Optical and electrical simulations of radiation-hard photodiode in 0.35µm high-voltage CMOS technology

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***Abstract* — Many imaging applications, like medical or space applications, require radiation-hard sensors. Generally, during radiation, many different defects are created, depending on the type of the radiation. With TCAD software, cross-section of a radiation-hard photodiode was simulated, and afterwards the impact of different physical parameters was simulated. Physical parameters like epitaxial layer thickness or the trap density in the bulk, play a huge role towards the responsivity of the photodiode. This paper presents a variation experiment, where relevant physical parameters are varied and analysis of the spectral responsivity and dark current of the photodiode is discussed.**

Keywords—Image sensor, Imaging applications, CT scanner, Ionizing radiation, Non-ionizing radiation, Radiation hardness, Radiation damage, TCAD software, Parameter variability, Screening, DoE, Spectral responsivity, Dark current

I. Introduction

Image sensors find their usage in many different applications. Ranging from standard environment settings like security and automotive applications, up to radiation environment like medical and space applications. In general, an image sensor consists of a sensing device (a photodiode) and a readout circuit. There are multiple varieties of image sensors, like CCD elements and CMOS image sensors (CIS). In strong radiation environments, usually CMOS image sensors are used due to their radiation hardness and cheaper and simpler fabrication. Main parameters that define an image sensor are the quantum efficiency, spectral responsivity, signal-to-noise ratio and the dark current [1,2]. In radiation environments, radiation-induced damage alters and degrades those charactersitics. In order to make the device more reliable, radiation hardening techniques like temperature annealing and implementation of specific passivation implants are used.

The aim of this paper is to examine the impact of geometrical parameters and trapping mechanisms on a radiation-hard photodiode electrical characteristics used in a Computed Tomography (CT) scanner. Spectral responsivity and dark current of the photodiode are simulated as a function of varied geometrical and physical parameters. It is shown that deep level donor traps have the highest impact on both the spectral responsivity and dark current, while the epitaxial thickness impact mostly the spectral responsivity.

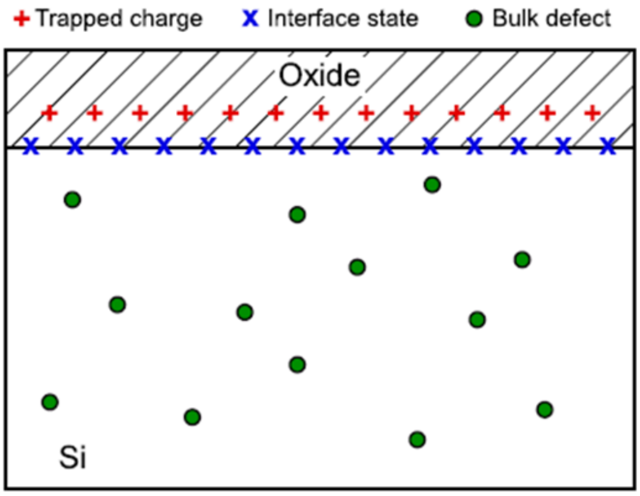

Fig. 1. Radiation induced defects: trapped charges and interface states are generated by ionization, whereas bulk defects are due to displacement damages.

II. Radiation types and radiation damage

During irradiation, not only charge carriers are created, but also different defects that depend on the type of the radiation. This damage degrades the performance of many semiconductor devices, limiting the overall performance and reducing the lifetime and stability of sensors. Moreover, the detector noise and the dark current are increased. Apart from that, the homogeneity of charge collection becomes distorted and the overall detection efficiency decreases [3]. Cumulative radiation effects include effects due to ionizing radiation and nonionizing radiation. In Fig. 1, primary radiation induced defects are presented.

A. Total-ionizing dose effect

Ionizing radiation is caused by charged particles and photons with high energy. It creates charge carriers in insulating layers (e.g. SiO_2) where some of them are trapped, which leads charge buildup. The positive charges in the oxide have a very low mobility and can get trapped near the interface Si-SiO_2. This causes the electrons to accumulate on the silicon side, thus increasing the photodiode dark current [4]. Dangling silicon bonds (interface states) are also created on the interface of the silicon with the SiO_2. They increase surface recombination velocity which contributes to overall degradation of sensor characteristics [5,6]. Radiation hardening techniques include both process and layout design optimizations, as well as temperature annealing procedures. By introducing a shallow p-type implant to the silicon surface, the effect of trapped charge in the oxide is reduced by pushing the space charge region (SCR) away from the surface. Temperature annealing repairs almost fully the interface states, but only partially trapped charge in the oxide [7,8].

B. Non-ionizing energy loss effect

The interaction of radiation with the silicon lattice depends not only on the particle type, but also its energy. Generally, charged particles lose a significant part of their energy by ionization, where the energy is used to create electron-hole pairs. The Non-Ionizing Energy Loss (NIEL) occurs for high-energetic charged particles and neutrons which cause permanent displacement damage in the silicon bulk. If sufficient energy is transferred, a silicon atom is displaced from its lattice position and a so called Primary Knock-on Atom (PKA) is created. The PKA can have enough energy to move through the silicon lattice, displacing atoms and creating vacancy-interstitial (V-I) pairs. Due to NIEL effect, additional energy levels are created in the bandgap, most of them near the mid band-gap region. They act as recombination centers, trapping the generated charge and thus increasing the Shockley-Read-Hall (SRH) recombination rate and the dark current. The effective way to make a device radiation tolerant towards NIEL effect is to collect charge via drift, in order to reduce the probability of charge trapping and to make the device more resilient towards displacement damage [9-11].

III. SIMULATED PHOTODIODE STRUCTURE AND MAIN PARAMETERS

The photodiode that is used in CT scanners consists of multiple n-well islands that act as the collection electrode for the photo-generated charge. The operating temperature of the CT scanner can reach 67°C (340K), therefore the leakage current is simulated at that temperature. The simplified cross-section of the simulated photodiode is presented in Fig. 2, where only one island is simulated, and the area of the island, as well as the light intensity have been scaled to correspond to the full structure region.

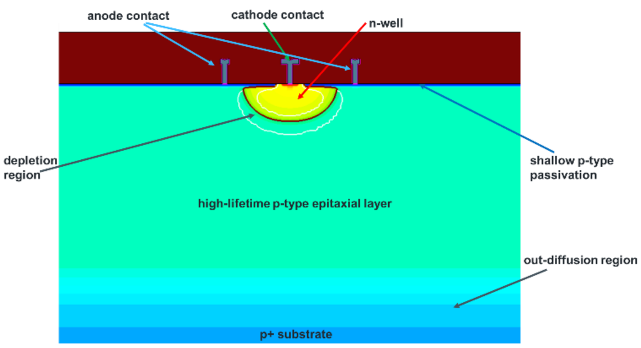

Fig. 2. Cross-section of the simulated photodiode under the reverse voltage of 1.25V. The photodiode consists of a small n- well collection electrode, surrounded by the highly doped p-type passivation layer ($N_A > 10^{19}$ cm^{-3}), inside the p-type epitaxial layer which is grown on top of p-type substrate material.

Table 1. Input parameter names and their initial values. Energy bandgap was not varied in the simulations, but it is dependent on the temperature and it was used to calculate the energy position of acceptor and donor traps.

Input parameters and initial values	
Parameter	***Initial value***
Substrate resistivity	0.03 Ω.cm
Epitaxial thickness	18 µm
Epitaxial doping concentration	7e14 cm^{-3}
Maximum electron lifetime	1 ms
Maximum hole lifetime	0.34 ms
Oxide trap density	1e11 cm^{-3}
Bulk trap density	5e11 cm^{-3}
Acceptor trap energy position	0.75 Eg
Donor trap energy position	0.25 Eg
Energy bandgap @ 300K (Eg)	1.12974 eV

In order to design a radiation-hard device, the impact of different geometrical and physical parameters needs to be taken into account. Using TCAD software [12], it is possible to simulate a variability experiment of those parameters. The results of these simulations give us the information on how each parameter impacts the observed responses – in this case, the spectral responsivity and the dark current. In Table 1, parameters with their initial values are shown.

A. Process parameters

1) Substrate resistivity

The substrate resistivity is a main parameter to take into account when considering charge collection efficiency. Usually sensors have a low-resistivity substrate material on top of which a higher-resistivity epitaxial layer is grown in order to achieve a larger depleted region to efficiently collect charge by drift. As the epitaxial layer is thermally grown on top of the substrate, the out-diffusion of the substrate could cause the gradient in doping profile near the border with the epitaxial layer. This would then impact the charge lifetime for higher wavelength regions, as the lifetime is inversely dependent on the doping profile, thus the carriers would recombine and not be collected by the collection electrode.

2) Epitaxial thickness

As already mentioned, epitaxial layer is usually lowly doped and therefore a higher depletion region could be achieved. As the silicon becomes more transparent for higher wavelengths (>750 nm), it means that the charge is generated deeper into the sensor structure. In order to have a higher spectral responsivity for near-infrared (NIR) wavelength region, a thicker epitaxial layer is needed.

3) Epitaxial doping concentration

In order to efficiently collect charge, large depletion regions are needed. This is achieved by having a low-doped epitaxial layer. Charges are then collected by drift mechanisms and the probability of charge trapping is reduced. The downside of having a large depletion region is the increase in the leakage current. There are also applications which use high-lifetime starting materials, where charge carriers are collected by diffusion and not by drift. Due to the high-lifetime property of the material, the carrier lifetime is large enough, and thus the diffusion length is sufficient for carriers to reach the collecting electrode. Since the depletion region is quite small, dark current is also better, but the collection speed is then reduced, as diffusion is quite slower than drift collection.

B. Device parameters

1) Electron and hole lifetime

Lifetime of generated charge also plays a huge role in terms of designing a radiation-hard sensor. As already mentioned, collection by diffusion requires high-lifetime materials. The overall effective lifetime is not only dependent on the radiative recombination, but also on other recombination effects, like the Shockley-Reed-Hall (SRH) and Auger recombination. This parameter is modeled such that the maximum hole lifetime is one third of the maximum electron lifetime [13]. This parameter hugely impacts the dark current and is usually defined by the properties of the silicon, as well as with the processing procedure during fabrication.

2) Oxide trap density

Oxide traps are defined by the amount of fixed charge that is present in the oxide due to ionization effects. This parameter mostly impacts the dark current and also affects the lower spectrum region (200 nm – 400 nm).

3) Bulk trap density

Dislocation damage in the silicon lattice is caused by non-ionizing radiation, but also during processing steps. In TCAD, bulk defects are defined by specifying trap density, energy type, energy position corresponding to the bandgap of the silicon, the trap capture cross-section which describes the probability that the charge will be trapped by the trap and the type of the trap. To simplify the model, only the energy position of acceptor and donor traps have been varied, in addition to the trap density.

4) Acceptor trap energy position

Acceptor trap energy position is specified in TCAD by specifying the energy position from either conduction or valence band. In our case, we observed acceptor traps only in the region between the conduction band and the mid bandgap energy levels. Acceptor traps indicate the trapping and releasing of electrons.

5) Donor trap energy position

Donor traps act similar to the acceptor traps, but instead of electrons, they cover the physics of trapping and releasing of holes. Also in our model we observed the energy levels from the valance band to the mid bandgap.

IV. Methodology and Results

All of the above mentioned parameters have an impact on optical and electrical responses of the examined photodiode. As some of them are process parameters and the others are more related to device characterization, a specific Design of Experiments (DoE) is generated. Process parameters are integrated in the process flow, describing an industry standard 350nm high-voltage (HV) technology while device parameters are defined in the device simulation part according to specific device models. These device models describe carrier mobility, SRH recombination, Auger recombination, bandgap narrowing, etc.

In a first step of the methodology, simulation of process and device parameters, along with the limits of their physical variability has been performed. The analysis provided a first estimation of the independent variability of the electrical and optical responses to each of the input parameters. As an example, the effect of different epitaxial thickness on the spectral responsivity is shown in Fig. 3. For 500 nm wavelength, the variability of the spectral responsivity is roughly 10% and is less affected by epitaxial thickness variability. This is because the absorption depth of the 500 nm light is shallower and the generated carriers are closer to the depletion region and therefore are affected more by the drift collection mechanism. On the other hand, for 900 nm wavelength, the spectral responsivity alters up to 12-13% because of the deeper light absorption which means that the generated carriers could end up in the out-diffusion region, where the doping concentration is much higher, and the carriers recombine faster, meaning that they are not collected, thus resulting in a lower spectral responsivity.

The second step is the screening of each parameter which is designed by using Minitab software. There, the input parameters were modeled by the L20 Plackett and Burman design [14]. Parameter values are screened with the tolerances of 20% compared to the initial value and are then imported in TCAD software. The range to 20% is used according to the process flow variations [15]. The result of analyzing the responses provide Pareto graphs which indicate the importance of the impact of each parameter on the spectral responsivity and the dark current. In Fig. 4, the Pareto graph shows the impact of varied parameters on the spectral responsivity at 500 nm and 900 nm and the leakage current. It is clearly noticeable that trapping mechanisms (bulk traps and donor traps energy position), as well as the epitaxial thickness mostly impact the spectral responsivity. This is due to the fact that the trapping of charge highly reduces the charge collection efficiency, which critically impacts the responsivity. In addition to that, there is a higher impact of the substrate resistivity on the responsivity for higher wavelengths, where, due to the silicon absorption properties, light generates charge carriers deeper in the structure. If the charge is generated in the low-resistive substrate, it will quickly recombine and therefore be lost, thus reducing the overall spectral responsivity. In addition to those parameters, carrier lifetime also plays a significant role on the dark current. A lower lifetime results in the recombination rate increase, thus also increasing the dark current. According to this analysis, from eight initial parameters, the six most relevant have been selected: Substrate resistivity, Epitaxial thickness, Epitaxial doping concentration, Lifetime of charge carriers (relevant for the dark current), Bulk trap density and Donor trap energy position.

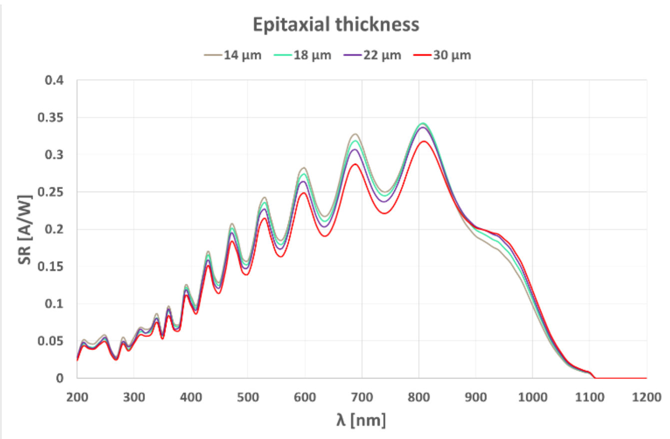

Fig. 3. The effect of different epitaxial thickness on spectral responsivity.

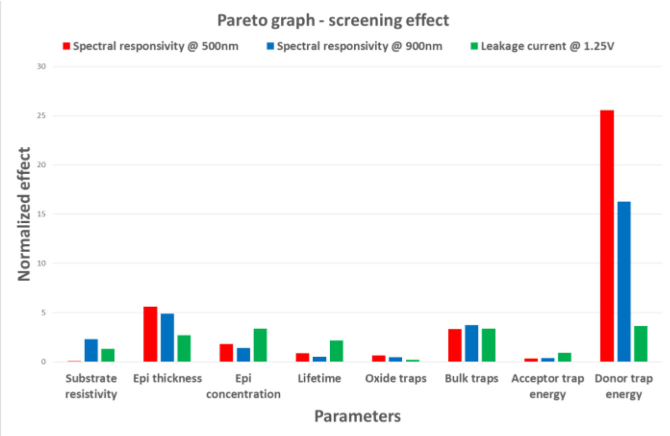

Fig. 4. Pareto graph for the screening analysis: It can be seen that the trapping mechanisms as well as the process parameters have the largest impact on the spectral responsivity, while in addition to those parameters, lifetime also affects the dark current. Apart from that, oxide traps and the acceptor trap energy position had the lowest effect and thus were neglected in the response surface model (RSM) analysis.

Lastly, according to the Pareto graphs from the previous step, oxide traps and acceptor trap energy position were removed from the design due to their negligible effect on the responsivity over the whole wavelength spectrum and on the dark current. Afterwards, according to a central composite full design (with face centered) a RSM is generated, which describes how each response such as dark current at 1.25V corresponds to the operating voltage of the photodiode or the spectral response variation at a selected wavelength as a quadratic function of the six most relevant process and device parameters. The sensitivity analysis of each model is obtained by RSM technics that deliver the variability of each response according to the variation of the input parameters within their variability range. Fig. 5 presents the variability of the spectral responsivity curve as a function of the variability of the donor trap energy position, which has the highest impact on spectral responsivity. The spectrum has its highest variability in 600 nm to 900 nm range and can vary by more than 15% in this range only because of the donor trap energy position parameter. In Fig 6, a histogram of the normalized dark current at the reverse bias voltage of 1.25V and at 340K is shown. The value is normalized to the single island region. The contribution of all parameters variability is contributing to a global variation of +/- 22pA/µm on the dark current that is calculated on the 6-sigma rule.

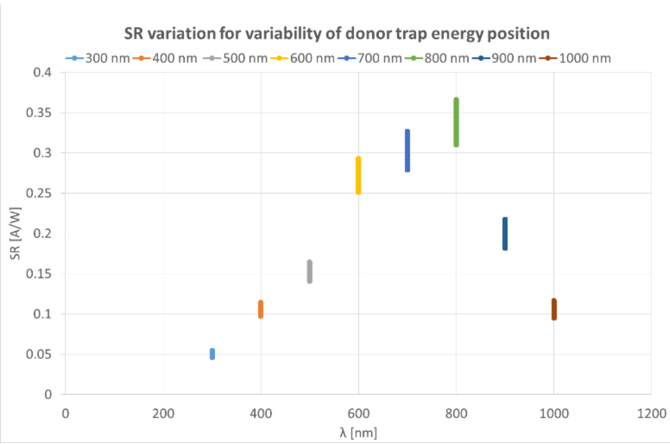

Fig. 5. Variation of the spectral responsivity according to the variability of the donor trap energy position in range from 0.2Eg to 0.3Eg, where Eg is the energy of the forbidden bandgap.

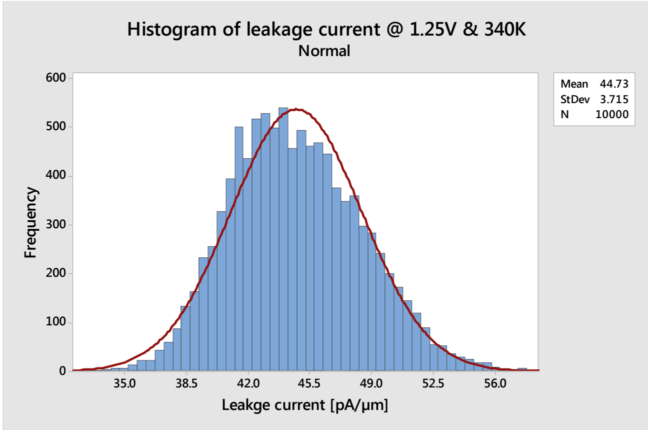

Fig. 6. Histogram of the normalized dark current at 1.25 reverse bias voltage and at the temperature of 340K. Varied parameters are: substrate resistivity, epitaxial thickness, epitaxial doping concentration, maximum lifetime of charge carriers, bulk trap density and donor trap energy position.

CONCLUSION

A radiation-hard photodiode structure is presented where its main characteristics were simulated. A variability methodology is used where geometrical and physical parameters are varied. Observed responses are then analyzed according to the importance of each input parameter. The outcome of the analysis provided Pareto graphs which showed that substrate resistivity, epitaxial thickness, epitaxial doping concentration, bulk trap density and donor trap energy position have the largest impact on spectral responsivity. In addition to that, lifetime of charge carriers has a large impact on the dark current. Finally, the response surface model was generated and simulated where only the most impacting parameters were taken into account. The analysis of this model showed the variation of the responses corresponding to the variability of the input parameters. Increasing the epitaxial thickness, spectral responsivity is improved in the NIR wavelength region. On the other hand, if the epitaxial layer is not fully depleted, charge collection is reduced if the diffusion length of the carriers is not large enough for them to reach the collection electrode. In addition to that, this study have shown that deep level traps have the highest impact on both the spectral responsivity and the dark current. The trade-off between charge collection speed and the increase of leakage current should be taken into account when designing a radiation-hard photodiode. In order to avoid charge trapping and to have a radiation-hard device, it is important to have a large depletion region, so that the trapping probability of charges is reduced. Larger depletion region results in an increased dark current. On the other hand, by choosing a starting material which offers a large diffusion length, charge collection is preserved and the need of a large depletion region is removed. This results in a lower dark current of the device, but also the charge collection speed is reduced.

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