

Accurate and independent spectral response scale based on silicon trap detectors spectrally invariant detectors

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Abstract. The established model for silicon detector responsivity is exploited to realize a very accurate independent spectral response scale with the aid of a spectrally invariant but noisy detector. Two different approaches are considered to estimate the parameters in the responsivity model, one based on a purely relative measurement between the silicon trap detector and the spectrally invariant detector, and one combining the traditional self-calibration procedure and the purely relative measurement to form a hybrid self-calibration method.

Introduction

Geist and Zalewski demonstrated in 1980 how silicon photodiodes can be used as an absolute measurements standard. Unfortunately, their earliest proposed methods turned out to change the detectors responsivity and hence made them unacceptable as a measurement standard. Since the introduction of the cryogenic radiometer in the mid eighties there has been little work of improving the self-calibration method. Large technological advances have improved the detectors and made the internal quantum efficiency more ideal. In addition, the fast technological advances of integrated circuit technology and computers have improved the availability of computational resources significantly, enabling more accurate calculations of the detectors and opened the way for improved models. In principle, it is these two improvements that are exploited in this new approach to the self-calibration procedure, which replaces the previous oxide bias method.

Theory

A silicon photodiode can be modelled as a modified ideal quantum detector, where the two loss mechanisms, reflectance from the surface and internal losses, are taken into account. The responsivity is modelled as

$$R(\lambda) = e\lambda hc(1 - \rho(\lambda))(1 - \delta(\lambda)), \quad (1)$$

where e is the elementary charge, h is Planck's constant, c is the speed of light in vacuum, and λ is the vacuum wavelength of the radiation. These quantities form the ideal term of a quantum detector. The spectrally dependent reflectance is given by $\rho(\lambda)$, and the quantum deficiency is given by $\delta(\lambda)$. Our approach to get a primary realisation is to estimate the reflectance and the internal quantum deficiency (IQD) separately and through that establish the link between the responsivity and fundamental constants.

Reflectance

Fresnel's equations allow us to calculate the spectral reflectance over the whole spectrum with an uncertainty of less than 1% from a single measurement, when the spectrally dependent refractive indices, polarisation, angle of incidence and oxide thickness is known. In a trap detector the geometry is fixed, and the spectral reflectance of a trap detector can be expressed by the oxide thickness only. In addition, the trap configuration reduces the reflectance by two orders of magnitude making the responsivity less sensitive to the uncertainty in the oxide thickness estimate.

Internal quantum deficiency

The IQD model $\delta(\lambda)$ is based on the assumption that the recombination probability for a generated electron hole pair (e-h) depends only upon the depth, x , into the detector where it is created. The quantum deficiency is found by integrating the product of the normalised distribution of photons and their recombination probability over the depth of the detector. The spectral dependence comes from the normalised distribution of photons given from the highly spectral dependent absorption coefficient. These values are given by the extinction coefficient of the refractive index of silicon. The recombination probability function used in our model is shown in fig. 1.

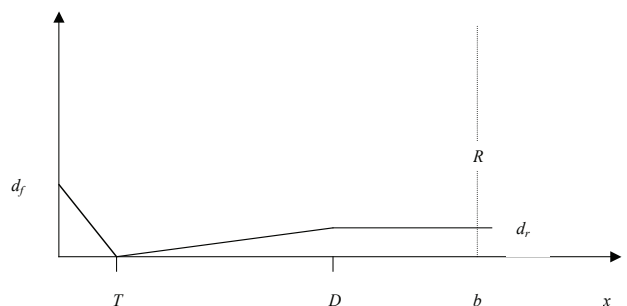


Figure 1. The recombination probability as a function of generation depth of electron – hole pairs.

The important property of the model is that the recombination probability of (e-h) pairs created at the pn junction (T) is zero. In the presented work this property is exploited by two different methods. In the purely relative method we estimated the IQD by measuring the silicon trap detector relative response to a spectrally invariant cavity pyroelectric detector (CPD) and fitted the recombination probability to the measurements. A fitted scaling constant is needed to convert the relative

measurement to an independent spectral response scale. The property of the model ensures correct scaling.

In our second method we combine the traditional self-calibration procedure and the purely relative method to a hybrid self-calibration method. The classical reverse bias experiment at 25 V was used to find the parameters d_r and D by fitting the responsivity change over the whole spectral range. The relative method was used to find the parameters that describe the losses in the front (d_f , T) and at the back of the detector (R , b) in two different but similar experiments. The uncertainty of this method is lower than the purely relative method, but it requires 3 separate experiments each determining 2 parameters in the model.

Results and uncertainty

The uncertainty in both approaches is calculated from the observed variance in the input measurement, brought through the calculations to the output covariance in the responsivity. The combined uncertainties are shown in fig. 2. The calculations are valid for random variables and are based upon the observed variance in these random variables, which requires a number of observations of those variables. Very low uncertainties are achieved by both methods.

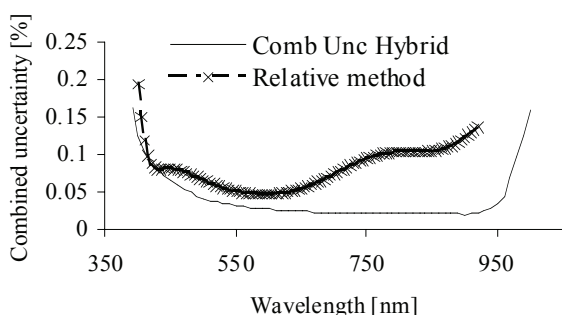


Figure 2. The calculated combined uncertainties in responsivity for the two methods are compared. The uncertainty is given with 1 σ level of confidence.

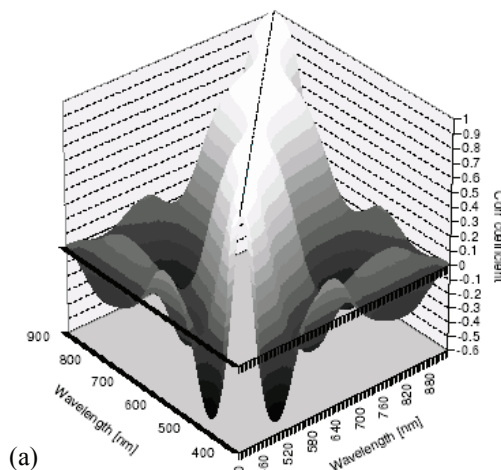
The fitting of a photodiode model to a set of responsivity measurements yields strongly correlated responsivity values. One interesting observation is the difference between the correlation coefficients of the fit function and the responsivity values in the relative method. The relation between the fit function $F(\lambda)$ and the responsivity $R(\lambda)$ is given as

$$F(\lambda) = R(\lambda) k, \quad (2)$$

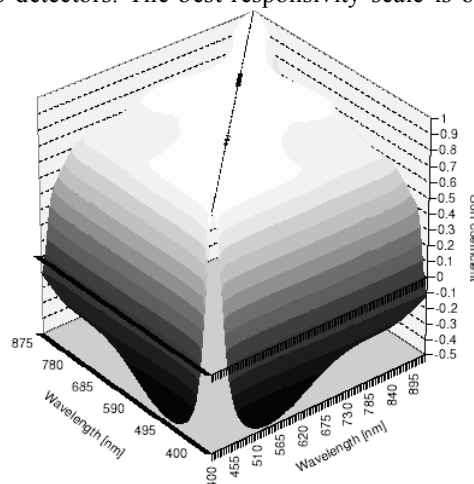
where k is a fitted scaling constant and λ is the optical wavelength. The correlation matrices for the fit function and the responsivities for a set of wavelengths are compared for the relative method in fig. 3. Whereas the correlation matrix of fit function values has a diagonal-like character, the responsivity values are strongly correlated. The responsivity values for the hybrid method have even stronger correlations than for the relative method.

Conclusions

Two different methods for using silicon photodiode trap detectors to realize spectral response scales have been investigated. In the purely relative method the uncertainty is limited by the signal noise ratio in the relative measurement, whereas in the hybrid method the uncertainty is limited by the uniformity and reflectance of



the trap detectors. The best responsivity scale is observed



to have a combined uncertainty of less than 0.04 % between 530 and 950 nm at the 1 σ level of confidence.

Figure 3. The correlation coefficients for the fit function (a) and the responsivity (b).

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