Measured and 3D modelled quantum efficiency of an oxide-charge induced junction photodiode at room temperature

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***Abstract*—Quantum deficiencies of charge induced junction photodiodes have been experimentally measured and 3D simulated. It is found that the internal quantum deficiency (IQD) is mainly limited by the surface quality at low optical power. With an achievable good surface, the simulations predicts an IQD below 10 ppm or, equivalently, an internal quantum efficiency higher than 99.999% when the photodiodes are operated at room temperature.**

I. Introduction

Traceble calibration of instruments is important to ensure international agreements in physical quantities. For the determination of optical power, national metrological institutes use cryogenic radiometers as the primary standard which has an uncertainty in the order of 40 parts per million (ppm) [1]. In recent years, significant focus is directed towards using photodiodes based on charge induced juntions as an alternative primary standard, in a so-called Predictable Quantum efficient Detector (PQED) [2], [3]. These photodiodes are predicted using 1D simulations to have an achievable uncertainty below 1 ppm [4] at 77 K. This uncertainty is deduced from the internal quantum deficiency (IQD) of the photodiode where losses of optically generated electron-hole (e-h) pairs are predicted to be below 1 ppm under certain conditions. However, 1D models are fundamentally different from a real device due to its dimension and will eventually reach its limitation of predictability. Thus, 3D models are necessary to further enhance the prediction of IQD of the photodiodes.

Apart from the technological benefits, using photodiodes can potentially reduce the calibration cost and time by several factors compared to cryogenic radiometers. This enables more frequent calibration of standard commercial optical measurement instruments which can affect their reliability and quality.

In this work, we have built a 3D simulation model of an induced junction photodiode and investigated the IQD under various conditions. The simulation results are compared with recent experimental measurements at room temperature, showing a good agreement. Moreover, the simulation suggests operational conditions of the photodiodes at room temperature to further reduce the IQD.

II. Experiment and simulation

The description of the photodiodes used in a PQED can be found in Ref.[2]. For the sake of completeness, the photodiodes

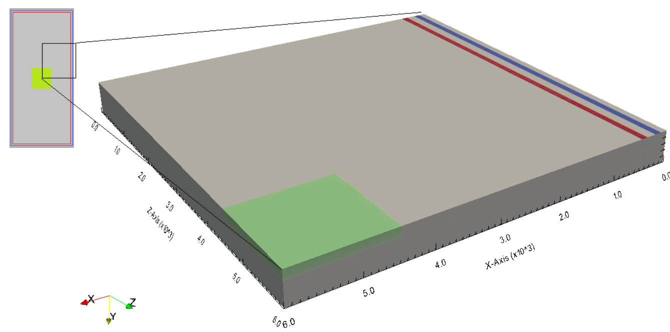

Fig. 1. Simulation structure with contacts (blue and red) and illumination area (green). A schematic drawing is inserted to show the simulation structure relative to the whole photodiode.

are made of p-type high resistive ($2{\times}10^{12}\,\mathrm{cm}^{-3}$) silicon and have the size of $12{\times}24{\times}0.5\,\mathrm{mm}^3$. A thermally grown oxide layer with a positive charge density of $6.2{\times}10^{11}\,\mathrm{cm}^{-2}$ attracts electrons from the bulk to the interface and creates an inversion layer, which in turn generates the diode junction [5].

A power stabilized laser source of 407, 532 or 850 nm is used to provide excitation for the cryogenic radiometer and the photodiodes. The cryogenic radiometer is used to determine the optical power of the laser source. The difference in output of the photodiodes as compared to ideal ones at the given optical power is interpreted as the external quantum deficiency (EQD). The PQED consists of two induced junction photodiodes in a 9-reflection trap configuration such that the reflection losses is reduced below 1 ppm [6]. Thus, in many cases, the EQD can be approximated to be IQD which is compared with the simulations. A reverse bias voltage of 5 (for 407 and 532 nm) or 20 V (for 850 nm) is also applied over the photodiode to expand the depletion width and minimize the internal recombination losses.

The simulation model is built and simulated using the software Cogenda Genius with version 1.8.0 [7]. Figure 1 shows the simulation structure which corresponds to 1/8 of the real device. Length truncation and symmetry are applied to reduce the computational demand. The IQD is calculated from the extracted ratio between the total optically generated and the total recombinated e-h pairs. These values are integrated using the software ParaView with version 4.0.1 [8]. Optical power, bulk lifetime and surface recombination velocity are varied in

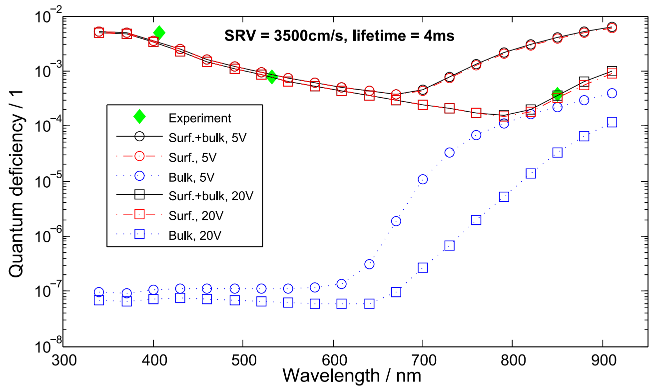

Fig. 2. Quantum efficiency as a function of wavelength, showing both experimental and simulation results.

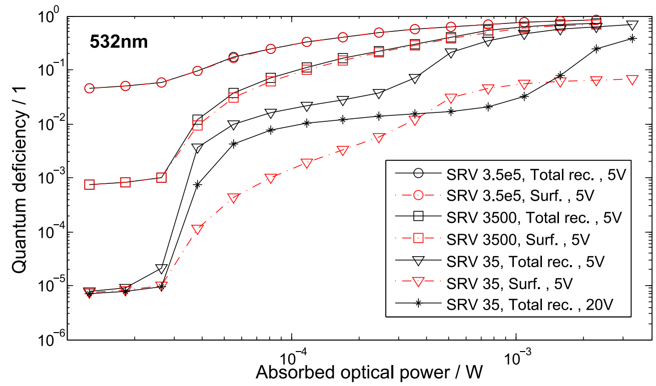

Fig. 3. Quantum deficiency as a function of optical power for 532 nm with a reverse bias voltage of 5 V and different surface recombination velocity of hole and electron.

the model to investigate their effect on the IQD and to fit the experimental data.

III. Results and Discussions

Figure 2 shows the quantum deficiencies from the experiment and simulation as a function of wavelength. It can be seen that the EQD from the experiment decreases as the wavelength increases or, equivalently, the absorption coefficient decreases. With the assumption of negligible external losses, the change in EQD originates solely from the loss of optically generated e-h pairs due to surface and/or bulk recombination. The two recombination rates are controlled by the surface recombination velocity (SRV) of hole and electron and the charge carrier lifetime. By varying these parameters in the simulation, a good agreement between simulation and experiment is achieved. This shows that the 3D model is reliable.

The simulation results reveal an optimum IQD depending on the applied reverse bias voltage. The lowest IQD can be achieved with 670 nm at 5 V and with 790 nm at 20 V. Furthermore, the results show that for wavelengths longer than 640 nm the IQD is highly affected by the bias voltage and that a decrease by one order of magnitude is possible for certain wavelengths when increasing the bias from 5 to 20 V. The highest accuracy is achievable for a limited range of wavelengths.

The simulated IQDs are shown with its components from surface and bulk recombination. It can be seen that the surface recombination is the dominant component for all wavelengths under these conditions. Thus, reducing the SRV can provide conderable reduction in the IQD even for long wavelengths. The effect of varying the SRV on the IQD as a function of optical power for 532 nm is shown in Figure 3. For low optical power, the IQD is completely dominated by the surface recombination. Furthermore, for power levels below 30 μW, the IQD changes proportionally with the SRV. An achievable SRV of 35 cm/s [9] can result in an IQD below 10 ppm. Thus, reducing the SRV is an important factor to reduce the IQD.

An IQD threshold appears around 30 μW where a sudden increase occurs. This threshold exists due to the disappearance of the junction potential barrier which allows significant amount of electrons to diffuse to the bulk and recombine. Simulations show that this threshold can be pushed slightly to higher optical power by increasing the reverse bias voltage. Thus, in order to achieve IQD as low as possible, the optical power needs to be low and the reverse bias voltage high.

IV. Conclusion

A 3D model of a charge induced junction photodiode is built and fitted with experimental results through quantum deficiencies. With a good agreement between simulation and experimental results, the model further reveals that an IQD below 10 ppm is possible with improved surface quality. Moreover, simulations shows that an optimal internal quantum efficiency can be reached by a proper combination of reverse bias voltage, optical power and wavelength.

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