Quantum yield of Predictable Quantum Efficient Detector at ultraviolet and short visible wavelengths

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The quantum yield of silicon photodiodes in a Predictable Quantum Efficient Detector (PQED) was determined experimentally at the ultraviolet and short visible wavelengths. Previous calculations of quantum yield in silicon have focused on high impact energies of the generated electrons and holes. We applied these calculations at low impact energies with the aim of obtaining information on the behaviour of quantum yield at short visible wavelengths. Such results are important to evaluate the reliability of PQED spectral responsivity below 450 nm wavelength when aiming at uncertainties lower than 100 ppm.

INTRODUCTION

Silicon photodiodes are widely used in optical power measurements across the visible spectral region. Their spectral responsivity in units A/W is given by

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

where $e\lambda/hc$ is the responsivity of an ideal quantum detector expressed by fundamental constants and the vacuum wavelength λ. Parameters $\rho(\lambda)$ and $\delta(\lambda)$ describe the losses by spectral reflectance and recombination of charge carriers, respectively, and $1 + g(\lambda)$ is the quantum yield caused by impact ionization of electrons and holes after absorbing a photon with an energy larger than twice the indirect energy gap $E_g = 1.12$ eV in silicon. In the PQED [1-3], $\rho(\lambda)$ can be reliably measured or calculated and $\delta(\lambda)$ can be estimated to be close to zero, which allows direct access to study the excess number $g(\lambda)$ of electron-hole pairs per absorbed photon.

Previous studies of quantum yield in silicon [4-8] provide information on experimental results and calculation methods, but their main interest has been at energies corresponding to incident photons in the ultraviolet (UV) range. We describe here how those results can be applied at short visible wavelengths. That spectral range has recently become important for quantum yield studies because of the need [1-3] to characterize the PQED spectral responsivity over the full silicon photodetector range. By extending the predicted spectral responsivity to UV wavelengths, PQED could be used as an absolute detector standard also at UV region.

QUANTUM YIELD CALCULATION

The excess number of electron-hole pairs per absorbed photon is given by [4,5]

$$g(\lambda) = \int_0^{hc/\lambda - E_g} P(\lambda, E)\cdot N(E)\, dE, \qquad (2)$$

where $P(\lambda, E)$ is the probability distribution of generating a hole or electron of kinetic energy E and $N(E)$ is the average number of electron-hole pairs produced by impact ionization by a carrier with initial energy E above the energy gap. The integration in Eq. (2) is carried out from zero to the maximum energy $hc/\lambda - E_g$ available for the charge carrier.

For very low energy transfer, $P(\lambda,E)$ can be approximated by a sum of two delta functions of E peaked at zero and at $hc/\lambda - E_g$ [4]. As low photon energies are our primary interest for extending the absolute spectral responsivity of PQED, we use the delta function approximation leading to $g(\lambda) = N(hc/\lambda - E_g)$, because $N(0) = 0$. It is then assumed that the charge carrier density of states can be described by that of free carriers which leads to [4,5]

$$g(\lambda) = \left[1 + A_1\left(\tfrac{hc}{\lambda} - E_g - E_{ph} - \Delta E\right)^{1/2} / \left(\tfrac{hc}{\lambda} - 2E_g - \Delta E\right)^{7/2}\right]^{-1}, \qquad (3)$$

where $A_1 = 105\cdot A/(2\pi) = 86.9$ eV^3 corresponds to the constant determined in [5], $E_{\mathrm{ph}} = 0.063$ eV is the energy of optical phonon in silicon and ΔE is an energy shift, which is nominally zero but can here be used to relax the above assumption on the charge carrier density of states. Wolf *et al.* [8] have compared the results in [5] with other experiments [6] and more realistic band structure calculations [7]. They found out that around the kinetic energy of 2 eV, the results of [6] and [7] seem to be shifted to lower energies by $\Delta E = 0.25$ eV relative to [5].

EXPERIMENTS AND DATA ANALYSIS

Our measurement setup consists of a xenon light source, a single monochromator, PQED under test, a broadband wire-grid polarizer for producing light with different polarization states, and a reference pyroelectric radiometer calibrated for measurement of optical power. The PQED consists of two custom-made induced-junction silicon photodiodes [1]. The photodiodes in the PQED are aligned so that several specular reflections take place before the non-absorbed fraction of light leaves the detector. Experiments were carried out with both p and s polarized incident light.

Photocurrent signal from the PQED was divided by the optical power obtained from the pyroelectric radiometer, to determine the measured spectral responsivity $R(\lambda)$ of Eq. (1). To reduce noise in data, measurements were repeated several times and then averaged. With known values of $e\lambda/hc$ and $\delta(\lambda) = 0$ [1,3], and after correcting for the effect of calculated reflectance $\rho(\lambda)$, the measured quantum yield corresponding to $1 + g(\lambda)$ is obtained as shown in Fig. 1. The expanded uncertainty of these data is 1%.

DISCUSSION

The calculated quantum yield in Fig. 1 is mostly below the measured data. The deviation at the peak of 290 nm can be understood by the emerging direct band gap transition which has much higher probability than the indirect transition. The remaining photon energy at 290 nm is just enough to produce a charge carrier capable of impact ionization via the indirect transition. The simplified calculation leading to Eq. (3) does not include such effects. Another resonance type deviation maybe caused at 370 nm with the excitation of two excess charge carriers via indirect transitions.

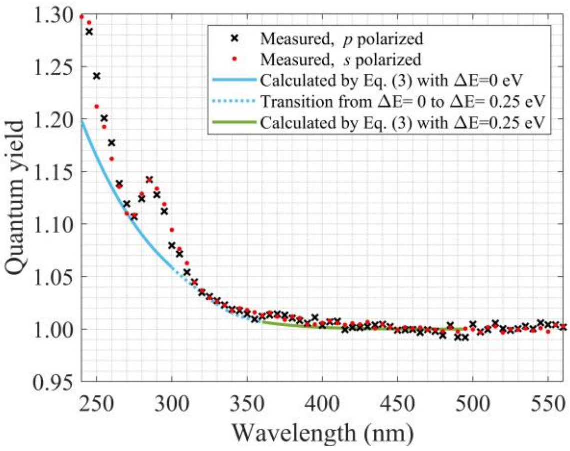

Fig. 1. Quantum yield measured with p (black crosses) and s (red circles) polarization. Solid line is calculated by Eq. (3) with $\Delta E = 0$ for $\lambda < 300$ nm (blue) and $\Delta E = 0.25$ eV for $\lambda > 360$ nm (green). Blue dotted line represents the transition from $\Delta E = 0$ to $\Delta E = 0.25$ eV.

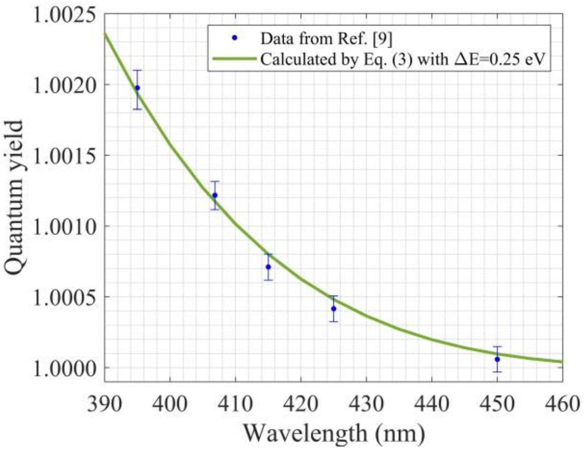

Fig. 2. Experimental quantum yield from Ref. [9] (dark blue dots) with quantum yield calculated by Eq. (3). Uncertainty bars indicate 95% confidence intervals.

The calculated quantum yield with $\Delta E = 0.25$ eV in Fig. 1 is expected to be applicable at wavelengths around 400 nm, corresponding to the charge carrier energy of about 2 eV. In Fig. 2, we apply those calculations to the external quantum efficiency data published in [9], after correcting for estimated reflection losses. The measured and calculated quantum yield values agree well when taking into account that the simplified calculated result does not include any fitted parameters. In the future, a refined version of the quantum yield calculation should consider the energy band structure of silicon.

ACKNOWLEDGEMENTS

This work was funded by the project chipS·CALe (contract 18SIB10) of the European Metrology Programme for Innovation and Research (EMPIR). The EMPIR is jointly funded by the EMPIR participating countries within EURAMET and the European Union's Horizon 2020 Programme.

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