Unidimensional photocurrent model for induced-junction photodiodes

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Abstract. At present, numerical simulations are the common method to predict the response of quantum efficient detectors based on induced-junction diodes. As alternative, this work proposes an analytical model based on photocurrent analysis where surface and bulk losses are modelled considering design and operation photodiode parameters and the characteristics of the incident beam. The model shows how, at short wavelengths, the surface recombination velocity dominates the losses that are directly proportional, whereas the bulk doping and reverse bias voltage determine the losses at long wavelengths. The results obtained by the here proposed analytical model are discussed for different values of surface recombination velocity and compared with simulations reported by other authors. For wavelengths from 400 nm up to 700 nm, the losses calculated by the analytical model at room temperature are in the order of tens of ppm for values between 1000 cm/s and 10000 cm/s of surface recombination velocity. Some simulations agree with a maximum difference of 80 ppm up to 700 nm, where the abrupt rise of bulk losses starts for the analytical model but it is shifted around 800 nm for reported simulations.

1. Introduction
In the last years, within the European joint projects “Candela: Towards quantum based photon standards” (qu-Candela) and “New primary standards and traceability for radiometry” (NEWSTAR), with the development and improvement of self-induced junction photodiodes [1] and the packaging in a wedged trap configuration, a high efficient light-detecting instrument called predictable quantum efficient detector (PQED) [2, 3] has been achieved. The potential of PQEDs as optical radiant power primary standard, based on photoelectric effect in silicon photodiodes, has been proved through comparison to the most accurate primary standard at present, a cryogenic electrical substitution radiometer.

The internal quantum efficiency (IQE) represents the number of electrons contributing to the measured photocurrent versus the number of photons absorbed; therefore, the ideal value of IQE is one assuming a unity quantum yield what would mean absence of internal losses. The IQE of a PQED is predictable from fundamental constants and the radiation wavelength, with small deviations from the ideal behaviour due to internal losses that can be calculated.

Nowadays, simulations performed by software for semiconductor devices are the only proved method to predict the internal losses of a PQED as it is shown by Gran et al., by means of PC1D [4], and Tang et al., by means of Cogenda Genius [5], with a subsequent new implementation of the surface charge. The new implementation of this last reference principally reduces the surface losses by around two orders of magnitude with the same surface recombination velocity.

This work proposes an alternative analytical method, based on the model of the photocurrent analysis developed by Ferrero et al. [6], which considers the different internal regions of the photodiode and...
the characteristics of the incident beam. This work also presents the adaptation of the original model, which considers a physical junction with different doping type on each side, to the self-induced junction of a PQED photodiode, caused by the surface charge resultant of growing a silicon oxide layer on a p-type doped substrate.

2. Internal quantum efficiency and analytical model for induced-junction photodiodes
The produced electrons within every region of the photodiode, dependant on the wavelength of the incident radiation, behave differently, being affected by differentiated surface and bulk losses. In order to predict the IQE of a PQED, it is necessary to quantify the losses due to the radiation not absorbed in the depletion region, where recombination losses are considered to be negligible. If the whole radiation was absorbed within the depletion region, for each absorbed photon a carrier would contribute to the photocurrent and the IQE would reach its ideal value.

Following this reasoning, IQE of a photodiode can be predicted by the equation (1) quantifying the surface losses (\( \Delta_{\text{surf}} \)) due to the radiation absorbed at the interface oxide-substrate, bulk losses (\( \Delta_{\text{bulk}} \)) due to the radiation absorbed in the bulk beyond the depletion region and losses due to the radiation which goes through the photodiode without being absorbed (\( \Delta_{\text{out}} \)).

\[
IQE = 1 - \Delta_{\text{surf}} - \Delta_{\text{bulk}} - \Delta_{\text{out}}.
\] (1)

In the following subsections the meaning of each item in equation (1) is described and how to adapt them to the self-induced photodiodes used as detectors in PQEDs is explained.

2.1. Internal regions of a self-induced photodiode
For an induced-junction photodiode, schematically represented in figure 1, the parameters of the original model [6] require to be redefined mainly to include the surface charge (\( Q_{SS} \)) resultant from growing a silicon oxide layer on a doped p-type substrate, and to eliminate the front recombination region, which is meaningless here.

![Figure 1. Simplified diagram of a self-induced junction structure in a p-type silicon substrate. The silicon oxide layer, grown on the substrate, induces the surface charge \( Q_{SS} \) producing a free charge depletion region.](image)

2.1.1. Surface losses. Bearing in mind the separated contribution of the surface and bulk recombination to the effective lifetime of the charge carriers (\( \tau_{\text{eff}} \)) given by [7]:

\[
\frac{1}{\tau_{\text{eff}}} = \frac{1}{\tau_{\text{bulk}}} + \frac{2S_{\text{eff}}}{H},
\] (2)

where \( \tau_{\text{bulk}} \) is the bulk carriers’ lifetime, \( S_{\text{eff}} \) the surface recombination velocity and \( H \) the silicon wafer thickness; the losses produced at the interface between the oxide and the silicon can be modelled by
equation (3), which is an expression based on a comparison with the saturation current density factors [8, 9] divided by the photocurrent assuming a unity quantum yield:

$$\Delta_{\text{surf}} = \left( \frac{n_i^2 S_{\text{eff}}}{Q_{\text{sff}}} \right) \left( \frac{n_\lambda P (1 - \rho)}{hc} \right),$$  \hspace{1cm} (3)

where $n_i$ is the intrinsic concentration of carriers, $S$ the cross section of the beam, $n$ the refractive index of air, $\lambda$ the wavelength of the incident radiation in air, $h$ the Planck’s constant, $c$ the speed of light in vacuum, $P$ the optical power of the beam and $\rho$ the reflectance of the detector.

2.1.2. Bulk losses. In the bulk, the recombination rate depends on the fraction of the optical radiation absorbed beyond the depletion region ($\delta_{\text{bulk}}$) and the probability of finding free recombination centres in this region ($\varepsilon_{\text{bulk}}$), as it is described in equation (4). Therefore, $\varepsilon_{\text{bulk}}$ takes values between 0 and 1 and depends on the bulk dopant concentration ($N_A$), bulk carriers’ lifetime ($\tau_{\text{bulk}}$) and the irradiance in the way mentioned in Ferrero et al. model [6]:

$$\Delta_{\text{bulk}} = \frac{\delta_{\text{bulk}}}{2} \left[ 1 + \varepsilon_{\text{bulk}} (\lambda, N_A, \tau_{\text{bulk}}, P, S) \right],$$  \hspace{1cm} (4)

$$\delta_{\text{bulk}} = \exp(-\alpha_{si} x_{d,max}) - \exp(-\alpha_{si} H),$$  \hspace{1cm} (5)

where $\alpha_{si}$ is the absorption coefficient of silicon and $x_{d,max}$ the width of the depletion region. The width of the depletion region of a self-induced photodiode can be modified by changing the reverse bias applied and the bulk dopant concentration [10], according to the equation (6):

$$x_{d,max} (\text{bias}) = \left( \frac{2 \varepsilon_{\text{rel}} \varepsilon_0}{q N_A} (V_{\text{s(inv)}} - V_{\text{bias}}) \right)^{1/2},$$  \hspace{1cm} (6)

with $q$ the elementary charge constant, $\varepsilon_{\text{rel}}$ the relative permittivity of silicon, $\varepsilon_0$ the vacuum permittivity, $V_{\text{bias}}$ the bias voltage applied through the photodiode and $V_{\text{s(inv)}}$ the strong inversion surface potential, considered equal to the double of the bulk Fermi potential [10]:

$$V_{\text{s(inv)}} = 2 k_B T \ln \frac{N_A}{n_i},$$  \hspace{1cm} (7)

with Boltzmann’s constant, $k_B$, and temperature, $T$.

2.1.3. Not absorbed radiation losses. Finally, the radiation which goes through the photodiode without being absorbed is given by:

$$\Delta_{\text{out}} = \exp(-\alpha_{si} H).$$  \hspace{1cm} (8)

Reflection from the back surface is not taken into account in this model because the radiation which goes through the photodiode without being absorbed, without considering back reflection, is negligible between 400 nm to 900 nm compared with surface and bulk losses.

3. Results of the analytical model

3.1. Input data

The aim of this work is to propose an analytical expression for equation (1) as an alternative to software simulations in order to determine the internal losses of PQEDs. As seen above, the
expressions of the analytical model depend on design and operation parameters of the device whose values in the case of photodiodes used in PQEDs are shown in Table 1, taken from reference [2], so that result yields by this model can be compared to those published from the numerical model [4, 5].

Table 1. Reference design and operation parameters of the induced-junction photodiodes used in PQEDs.

| Parameter                | Symbol | Reference value       |
|--------------------------|--------|-----------------------|
| Wafer thickness          | $H$    | $525 \, \mu m$        |
| Surface charge density   | $Q_{ss}$ | $6.2 \times 10^{11} \, \text{cm}^{-2}$ |
| Bulk dopant concentration| $N_A$  | $2 \times 10^{12} \, \text{cm}^{-3}$ |
| Reverse bias voltage     | $V_R$  | $-5 \, \text{V}$      |
| Optical power            | $P$    | $100 \, \mu W$        |
| Beam cross section       | $S$    | $10 \, \text{mm}^2$   |

3.2. Spectral behaviour

As PQEDs are highly efficient detectors, it is more interesting to present the results of the internal quantum deficiency (IQD), defined as the default to unit. The following graphs represent the spectral IQD, in parts per million (ppm), predicted by the analytical model for a single photodiode with design parameters from Table 1. In order to verify whether the model yields expected results, the effects of reverse bias voltage, surface recombination velocity, bulk dopant concentrations and bulk carriers’ lifetime over IQD have been calculated.

3.2.1 Reverse bias voltage and surface recombination velocity influence. Using parameters in Table 1, with different values of reverse bias voltage and surface recombination velocity, the results shown in figure 2 are obtained for IQD. Increasing the reverse bias voltage extends the depletion region depth and, hence, shifts the rise of the bulk losses towards longer wavelengths; whereas, increasing the surface recombination velocity by one order of magnitude produces an increase of the same order of the surface losses, this effect is illustrated in figure 2 by the represented IQD at short wavelengths. This behaviour is similar to that it is shown by Gran et al. [4] and Tang et al. [5] in their reported simulations. PC1D simulations [4] show an IQD curve, calculated for a 10 cm/s value of surface recombination velocity, very close to the 1000 cm/s curve in figure 2. On the other hand, Cogenda Genius TCAD simulations [5], which have a surface recombination two order higher than PC1D simulations for the same IQD results, show an IQD from 80 ppm (at 400 nm) up to 1 ppm (at 800 nm) calculated for a 4500 cm/s value of surface recombination velocity. Comparing with the analytical model, this Cogenda Genius TCAD IQD curve is included between the 1000 cm/s and 10000 cm/s curves in figure 2. Around 700 nm, the main difference is found when the starting point of the abrupt rise of the bulk losses appears for the analytical model but for the Cogenda Genius TCAD simulations is shifted at longer wavelengths around 800 nm, in spite of using both the same depth of the depletion region in absence of radiation. Therefore, it can be extracted that, the IQD results predicted by the analytical model agree with Cogenda Genius TCAD simulations with a maximum difference of 80 ppm, between 400 nm and 700 nm.
3.2.2 Bulk dopant concentration and bulk carriers’ lifetime influence. Following the same strategy, but changing bulk dopant concentration and the bulk carriers’ lifetime rather than reverse bias voltage and surface recombination velocity, IQD values shown in figure 3 can be observed. The increase of the bulk doping shortens the depletion region depth and shifts the rise of the bulk losses towards shorter wavelengths; whereas, increasing the bulk carriers’ lifetime reduces the slope of the bulk losses. The reason is that dopant impurities behave as recombination centres increasing the bulk losses. The influence of the bulk dopant concentration and the shape of the IQD curves are similar to the reported simulations [4, 5], again with the exception of the rise of bulk losses, which starts at shorter wavelength for the analytical model.

4. Conclusions
An analytical model to predict the IQE of a PQED single induced-junction photodiode has been developed by adapting the Ferrero et al. model [6]. This analytical model is useful to quantitatively
determine how the design and operating parameters of the photodiodes contribute to the IQE. This work proposes the analytical model as an alternative method to predict the IQE of a PQED radiometer, since its behaviour is similar to the software simulations. Qualitatively, the shape and the behaviour of the IQD curve predicted by the analytical model agree with the simulations performed by Gran et al. by means of PC1D [4] and Tang et al. by means of Cogenda Genius TCAD [5]. At short wavelengths, the surface recombination velocity dominates the losses being directly proportional, then, as the radiation penetrates into the depletion region, the losses drop slightly and, finally, the IQD increases quickly at longer wavelengths due to the abrupt rise of the bulk losses determined mainly by the bulk doping and reverse bias voltage. Quantitatively, the IQD predicted by the analytical model is in the order of tens of ppm for values between 1000 cm/s and 10000 cm/s of surface recombination velocity, for wavelengths from 400 nm up to 700 nm. Comparing these results with simulations, the curves of the IQD predicted by the analytical model and Cogenda Genius TCAD simulations, which reduce the surface losses by around two orders of magnitude with the same surface recombination velocity respect PC1D simulations, both agree with a maximum difference of 80 ppm for wavelengths between 400 nm and 700 nm. However, around 700 nm, the main difference appears when the rise of bulk losses starts for the analytical model but it is shifted at longer wavelengths around 800 nm for the reported simulations, in spite of using both the same depth of the depletion region in absence of radiation. For future improvements, it is required to study deeper the mechanisms of the minority carriers diffusion and the influence of the irradiance over the width of the depletion region.

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