Quantum efficiency of Predictable Quantum Efficient Detector in the ultraviolet region

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The internal quantum efficiency of a Predictable Quantum Efficient Detector (PQED) was studied by experiments in the ultraviolet and visible wavelength region. We report and discuss the spectral quantum efficiency behaviour, which is quantitatively different in the PQED photodiodes as compared with Hamamatsu photodiodes.

INTRODUCTION

Accurate optical measurements are of great importance in photometry and radiometry. In these research fields, silicon (Si) photodiodes are widely used and they are the most appropriate photodetector for measuring power levels <1 mW of visible and ultraviolet (UV) light. The spectral responsivity of a quantum detector is given by

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

The factor $e\lambda/hc$ is the responsivity of an ideal quantum detector expressed by fundamental constants and the vacuum wavelength λ of the applied radiation. Parameters $\rho(\lambda)$ and $\delta(\lambda)$ describe the spectral reflectance and internal quantum deficiency (IQD), respectively, and $1 + g(\lambda)$ is the quantum gain. Since Si bandgap is 1.12 eV at room temperature, UV photons have at least twice the energy corresponding to the bandgap energy in Si. For that reason, the generated charge carriers may have so much energy that they produce new electron-hole pairs by impact ionization. Understanding of the behaviour of internal quantum efficiency (IQE) in the UV region of the PQED photodiodes helps to evaluate photon flux more precisely in that spectral range.

COLLECTION EFFICIENCY

Silicon photodiodes can be produced by diffusing thin layers of impurity atoms on the surface of the Si wafer. The resulting collection probability model of charge carriers [1] in Fig. 1 describes the IQE of Hamamatsu photodiodes. In this three-parameter model the collection probability rises from a value of $P_f \approx 0.98$ at the front of the photodiode to a value $P_r \approx 0.999$ over a distance $T \approx 0.3$ µm and stays at P_r to the back of the photodiode.

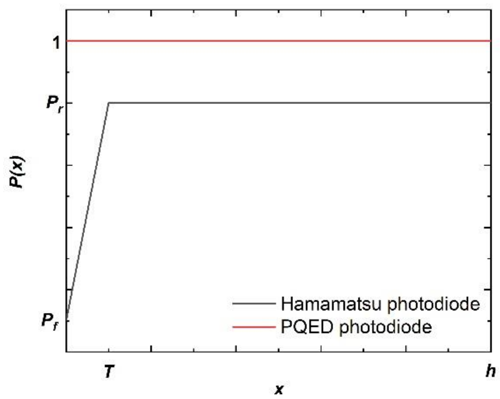

Figure 1. Models for variation of the collection probability $P(x)$ with distance into a photodiode of thickness h. The black line shows the three-parameter model for Hamamatsu photodiodes [1]. The red line shows collection probability for the PQED photodiodes [2, 3].

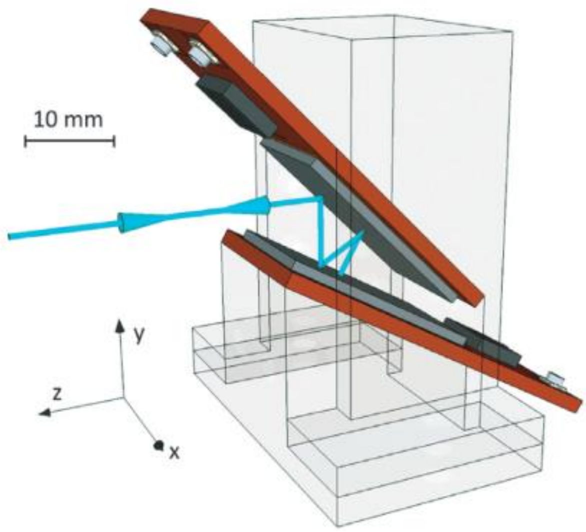

Figure 2. Schematic diagram of the PQED photodiodes' assembly. The blue arrows depict the incident beam. The beam undergoes seven absorptions and reflections at the photodiode surfaces before the remaining fraction of the beam exits through the entrance aperture [2].

For PQED photodiodes, the collection probability model of charge carriers is simple. When the PQED is reverse biased, the value is between 1.0000 and 0.9999 throughout the photodiode thickness [2, 3] as shown in Figure 1. Such charge-carrier collection probability is achieved by the induced-junction structure of the PQED photodiodes, which contains very few recombination centres formed by impurity atoms.

EXPERIMENT AND DATA ANALYSIS

The measurement setup consists of a xenon (Xe) light source, a single monochromator, a detector under test (PQED or a 3-element Si trap detector made of Hamamatsu photodiodes), 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 Si photodiodes [2]. The photodiodes in the PQED are aligned so that seven specular reflections take place before the non-absorbed fraction of light leaves the detector (Fig. 2).

Photocurrent signal from the test detectors was divided by the optical power obtained from the pyroelectric radiometer, to determine the measured spectral responsivity $R(\lambda)$ of equation (1). To reduce noise in data, measurements were repeated several times and then averaged. After correcting for the effect of reflectance, factor $1 - \rho(\lambda)$ in equation (1), the IQE values corresponding to $(1 - \delta(\lambda))\cdot(1 + g(\lambda))$ are obtained.

RESULTS AND DISCUSSION

Figure 3 shows the measured spectral responsivity for the PQED and the trap detector made of Hamamatsu photodiodes. The solid line shows the ideal spectral responsivity $e\lambda/hc$ where each absorbed photon generates one electron-hole pair.

Figure 4 shows the IQE, where it can be clearly seen the differences between the PQED and Hamamatsu photodiodes. As the wavelength decreases below 450 nm, more photons are absorbed near the surface of the Hamamatsu photodiode. According to Figure 1, the collection probability of the trap detector is lower at the surface than in the bulk, and thus the IQE decreases clearly below 1. At the wavelengths below 350 nm, the quantum gain becomes significant and the IQE increases again above 1.

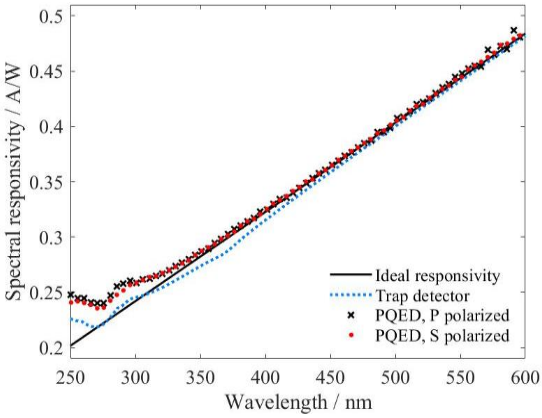

Figure 3. Spectral responsivities of the PQED for S and P polarization, and spectral responsivity of the trap detector. For clarity, only the trend line is shown for the trap detector. The solid line depicts ideal responsivity of a quantum detector.

For the PQED photodiodes, the IQE remains constant for wavelengths down to 400 nm, agreeing with the model of the PQED charge-carrier collection probability of Fig. 1. At the UV wavelengths below 400 nm, the IQE increases due to quantum gain, similar to the behaviour of Hamamatsu photodiodes. Impact ionization is determined by bulk properties of Si, whereas there is a significant difference in the charge-carrier losses due to impurity recombination centres in the two studied types of photodiodes.

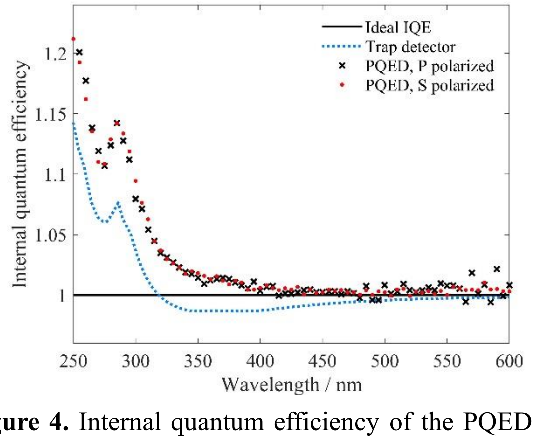

Figure 4. Internal quantum efficiency of the PQED for S and P polarization, IQE of trap detector, and ideal IQE. Measured IQE of PQED is similar for P and S polarizations.

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