Three-dimensional modelling of photodiode responsivity

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The responsivity of silicon trap detectors commonly used as calibration standards today is to 99.5 % defined by the values of fundamental constants when accounting for calculable reflectance losses. With predictable quantum efficient detectors (PQEDs) the percentage contribution from fundamental constants to the responsivity increases to 99.99%. The simple structure of the PQEDs makes them well suited for three-dimensional modelling and opens a new path of traceability where the spectral response over a wide spectral range can be extracted from a model fit of current – voltage (I-V) characterisations done at one wavelength only.

INTRODUCTION

Through the silicon technology developments in the latter half of the 20th century two important benefits were achieved:

I. "impurity free" manufacturing of silicon photodiodes and
II. computational resources became widely available at a low cost.

The computational resources have continued to develop into this century and are expected to increasingly do so also in the future when quantum computers becomes available. However, the radiometric community has so far exploited the beneficial computational technology developments in the calibration of detectors and optical measurement systems to a limited extent.

Some measurement systems are not easily available once they are installed in a possibly remote and unattended location where the metrological quality relies on the initial pre-installed calibration. New experimental techniques capable of performing calibrations of integrated measurement systems in possibly remote operation will increase confidence and add value to the measurement data.

In the following sections a presentation of the principles and possible methods to exploit photodiodes as independent primary standard detectors is given.

BASIC PRINCIPLE

The responsivity of a silicon photodiode can be modelled as

$$R(\lambda) = \frac{e\lambda}{hc}(1-\rho(\lambda)) \cdot (1-\delta(\lambda)), \qquad (1)$$

where the electron charge e, plancks constant h, speed of light in vacuum c and radiation wavelength in vacuum λ define the ideal responsivity term where one photon generates exactly one electron hole pair. An independent spectral response scale realisation with photodiodes is converted into a problem of quantifying the spectrally dependent reflectance $\rho(\lambda)$ and internal quantum deficiency (IQD) $\delta(\lambda)$. Reflectance losses can be predicted over a wide spectral range from well known material parameters and the oxide thickness or made arbitrarily small by mounting two or more photodiodes in a trap structure.

Different strategies and techniques have been used to independently predict the IQD. One method is to develop experimental techniques to measure and estimate the spectrally dependent losses as done in the past [1-4]. Another way is to construct photodiodes with negligible IQD (~100 ppm) as made with the predictable quantum efficient detector (PQED) [5-8] and use the photodiode trap structure as an ideal photodiode possibly corrected for IQD depending on needed measurement accuracy.

PREDICTABLE RESPONSE

The PQED photodiode is a simple structure consisting of a low-doped wafer with fixed charges in the oxide structure. Once a high quality PQED photodiode is manufactured its structure is defined. This means that when the photodiode is irradiated with a beam the charge carriers inside the photodiode will move in a predictable way depending primarily on the fixed charge density Q_f, surface recombination velocity SRV, bulk lifetime τ_B in addition to experimental parameters such as beam shape, wavelength and bias voltage. With new simulation tools it is possible to model the simple structure of the

PQED photodiodes and hence predict the expected responsivity of the photodiodes.

Measured relative change in photocurrent with bias voltage of a 7 – reflection p-type PQED at 4 different power levels (100 µW to 560 µW) is shown in Fig.1. The curves are normalised to the maximum value of the photocurrent in the experiment. The experiment is made at 488 nm with a gaussian like, slightly elliptical shaped beam with $1/e^2$ axis of 1223 µm by 806 µm.

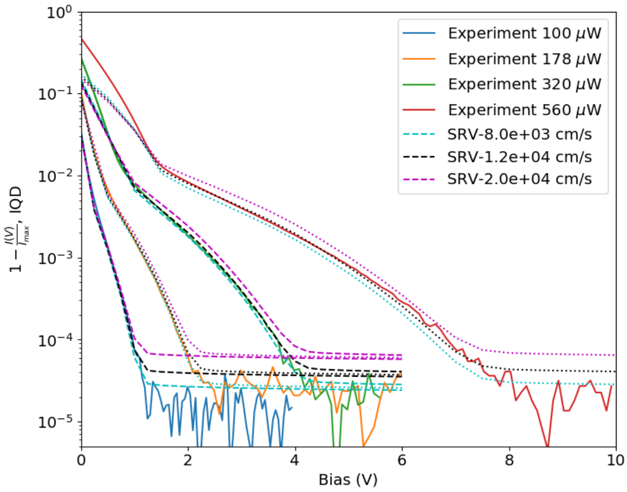

Figure 1. Measured relative change in photocurrent as a function of applied bias voltage plotted against its maximum value in solid lines. Simulated IQD with 3 different values of SRV is shown as dashed lines.

When simulating a PQED instead of a single photodiode several approximations has to be made. At 488 nm p-polarization, 87 % of the optical power is absorbed in the first photodiode, which is hit at a 45 degree angle of incidence. The projected beam profile is modified with the 45 degree angle of incidence to an elliptical beam with axis of 1367 µm by 1067 µm. By fitting various model parameters to the experimental curves an independent prediction of the responsivity can be achieved. In order to limit the number of fitting parameters as much as possible we assumed that experimental curves were defined by the absorbed power in the first photodiode (87 % of the total irradiance) and that the beam size is a flat top approximation of the elliptical beam size of 1367 µm by 1067 µm. It should be noted that the fitted IQD is very sensitive to beam size and charge carrier concentration.

As seen from Fig. 1 a surprisingly good fit is achieved with the approximations given above with the Cogenda Genius Device Simulator. By adjusting the fitting parameters to values enveloping the experimental curves, uncertainty bands of the various parameters can be obtained as demonstrated with the SRV in Fig. 1.

Table 1. Fitted parameters used in the simulations

Fixed oxide charge, Q_f	$6.5 \cdot 10^{11}$ cm^{-2}
SRV	$1.2 \cdot 10^4$ cm/s
Bulk lifetime τ_B	2.9 ms
Bulk doping	$1.4 \cdot 10^{12}$ cm^{-3}

DISCUSSION

Fitting 3D model parameters to simple I-V measurements of a PQED at multiple power levels is a promising primary technique to extract the photodiode parameters necessary to independently predict the PQED response. The first demonstration here must be validated and possibly improved, which is the task of the on-going European project 18SIB10 *chip*S·CAL*e* (2019 – 2022) [9]. One of the benefits of the technique is the ability of independently predicting the IQD of a PQED over a wide spectral range from the measurement at one wavelength only.

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REFERENCES

1. E.F. Zalewski and J. Geist, Silicon photodiode absolute spectral response self-calibration, Appl. Opt., 19, 1214-16, 1980.
2. J. Gran and A.S Sudbø, Absolute calibration of silicon photodiodes by purely relative measurements, Metrologia, 41, 204-12, 2004.
3. J. Gran, Accurate and independent spectral response scale based on silicon trap detectors and spectrally invariant detectors, Dissertation for the Degree of Doctor Scientarum, ISSN 1501-7710 No 434, University of Oslo, 2005.
4. M. U. Nordsveen et. al., Demonstration of dual-mode Si detector as a self-calibrating device at room temperature, Opt. Express, 25, 8459-69, 2017.
5. J. Geist, G. Brida and M.L. Rastello, Prospects for improving the accuracy of silicon photodiode self-calibration with custom cryogenic photodiodes, Metrologia, 40, S132-35, 2003.
6. M. Sildoja et.al., Predictable quantum efficient detector: I. Photodiodes and predicted responsivity, Metrologia 50, 385-94, 2013.
7. Muller et. al.: Predictable quantum efficient detector: II. Characterization and confirmed responsivity, Metrologia, 51, 197-202, 2013.
8. T. Dönsberg et. al.: Predictable quantum efficient detector based on n-type silicon photodiodes, Metrologia, 54, 821-36, 2017.
9. J. Gran, Publishable Summary for 18SIB10 chipS·CALe. Zenodo Jun.2019. *http://doi.org/10.5281/zenodo.354567*.