Quantum Yield in Induced Junction Silicon Photodiodes at Wavelengths around 400 nm

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The quantum yield in induced junction photodiodes has been measured. The results show that the quantum yield can be larger than unity at wavelengths longer than 400 nm. This observation has to be considered when applying spectral responsivity models which usually assume a quantum yield of exactly unity.

INTRODUCTION

The quantum yield $y(\lambda)$ is defined as the ratio of the number of generated electron-hole pairs and the number of absorbed photons in a semiconductor photodiode. It is one of the quantities determining the spectral responsivity $R(\lambda)$ of a photodiode which is defined as the ratio of the photocurrent and the incident radiant power generating this photocurrent. Thus, the knowledge of the quantum yield is necessary to model the spectral responsivity.

The quantum yield equals unity if the energy of the absorbed photon is between one and two times the band gap energy E_g. For silicon photodiodes with a band gap energy of 1.12 eV this is the wavelength range from about 550 nm to 1100 nm.

The quantum yield can exceed unity if one of the generated charge carriers, the electron or the hole, has enough energy to create a second electron-hole pair via impact ionisation. For this, the photon energy must exceed $2E_g$. However, because of the requirement of simultaneous energy and momentum conservation in combination with the band structure of silicon, a quantum yield above unity occurs only for photon energies much larger than $2E_g$. The longest wavelength at which a quantum yield above unity has been derived for silicon from experimental data varies between 365 nm and 415 nm [1 - 3].

At high photon energies above 12.4 eV, which corresponds to wavelengths shorter than 100 nm, the quantum yield in silicon seems to be proportional to the energy of the absorbed photon [4].

Models of the quantum yield suffer from free parameters [3, 5] and accurate experimental data and are far away from being applicable at the 100 ppm level. This is crucial for the attempt to establish a new primary detector standard for radiant power measurements, called predictable quantum efficient detector (PQED) [6, 7], which is based on specially designed silicon photodiodes with predicted spectral responsivity.

In the following, the determination of the quantum yield in silicon is described to identify the wavelength range where the assumption $y(\lambda) = 1$ holds and can be used in the spectral responsivity prediction.

QUANTUM YIELD DETERMINATION

The external quantum efficiency of a semiconductor photodiode is given by

$$Q(\lambda) = \big(1 - \rho(\lambda)\big) y(\lambda) \big(1 - \delta(\lambda)\big) \qquad (1)$$

The parameters $\rho(\lambda)$ and $\delta(\lambda)$ describe the external losses due to the reflectance of the photodiode detector and the internal losses due to recombination of charge carriers generated by the incident photons, respectively. Equation (1) can be rearranged for the determination of the quantum yield:

$$y(\lambda) = Q(\lambda)\big(1 + \rho(\lambda) + \delta(\lambda)\big) \qquad (2)$$

Here, it is assumed $\rho(\lambda) \ll 1$ and $\delta(\lambda) \ll 1$.

$Q(\lambda)$ can be calculated from the measured spectral responsivity $R(\lambda)$ via

$$Q(\lambda) = R(\lambda) / \left(\frac{e\lambda}{hc}\right) \qquad (3)$$

where e is the elementary charge, h is the Planck constant, c is the speed of light in vacuum and λ is the vacuum wavelength.

The external losses $\rho(\lambda)$ can be measured or calculated. An experimental determination of the internal losses $\delta(\lambda)$ at wavelengths where the quantum yield $y(\lambda)$ is unknown is difficult as an experimental separation between both is not possible. Thus, $\delta(\lambda)$ must either be calculated or extrapolated from a wavelength region where the quantum yield is known to be equal unity. For both options, a model is required to obtain an estimation of the internal losses with sufficiently low uncertainty.

The PQED [6, 7], constructed from two induced junction silicon photodiodes arranged in a wedge trap configuration, is a good candidate for the experimental determination of the quantum yield.

The windowless photodiodes have a 230 nm thick silicon dioxide layer and were manufactured in the second processing round of the iMera Plus JRP "q-Candela". The angle between the photodiodes is 11.25° yielding 9 reflections of an incoming laser beam if the PQED is aligned so that the reflected beam and the incident one are colinear.

The external losses of the PQED due to reflectance are small, can be measured and calculated by using the thickness of the silicon dioxide passivation layer on top of the silicon substrate and the optical constants of silicon and silicon dioxide. Also, the internal losses are small being widely studied experimentally and described by a one-dimensional, as well as, by using a more sophisticated three-dimensional theoretical model [8, 9].

MEASUREMENTS AND RESULTS

The spectral responsivity of the PQED described above was measured in the wavelength range from 360 nm to 531 nm for p-polarised laser radiation. The measurements were performed at the laser-based cryogenic radiometer facility of PTB. The facility is equipped with a common Brewster window which means that cryogenic radiometer and PQED under test are irradiated through the same window. Thus, the correction for and the uncertainty contribution from the Brewster window transmittance can be avoided. The detector cavity of the cryogenic radiometer and the PQED are equipped with input apertures with the same diameter of 7 mm and were irradiated at the same position with respect to the laser beam. Thus, the uncertainty contribution arising from the scattered radiation around the laser beam is drastically reduced. A relative standard uncertainty of spectral responsivity between 25 ppm and 45 ppm has been achieved.

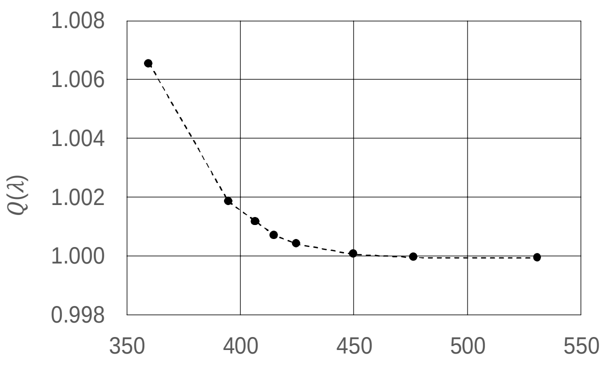

Figure 1. External quantum efficiency of a PQED for p-polarised laser radiation.

In Fig. 1, the preliminary external quantum efficiency calculated from the measured spectral responsivity according to equation (3) is shown. According to equation (2) $y(\lambda) \geq Q(\lambda)$ and, thus, Fig. (1) indicates that, even without the knowledge of $\rho(\lambda)$ and $\delta(\lambda)$, the quantum yield is significantly larger than unity at wavelengths shorter or equal about 425 nm.

The quantum yield will be derived according to equation (2) and considering both, calculated $\rho(\lambda)$ and modelled $\rho(\lambda)$.

CONCLUSIONS

The results show that the quantum yield can be larger than unity even at wavelengths significant longer than 400 nm. This must be considered when applying spectral responsivity models which usually assume a quantum yield of unity in this wavelength range. Further measurements should be done to investigate the artefact dependence of the quantum yield.

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