

Fault mechanisms in a CMOS N-diffusion photodiode

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Very little literature is today available describing defects and failure mechanisms in a photodiode. The study of defects is very important, as they can significantly reduce the performances of the photodiode. The reason for the lack of data in this field is the fact that the defects, that increase the dark current and reduce the photogenerated current, are not understood well enough to enable the development of a general model. In this paper we performed an analysis of the defects and failure mechanisms in the photodiode, pointing out their characteristics and their influence on the parameters of the photodiode (photogenerated current, dark current).

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1. Introduction

The electronic image sensors were invented in the late 1960s. The first image sensors, the CCDs (Charge-Coupled Devices) were soon followed by the CMOS (complementary metal oxide semiconductor) image sensors, but only in the early '90s the CMOS image sensors began to be a competitor for the CCDs. The main explanation for this was the fact that the first CMOS image sensors were passive pixel sensors, having a low sensitivity and a high level of noise. The creation of the active pixel sensors (APS) succeeded in solving some of the problems of the first image sensors. Between the advantages of APS sensors we can mention: we can use for their fabrication the standard CMOS technological process, and so their cost is significantly lower; they have a much lower power consumption; they have a single-voltage power supply, unlike the CCDs that frequently require 5 or more supply voltages, with significantly higher power consumption.

Due to their advantages, both CCDs and CMOS image sensors start to eclipse the traditional technology for image recording, such as film, video tubes and photomultipliers, and have various applications for example in digital radiography, military ultra high speed image acquisition, high resolution "smart" security cameras, optical navigation and in various other fields of optoelectronics [1-4].

2. Experimental details

The defect and failure mechanisms in a CMOS photodiode represent a domain without significant results until now, because of the difficulty of obtaining a general model describing them. Some possible sources of defects in CMOS photodiodes were pointed out, though, in literature: doping concentrations, bandgap width, temperature, tunnelling, impact ionization, Shockley-Read-Hall (SRH) thermal generation, device geometry

(number of rounded corners, their angle) and noise (mainly shot noise) [5-9]. ATLAS, which is a T-CAD tool from Silvaco, provides a theoretical description of some of those mechanisms [10]. In spite of that, from our knowledge there are no papers concerning the simulation in ATLAS of these defects. There are also some types of defects that ATLAS cannot deal with, such as for example the device geometry. This source of defects (more precisely the geometry dependence of the dark current of a CMOS photodiode) was one of the very few that were pointed out in an empirical model in a paper. The model emphasizes the dark current dependence of the presence of *corners* (internal and external) in the photodiode structure, taking into consideration both the corner angle and the number of such corners present in the photodiode. The model can be described by the following equation:

$$I_{dark} = \alpha \cdot A + \beta \cdot n \quad (1)$$

where α = the coefficient that determines the junction unity area contribution, A = the junction area, β = the coefficient that determines the corner contribution to the overall dark signal, and n = the number of corners present in the design. This model takes also in consideration the *angle* dependence of the coefficient β . It was shown that β grows inversely with the angle. For the particular case of commonly used pixel designs that contain *rounded and nonrounded corners*, equation (1) becomes:

$$I_{dark} = A + n \cdot R + m \cdot N \quad (2)$$

where A = the contribution to the dark current of the active area of the device, n = the number of rounded corners, R = the coefficient describing the contribution to the dark current of the rounded corners, m = the number of nonrounded corners, and N = the coefficient describing the contribution to the dark current of the nonrounded corners.

The conclusion is that *each rounded corner significantly reduces the magnitude of the dark current* [11].

Also, ATLAS does not provide facilities to analyze the types of noise that may appear in CMOS photodiodes. Despite of that, ATLAS supports a lot of other possible studies of the defects in these devices. Next, we present the results obtained with ATLAS from the simulations of the fault mechanisms in a CMOS n-diffusion photodiode implemented in an AMS 0.35 μm process [12].

3. Results and discussion

The first source of defects we dealt with is represented by the variations of the doping concentrations. We increased and decreased, respectively, the doping concentrations of each type of layer (substrate, p-epitaxial layer, n-diffusion layer, p and n contacts) and observed the impact on the photocurrent and on the dark current of the photodiode. The results we obtained are presented in the following table.

Table 1. Results obtained for the doping concentrations.

Type of layer	Higher/lower doping	Effect on the photocurrent, for high levels of the illumination	Effect on the photocurrent, for low levels of the illumination	Effect on the dark current
Substrate	Higher	Remains the same	Remains the same	Slightly increases
	Lower	Slightly increases	Increases significantly	Increases significantly
P-epitaxial	Higher	Slightly decreases	Decreases significantly	Remains the same
	Lower	Slightly increases	Increases significantly	Increases significantly
N-diffusion	Higher	Slightly decreases	Decreases	Decreases
	Lower	Slightly increases	Increases significantly	Increases significantly
P and n contacts	Higher	Decreases	Simulation problems	Chaotic behaviour
	Lower	Increases	Slightly increases	Simulation problems

In all the previous simulations, we considered that the bandgap does not have a variation with the temperature. If we take into account this variation, we obtain the

dependence of the characteristics of the photodiode with the bandwidth, presented in Table 2.

Table 2. Results obtained for the bandgap width.

Type of defect	Case study	Effect on the photocurrent, for high levels of illumination	Effect on the photocurrent, for low levels of illumination	Effect on the dark current
Bandgap width	Temperature=450K	Significantly increases	Significantly increases	Increases
	Temperature=250K	Remains the same	Significantly decreases	-

If we consider that the bandgap has no variation with the temperature and we take into account only the effect of increasing or decreasing the temperature on the photodiode behaviour, we obtain the results from Table 3.

Another defect source is the impact ionization, which is the process in a material by which one energetic charge carrier can lose energy by the creation of other charge carriers. The generation rate of electron-hole pairs due to impact ionization is modelled according to *Selberherr*:

$$G = \alpha_n \cdot \frac{J_n}{q} + \alpha_p \cdot \frac{J_p}{q} \quad (3)$$

where α_n and α_p are the *ionization rates* for electrons and for holes, respectively, and depend of the electrical field and the temperature. For these two parameters there are three available models: Grant, Selberherr (recommended for most cases) and Crowell-Sze. Grant model is the default model in ATLAS, but Selberherr model is recommended in most situations. The results for these defects are presented in Table 4.

Table 3. Results obtained for the defects induced by temperature.

Type of defect	Case study	Effect on the photocurrent, for high levels of illumination	Effect on the photocurrent, for low levels of illumination	Effect on the dark current
Induced by temperature	450 K	Significantly increases	Significantly increases	-
	250 K	Remains the same	Significantly decreases	-

Table 4. Results obtained for the impact ionization.

Type of defect	Case study	Effect on the photocurrent, for high levels of illumination	Effect on the photocurrent, for low levels of illumination	Effect on the dark current
Induced by ionization impact	Selberherr model	Slightly increases	Simulation problems	Slightly increases
	Higher impact ionization	The same results as before	The same results as before	The same results as before

In the presence of a high electrical field, electrons can tunnel by internal field emission from the valence band into the conduction band. The resulting tunnelling generation rate can be modelled as:

$$G_{BBT} = A_{BBT} \cdot E^\gamma \cdot \exp\left(-\frac{B_{BBT}}{E}\right) \quad (4)$$

where E is the magnitude of the electrical field, and A_{BBT} , B_{BBT} and γ are parameters, their default values being : $A_{BBT} = 9.66 \times 10^{18}$ V/cm, $B_{BBT} = 3 \times 10^{17}$, $\gamma = 20$. For the band-to-band tunnelling, the impact on the photodiode behaviour is shown in Table 5.

Table 5. Results obtained for the band-to-band tunnelling.

Type of defect	Case study	Effect on the photocurrent, for high levels of illumination	Effect on the photocurrent, for low levels of illumination	Effect on the dark current
Band-to-band tunnelling	Higher tunnelling generation rate	Remains the same	-	Slightly increases

The presence of trap and defect centres in semiconductor substrates can influence significantly the electrical characteristics of the device. The trap centres, which have the associated energy located in a forbidden gap, exchange charge with the conduction and valence bands through the emission and recombination of electrons and holes. The trap centres change the density of space charge in the semiconductor bulk and influence the recombination statistics. The densities of the trapped carriers on the discrete set of defect/trap centres are given by:

$$n_t = \sum_{\alpha=1}^k n_t^\alpha, \quad p_t = \sum_{\beta=1}^m p_t^\beta \quad (5)$$

where k is the number of acceptor-like traps and m is the number of donor-like traps, and n_t^α and p_t^β are given by the following equations:

$$n_t^\alpha = N_{ta}^\alpha \cdot \frac{K_n^\alpha + G_p^\alpha}{G_p^\alpha + G_n^\alpha + K_p^\alpha + K_n^\alpha} \quad (6)$$

$$p_t^\beta = N_{td}^\beta \cdot \frac{K_p^\beta + G_n^\beta}{G_p^\beta + G_n^\beta + K_p^\beta + K_n^\beta} \quad (7)$$

where:

$$K_p = \sigma_p \cdot V_p \cdot p, \quad K_n = \sigma_n \cdot V_n \cdot n \quad (8)$$

$$G_p = \frac{1}{\gamma} \cdot \sigma_p \cdot V_p \cdot n_{ie} \cdot \exp\left(\frac{\varepsilon_i - \varepsilon_t}{k \cdot T}\right) \quad (9)$$

$$G_n = \gamma \cdot \sigma_n \cdot V_n \cdot n_{ie} \cdot \exp\left(-\frac{\varepsilon_i - \varepsilon_t}{k \cdot T}\right) \quad (10)$$

where: ε_t = the energy level of each discrete trap centre; N_{ta} , N_{td} = the density of the trap centres; σ_n , σ_p = the carrier capture cross sections; γ = the

degeneracy factor of the trap centre; V_n , V_p = the thermal velocities for electrons and holes; \mathcal{E}_i = the intrinsic Fermi level position. The results obtained with the simulation in ATLAS for this type of defect are

presented in Table 6, for the default values of the model, for a greater and for a smaller number of trap centres.

Table 6. Results obtained for discrete and distributed trap centres.

Type of defect	Case study	Effect on the photocurrent, for high levels of illumination	Effect on the photocurrent, for low levels of illumination	Effect on the dark current
Discrete and distributed trap centres	Trap model, default values	Slightly increases	Significantly increases	Significantly increases
	Trap model, greater number of trap centres	Decreases*	Slightly increases*	Increases*
	Trap model, smaller number of trap centres	Increases*	Slightly decreases*	Slightly decreases*

* as compared to the case of trap model with default values

Other possible sources of faults in the photodiodes are the defect states in the bandgap of the semiconductor material. The density of defect states within the bandgap can be evaluated using the following expressions:

$$g(E) = g_{AT}(E) + g_{DT}(E) + g_{AG}(E) + g_{DG}(E) \quad (11)$$

where:

$$g_{AT}(E) = N_{TA} \cdot \exp\left(\frac{E - E_C}{W_{TA}}\right) \quad (12)$$

$$g_{DT}(E) = N_{TD} \cdot \exp\left(\frac{E_V - E}{W_{TD}}\right) \quad (13)$$

$$g_{AG}(E) = N_{AG0} \cdot \exp\left[-\left(\frac{E - E_{GA}}{W_{GA}}\right)^2\right] \quad (14)$$

$$g_{DG}(E) = N_{DG0} \cdot \exp\left[-\left(\frac{E - E_{GD}}{W_{GD}}\right)^2\right] \quad (15)$$

where: N_{TA}/N_{TD} = the density of acceptor-like/donor-like states in the tail distribution at the conduction/valence band edge; W_{TA}/W_{TD} = the characteristic decay energy for the tail distribution of acceptor-like/donor-like states; E_{GA}/E_{GD} = the energy that corresponds to the Gaussian distribution peak for acceptor-like/donor-like states; W_{GA}/W_{GD} = the characteristic decay energy for a Gaussian distribution of acceptor-like/donor-like states; N_{GA}/N_{GD} = the total density of acceptor-like/donor-like states in a Gaussian distribution. Table 7 presents the results for this defect model in three situations: for the default values, for a greater and for a smaller number of defect states.

Table 7. Results obtained for the defect states in the bandgap of the semiconductor material.

Type of defect	Case study	Effect on the photocurrent, for high levels of illumination	Effect on the photocurrent, for low levels of illumination	Effect on the dark current
Defect states in the bandgap of the semiconductor material	Defect model, default values	Significantly increases	Significantly increases	Significantly increases
	Defect model, greater number of defect states	Slightly increases*	Slightly increases*	Increases*
	Defect model, smaller number of defect states	Slightly decreases*	Slightly decreases*	Slightly decreases*

* as compared to the case of defect model with default values

4. Conclusions

From the results presented in this paper we can conclude that all the defect mechanisms studied have an important impact on the electrical properties of the photodiode (we can see from Tables 1-7 to what extent each defect modifies the values of the photocurrent and of the dark current) and must be taken into consideration in order to obtain an accurate modelling of the photodiode behaviour.

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