An improved BDJ photodetector physical model implemented under SPICE

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ABSTRACT

The physical model of the BDJ photo-detector is evaluated by comparing experimental results with simulations. The model is then improved using a parameter extraction method and by calculating the oxide layer effects. Finally the result model is implemented under SPICE simulators to provide electric simulation of the device.

Keywords: Optical detectors, SPICE models, BDJ, micro-systems, integrated sensors.

1 INTRODUCTION

With the increasing need of compact, accurate and low price systems, integrated sensors, show fast development last years. New and improved integrated circuits incorporating detecting elements with electronic circuitry on the same chip micro-sensors have been presented in the literature and are now widely available commercially. However, in many applications such as electronic imaging and color measurement, integrated sensors still suffer from the use of conventional optical detectors. Indeed, photodiodes and MOS capacitors (most popular sensing elements) needs a set of RGB color filter to provide color components of incident light. This leads to several limitations due to the increase in sensor surface and the additional filter deposition process.

In order to overcome the above limitations we recently developed, in a standard CMOS technology, a wavelength and light intensity sensitive detector[1][2]. The device called BDJ (Buried Double PN Junction), is made up of two buried junction in a stacking form which under illumination gives two photocurrents, I_1 and I_2. As the spectral response is peaked in the blue wavelength region for I_1 and in the red one for I_2, the ratio I_2/I_1 exhibit a monotonous increase versus wavelength. The corresponding curve is thereby used as a reference for wavelength identification, thereafter light intensity is determined using I_1 or I_2 values.

However designing integrated sensors incorporating BDJ detectors seems to be a hard task through lack of a device model implemented under CAD tools. Hence we developed a SPICE model, that describes BDJ behavior if implemented with electronics. The modeling approach we used consists of : i) development of a physical model, ii) evaluation of the model accuracy by comparing simulations with experimental results, iii) improvement of the physical model using a parametric extraction method, iiii) finally, implementing the result physical model under SPICE simulator by defining an electrical model.

2 PHYSICAL MODEL

When an incident monochromatic light with a wavelength $\lambda \leq hc / Eg$, penetrates in the silicon bulk, it is absorbed by the semiconductor and electron hole pairs are generated. The electron hole pairs generation rate depends on the wavelength of the incident light and on the depth x_d from the silicon surface :

$$g(x,\lambda) = \Phi_S \alpha(\lambda) \exp(-\alpha(\lambda) x_d) \qquad (1)$$

where $\alpha(\lambda)$ is the silicon absorption coefficient and ϕ_S is the flux of the incident light at silicon surface.

If a buried p-n junction is formed at x_d and under reverse bias conditions, the photo-generated carriers in the depletion layer will be separated by the electric field leading to a drift current; in neutral regions the photo-generated carriers moving to the depletion layer edge before recombining contribute to diffusion currents.

By implementing two buried junctions at different depths from the silicon surface, under illumination and reverse-biasing conditions two photo-currents I_1 and I_2, flow respectively trough the shallow junction and the deep one. Each of them consists of three current components : a drift current resulting from electron hole-pairs generated in the depletion layer and separated by the electric field; two diffusion currents due to carriers produced in the neutral layers and reaching the depletion edge before recombining.

The two drift currents Idr_1 and Idr_2 produced respectively in the depletion layer of the shallow and the deep junctions (with hypotheses of no recombination in the depletion layer) can be calculated by :

$$I_{dr} = Aq\phi(1 - R(\lambda)) \int_{depletion\ layer} g(\lambda, x)dx \qquad (2)$$

where A is the device active surface, q the electron charge, ϕ the incident photon flux and $R(\lambda)$ is the SiO_2 surface passivation layer reflection coefficient.

To determine the diffusion current components, we first solve the diffusion equation to evaluate minority carrier excess density :

$$D_c \frac{f^2 \Delta c}{f x^2} - \frac{\Delta c}{\tau_c} + g(\lambda, x) = 0 \quad (c = p, n) \qquad (3)$$

under boundary conditions (Δc=0 at depletion layer edge) involving the surface recombination velocity :

$$Sr = \frac{Dn}{\Delta n} \left(\frac{f \Delta n}{f x} \right) \Big|_{x=0} \qquad (4)$$

where D_c is the diffusion constant and τ_c the minority carrier lifetime. Thus diffusion photocurrents are easily calculated using

$$I_{diff} = -AqD_c \frac{f \Delta c}{f x} \Big|_{depletion\ layer\ edge} \qquad (5)$$

Thus one can obtain the following expression for the BDJ two photocurrents :

$$I_1(\lambda) = Aq(1 - R(\lambda)) \phi S_1(\lambda, Sr/Dn, Lnpp, Lp) \qquad (6)$$
$$I_2(\lambda) = Aq(1 - R(\lambda)) \phi S_2(\lambda, Lp, Ln) \qquad (7)$$

where S_1 and S_2 are the junction quantum efficiency.

In fact, the parameter which appear in S_1 and S_2 expression are minority diffusion lengths in the three neutral layers (where $L_c = \sqrt{D_c \tau_c}$) and surface recombination velocity to diffusion constant ratio Sr/Dn.

3 EVALUATION OF THE ANALYTIC MODEL ACCURACY

The model accuracy is evaluated by comparing simulated spectral responses of the device with experimental results. To run simulations, physical parameters of the different device layer's had to be inserted in the analytic model. As the foundry data sheet, gives only dopant levels and junction depths, it is common to use analytic expression given in the literature. However not every parameter has an adequate and available analytic model such as silicon absorption coefficient[6][10][11]. In addition we lack in accurate values of many parameters such as minority carriers diffusion length, surface recombination rate and thickness of the SiO_2 surface passivation layer, which are technology dependent.

Thus in a first approach [3] we neglected reflection on the oxide layer by taking R(λ) = 0, and we retain some realistic values for physical parameters such as surface recombination rate minority carrier diffusion length etc. In another hand we used a G. Geist 11 parameters equation for the silicon absorption coefficient [11] which gives a best fit to W&R experimental results at 298 K. Fig. 1 shows the spectral response of the two junction currents I_1 and I_2 obtained experimentally and simulated results obtained with above described approach. However they have the same form, a significant disagreement between the two curves can be observed. To evaluate our model accuracy we calculate, at every wavelength in the 450nm to 800nm range, the relative error obtained between simulated and experimental results.

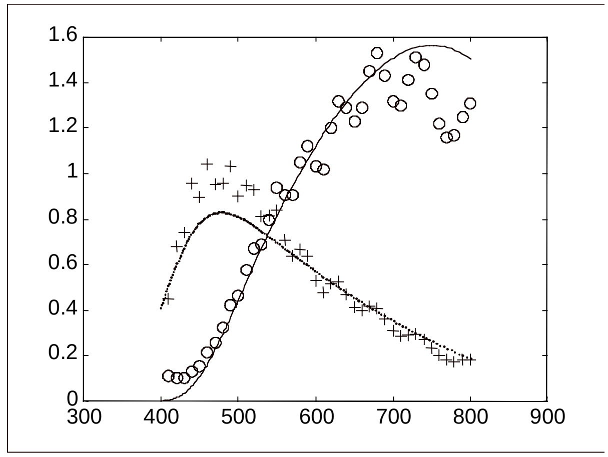

Figure 1 : Spectral response of BDJ detector

The results plotted on fig. 2 show a relative error ranging from 20 % and 30 %. This important error reveal the failure of the above approach that neglects the reflection phenomena on the surface oxide layer and take non rigorous values of physical parameters such as minority carrier diffusion length and surface recombination rate.

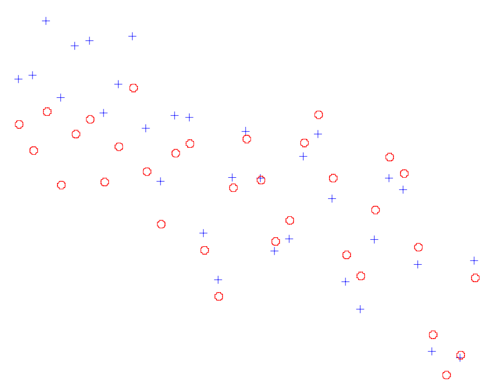

Figure 2 : relative error

4 IMPROVEMENT OF THE ANALYTIC MODEL ACCURACY

In order to improve the physical model accuracy, we used the least squares fitting method to determine the physical parameters in the different layers of the device. We also studied the oxide layer effect on the photocurrents and determined the oxide thickness with the same extraction method.

4.1 Parameters extraction

As we mentioned above, minority carrier diffusion lengths in different layers of the device and the surface recombination rate are technology dependant. Thus the use of values given in the literature leads to significant error between simulation and measurement. As the photocurrent ratio :

$$r(\lambda) = \frac{I_1(\lambda)}{I_2(\lambda)} = \frac{s_1(\lambda)}{s_2(\lambda)} \quad (8)$$

depends only on these parameters, it can be used to extract values that gives best fit to the experimental results.

We used the least squares fitting method to determine the parameter values that reduce the error between simulated and measured r(λ) [4]. Parameter values that lower the error are given in table 1. As it can be seen in fig. 3 plotting r(λ), simulation gives best fit to experimental results using the extracted parameters.

Sr/Dn (µm)	Lnpp (µm)	Lp (µm)	Ln (µm)
744	0.72	0.253	10.748

Table 1: diffusion lengths and Sr/Dn ratio.

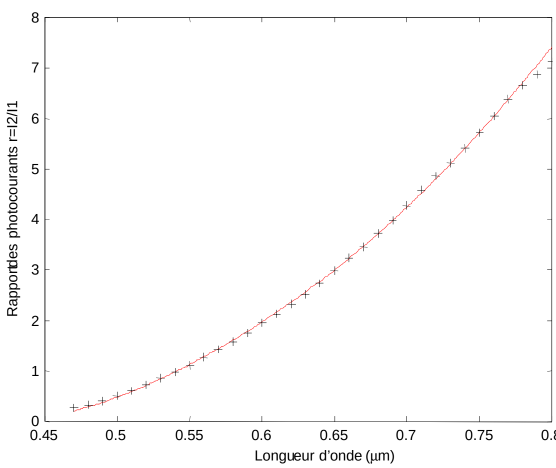

Figure 3 : Ratio of photocurrents I_2/I_1 versus wavelength after parameter extraction

4.2 Oxide layer effect

The fluctuations due do the oxide layer can be given by the following expression :

$$\frac{I_{1mes}(\lambda)}{s_1(\lambda)} = \frac{I_{2mes}(\lambda)}{s_2(\lambda)} = Aq(1 - R(\lambda))\phi(\lambda) \quad (9)$$

where $S_1(\lambda)$ and $S_2(\lambda)$ are calculated using the extracted parameters given in Table.1.

As the oxide layer is assumed as a non absorbing medium, the transmission coefficient is equal to (1-R), where R is the reflection coefficient. This reflection coefficient R(λ) can be calculated by solving Maxwell equations for a sandwiched SiO_2 layer between air and Si mediums. R(λ) depends on air and Si refraction coefficients, Si extinction coefficient and SiO_2 thickness.

As the Si extinction coefficient is proportional to the absorption coefficient and to the wavelength, we used G. Geist equation [11] (giving α(λ)) to determine its values. Because only experimental results are available for the Si index of refraction we used a 5^{th} order polynomial function to fit the data [5][7][8][9][12].

Thus one can obtain the following expression for extinction rate [13]:

$$r = \frac{r_1 + r_2 e^{-2jk_1 d}}{1 + r_1 r_2 e^{-2jk_1 d}} \quad (10)$$

where r_1, r_2 are the reflection rate between air and SiO_2; SiO_2 and Si respectively; k_1 is the wave vector of the incident light.

The reflection coefficient is equal to the square of r modulus and shows fluctuation versus wavelength. Using the least squares fitting method we determined the oxide layer thickness that gives best fit between the two members of equation (9). The corresponding value is equal to 3µm and gives the fluctuation plotted in fig.4.

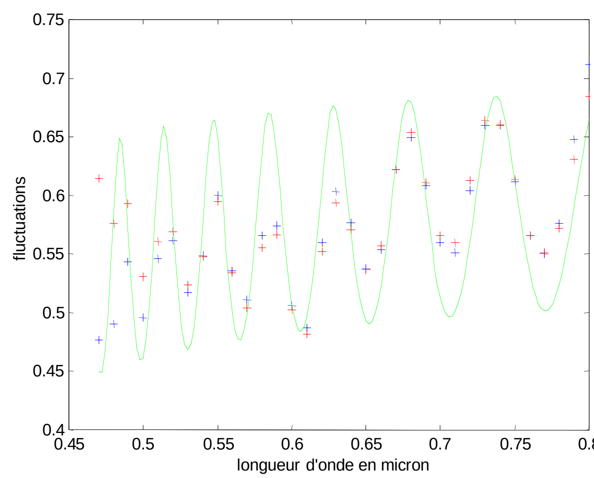

Figure 4: Fluctuations.

The results obtained using the extracted parameters are shown in fig.5, it can be seen the simulation fits well the experimental results for both I_1 and I_2..

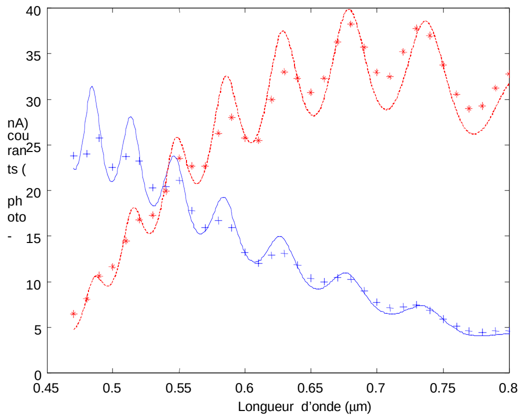

Figure 5 : Spectral responses of BDJ detector after parameter extraction

The error between simulation and measurement (fig.6) is lowered compared with that of fig.2.

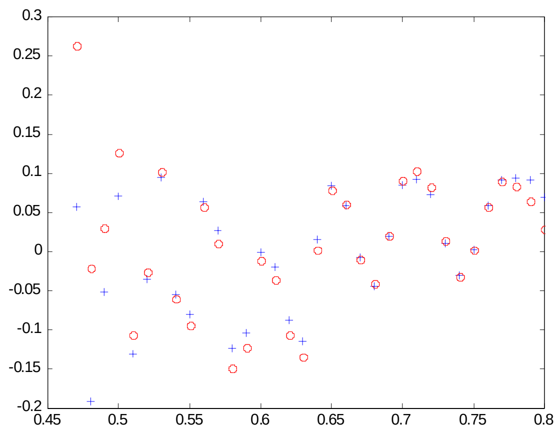

Figure 6 : relative error

5 ELECTRICAL MODEL IMPLEMENTED UNDER SPICE

The improved physical model is then implemented under SPICE simulator, to provide BDJ device simulation with electronics. The corresponding electrical circuit is presented in fig.7. It incorporates two ideal diodes each one being connected in parallel to a capacitor and represents the two buried junctions and their junction capacitors; the photo-conductive effect is represented by two current sources. In a first approach the input resistors are not represented in the electric model assuming that their contribution can be neglected since photocurrent values are the order of nA.

Under SPICE, BDJ electric model consists of a sub-circuit with four nodes. One node is used to determine wavelength, two nodes can be used for device connection to other circuits and the last is connected to substrate bias.

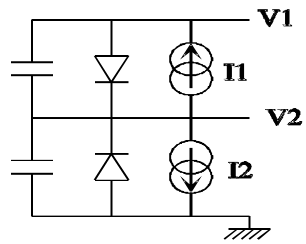

Figure 7 : Large signal schematic diagram for BDJ detector

6 CONCLUSION

In order to provide a SPICE model for the BDJ device, we first evaluated a physical model by comparing simulated results with the detector spectral response determined experimentally. An important error is observed and is due to neglecting the oxide layer effect and to non rigorous parameters values used in our model. In order to improve the physical model accuracy we developed a parameter extraction method and determined the oxide layer thickness. Thus the lowered the error between simulation and experimental results. The resulting model is then implemented under SPICE to provide electrical simulation.

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