this plot at the point where transmission peaks are closest to the measured peaks.

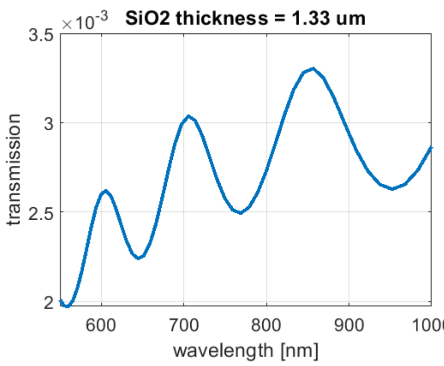

Fig. 6. Transmission function as simulated by FDTD [4] showing the probability that a photon created at the avalanche location will be collected by the measuring microscope objective.

IV. The Avalanche Photon Production Spectrum

We extract the avalanche photon production spectrum by taking the ratio of the measured emission spectrum and the simulated transmission function, Fig. 7. The extracted spectrum does not show interference-related oscillations any longer. This production spectrum is then used as the actual source in the electromagnetic simulation to extract the polar angle resolved secondary emission, Fig. 8.

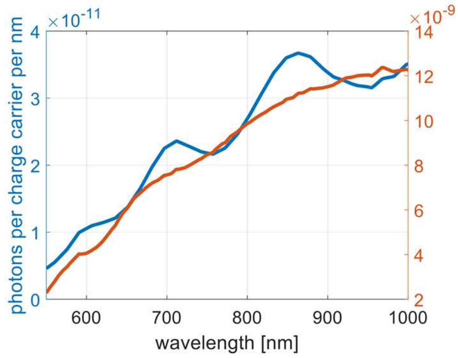

Fig. 7. The measured far field secondary emission spectrum due to avalanche [5] and the extracted avalanche photon production spectrum.

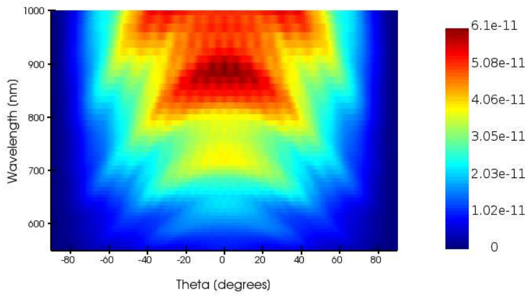

Fig. 8. FDTD simulated secondary emission far field photons per charge carrier per nm per polar angle. The avalanche photon production spectrum extracted previously is applied as the source. Integrating this result in polar angle and assuming the azimuthal symmetry, we can obtain the measured secondary emission spectrum.

V. Conclusion

We presented the simulation methodology and results for the most important electrical and optical characteristics of SPADs. The simulation results are either well matched to the measurement (dark count rate) or combined with measurements to extract unknown quantities (avalanche photon production spectrum). With the popularity of SPADs in an increasing number of applications we believe the simulation methodologies and solvers presented here will be of use to the academic and industrial community.

References

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