Simulation of Predictable Quantum Efficient Detector Responsivity with Temperature

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***Abstract*—This paper presents the results of simulated responsivity of predictable quantum efficient detector (PQED) with temperature variation from 80 K to 300 K by using a 3D simulation model. The model is proven to well describe the PQED responsivity with change in radiant power, wavelength and beam size earlier [1]. It is shown that the saturated internal quantum deficiency (IQD) increases with temperature at 488 nm and is more complex but generally decreases with temperature at 900 nm.**

***Index Terms*—Simulation, Predictable Quantum Efficient Detector, Internal Quantum Deficiency, Temperature.**

I. Introduction

Predictable quantum efficient detector (PQED) based on self-induced photodiodes in light trap configuration can offer very low internal charge-carrier losses below 10 ppm [2]. This makes the PQED an attractive standard for radiant power measurement. By measuring the PQED at low temperature, better signal-to-noise ratio is achieved due to low dark current. However, measurement of PQED at cryogenic temperature faces some difficulties such as complexity, high cost and time consuming to operate.

A 3D simulation model is proved to be able to determine the responsivity of a PQED with an uncertainty of 27 ppm at room temperature and at 476 nm [1]. By using only one set of photodiode defining parameters, the model shows an excellent fit with experimental data with variation in radiant power, wavelength and beam size. The photodiode defining parameters are extracted by fitting simulation results to the experimental data. The extracted parameter values are in close agreement with values derived by other measurements. As the 3D simulation model well describes responsivity of PQED, it can be used to determine the PQED responsivity at cryogenic temperature. This paper presents the dependence of PQED responsivity on temperature from 80 K to 300 K.

II. Simulation model

The simulation is performed using Cogenda Genius Device Simulator. Simulation model of p-type PQED photodiode corresponds to $1/8$ of the size of single photodiode PQED that is reported by Sildoja *et al* [3]. The simplification of simulation model with symmetry boundary condition helps to reduce computational time and memory. The simulation structure with a size of 5500 μm $\times$ 5500 μm consists of a p-doped silicon substrate with a SiO_2 layer on top. A trapped surface charge area between the substrate and oxide layer is defined by fixed charge density Q_f. Electrical contacts p-doped and n-doped have a width of 100 μm. An illumination area is defined at the corner of the simulation structure to represent illumination at the center of photodiode. The model simulates responsivity of a seven reflections PQED trap detector which consists of two single photodiodes [3]. However, the PQED responsivity is mainly defined by the first photodiode. Based on the oxide thickness of the two photodiodes, the radiant power absorbed by the first photodiode is calculated to be about 86%. This means that with a 1000 μW incoming radiant power, the first photodiode absorbes about 860 μW radiant power.

TABLE I
Simulation parameters

Parameters	Values
Substrate doping	1.95×10^{12} cm^{-3}
Fixed charge density Q_f	3×10^{11} e cm^{-2}
Bulk lifetime	2.5 ms
Surface recombination velocity	3000 cm/s

III. Results and discussion

Extracted parameters of one of our PQED in [1] are used for the simulation with change in temperature. The parameters are listed in the Table I. The same elliptical Gaussian illumination beam profile with a $1/e^2$ diameter 4σ of 1067 μm$\times$968 μm is used. Relative flat top beam radius R used in the simulation is converted from the Gaussian beam width σ by $R = \sqrt{2}\sigma$ [1].

Fig. 1 shows the IQD responsivity of the PQED at wavelength of 488 nm with different temperatures from 80 K to 300 K. The simulation is performed with 1000 μW illumination radiant power and only 86% of this radiant power is absorbed by the first photodiode. In order to study temperature effect on only the internal charge carriers losses of the photodiode, the change in absorption coefficient and refractive index of the oxide top layer is not taken into account in the simulation. The absorbed radiant power of 860 μW on the first photodiode is therefore unchanged. It can be seen that low temperature offers lower IQD losses and better linearity. The PQED reaches saturated IQD at a lower bias voltage at low temperature. This means that smaller bias voltage is needed for the PQED to operate at low losses at low temperature.

The saturated IQD with temperature at 488 nm and at 900 nm is shown in Fig. 2. The saturated IQD increases with

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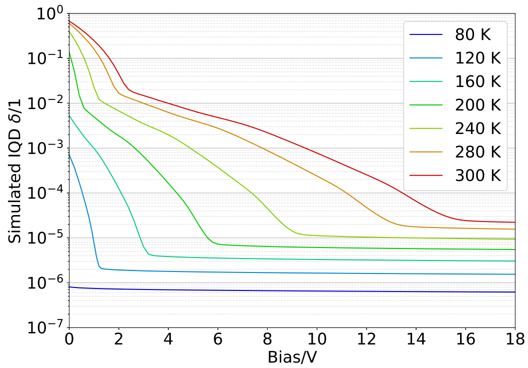

Fig. 1. Simulated IQD of the PQED at 488 nm–1000 μW radiant power with temperature.

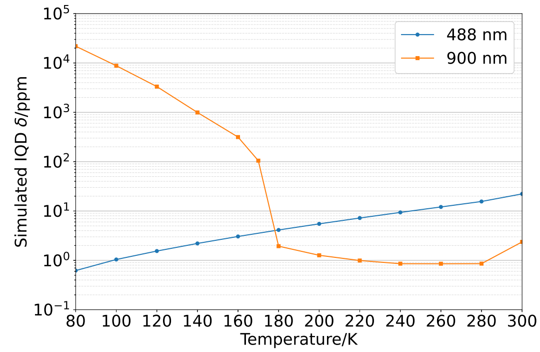

Fig. 2. Saturated IQD of the PQED with temperature at 488 nm and at 900 nm–1000 μW radiant power.

temperature at 488 nm. This can be explained by the increase of absorption coefficient of Silicon and reduction in mobility with temperature. The absorption coefficient of Silicon as a function of temperature in the simulation follows the power law as described by Green [4]. At 488 nm, the absorption coefficient changes from 13000 cm^{-1} at 300 K to 6700 cm^{-1} at 80 K. With the increase of temperature, more electron-hole pairs are generated at the surface of photodiode. Hence, the IQD losses increases. Moreover, the carriers are more energetic at high temperature. This results in a reduction of carrier mobilities due to increasing of collisions and the IQD is further increased. This is valid at short wavelength where the IQD is dominated by the surface recombination losses. At long wavelengths, illumination radiation penetrates deeper into the photodiode due to lower absorption coefficient in Silicon. Therefore bulk recombination is the dominant loss parameter in the PQED at long wavelength and the IQD response with temperature behaves differently. At 900 nm, combination of long wavelength and low temperature leads to low absorption coefficient. A part of illumination radiation is not absorbed but passes through the photodiode. This gives much higher IQD losses at low temperature at 900 nm as compared to at 488 nm. In addition, saturated IQD decreases with temperature as a result of increasing in carriers lifetime at high temperature. When the temperature is further increased, the rise in absoprtion coefficient and the reduction in carriers mobility start affecting the IQD. As a consequence, higher IQD at 300 K is observed.

Simulated IQD of the PQED at 120 K and at 488 nm with different radiant powers is shown in Figure 3. The change in IQD is more clearly at high radiant power. Therefore, $I-V$ measurement at cryogenic temperature and at high radiant power can be used to extract PQED's parameters. This allows an independent radiometric linkage to SI by extraction of fundametal constant ratio e/h [5].

IV. Conclusion

A method to determine responsivity of PQED at different temperatures from 80 K to 300 K by using a 3D model is presented. At 488 nm, saturated IQD increases with temperature due to higher absorption coefficient and lower charge carrier mobility in Silicon. At 900 nm, loss in absorption of illumination radiant power due to low absorption coefficient causes much higher IQD at 900 nm at low temperature as compared to at 488 nm. At high temperature, IQD generally decreases as a result of increasing in carrier lifetime.

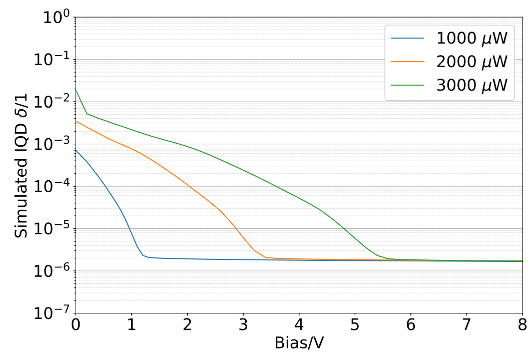

Fig. 3. IQD response of the PQED at 120 K–488 nm with radiant power variation.

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