Microelectronics Journal 43 (2012) 980–984

Contents lists available at SciVerse ScienceDirect

Microelectronics Journal

journal homepage: www.elsevier.com/locate/mejo

A Verilog-AMS photodiode model including lateral effects

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ARTICLE INFO

Article history:
Received 30 January 2012
Received in revised form
7 September 2012
Accepted 11 September 2012
Available online 17 October 2012

Keywords:
CMOS image sensors
Photodiode
Compact modelling
Lateral collection
Verilog-AMS
Circuit simulation

ABSTRACT

The market of CMOS image sensors is rapidly gaining an importance since optoelectronic devices are present in an increasing number of electronic systems. Therefore, accurate scalable optoelectronic models for photodetectors are necessary to predict their behaviour by circuit simulation. Hardware description languages (HDLs) offer an effective and efficient way to describe these systems. In this work, a Verilog-AMS model for the photoresponse of a CMOS photodiode including lateral effects is presented and a simplified equivalent electrical circuit of the photodiode is used to simulate two different pixel cells in Cadence framework.

1. Introduction

The reverse-biased p–n junction photodiode (PD) is one of the most popular types of photodetectors used in CMOS image sensors. Therefore, the prediction of its behaviour prior to manufacture is crucial for the design of these systems. The power and flexibility of current standard hardware description languages (HDLs) offers an effective and efficient way to describe these multiple domain and mixed-signal electronic systems. For this reason, accurate scalable optoelectronic models for photodetectors in HDLs are essential to verify the correct behaviour of the whole image device by means of circuit simulation in standard CAD tools.

At the moment, the dominant HDLs in the electronics industry are VHDL and Verilog. Although they were developed to be used in the digital domain, nowadays both provide analog and mixed-signal extensions which offer effective means to describe and simulate multi-discipline systems [1]. The extension of the VHDL standard that supports the description and simulation of analog, digital, and mixed-signal circuits and systems is informally known as VHDL-AMS, while Verilog-A and Verilog-AMS are the analog and mixed-signal Verilog extensions, respectively. Compared to SPICE language for circuit simulation, HDLs offer some benefits as the description of non-electrical mechanisms as far as they can be described with mathematical expressions. Moreover, the models can be directly interfaced with any circuit simulator owing an appropriate compiler.

Several authors have presented some attempts to address both the development of photodiode models and their implementation into HDLs. The large variety of models includes different devices (vertical, lateral, pinned, etc.) with different junctions (n^+–p_{subs}, n^+–p_{well}, p^+–n_{subs}, p^+–n_{well}, etc.). There are empirical, semi-analytical and analytical models and they deal with 1D, 2D and 3D geometrical descriptions. Regarding the translation into HDLs, there are only a few works published in the last decade. In Ref. [2] a collection of models for optoelectronic devices is presented, including a model for a high speed InGaAs PIN photodiode in VHDL-AMS. Although the photodiode model is based on a commercial device and the mathematical expressions are not given, the work is a good example of the HDLs potential. A Verilog-A photodiode model is presented in [3] within the framework of the development of an open source circuit simulator supporting Verilog-A standardization. However, the photocurrent model is not proposed in terms of physical and technological parameters and it must undergo a heavy characterization process prior to be used as a design element. Finally, several photodetectors and pixel sensors are modelled with VHDL-AMS in [4,5], respectively, but the mathematical models follow classical expressions. All the previous models share the characteristic of being based on classical 1D representations of photodetectors and neither of them include 2D lateral effects.

In this work a Verilog-AMS CMOS photodiode model including lateral effects is presented. Circuit simulations of two different pixel cells in a Cadence framework were performed, showing a

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0026-2692/$ - see front matter
http://dx.doi.org/10.1016/j.mejo.2012.09.001

good agreement with the expected behaviour. In Section 2 the geometry of the device is presented and the physical phenomena that appear in the reverse operation regime under uniform illumination are described. The current components included in the analytical model are summarized in Section 3. Finally, Section 4 focuses on the Verilog-AMS implementation and circuit simulation results.

2. Device description

A n^+–p photodiode of small dimensions under uniform illumination impinging perpendicularly onto the top surface is studied. To do so, a square-shaped photodiode will be considered without loss of generality, see Fig. 1. The total area of the device and the n^+ diffusion or active area are x_ℓ^2 and x_{ph}^2, respectively. The device has a junction depth y_j and thickness y_w. In reverse-bias operation three main regions are distinguished: two quasi-neutral regions and the depletion region with thickness W (in y-direction) and W_ℓ (in x-direction). We assume the depletion region to be located in the substrate because of its lower doping concentration.

The photodiode is operated in the visible range. The static characteristic is studied by solving the continuity equations to describe the carrier transport features in the device. The total steady-state current of the photodiode in the reverse operation regime comprises several components, Fig. 1. Firstly, the active area current I_{aa} generated by the diffusion of minority carriers and generation of electron–hole pairs in the depletion region. Secondly, the current generated in the lateral depletion region I_W where carriers mainly move by drift. This current component can be calculated by integrating the generation rate over the whole lateral depletion region, although it has been shown previously that its contribution is not very important [6]. Finally, the lateral current $I_{lateral}$ generated in the surroundings of the photodiode by minority carriers that reach the junction by diffusion. This phenomenon is most pronounced in small photodiodes due to the increase of the lateral-area to active-area ratio. It was proved that its magnitude is comparable to the active area current I_{aa} for small photodiodes, showing a strong dependence on the dimension of the active area in relation to the collecting surrounding area [6].

3. Analytical model formulation

There are previous works that have tackled the calculation of the output current density when the active area is illuminated. In [7] a mathematical model of the photogenerated current density on a p^+–n junction PD is presented. In our case, proceeding in a similar way, the stationary continuity equation in one dimension is solved in the quasi-neutral regions as the minority carriers mainly move by diffusion:

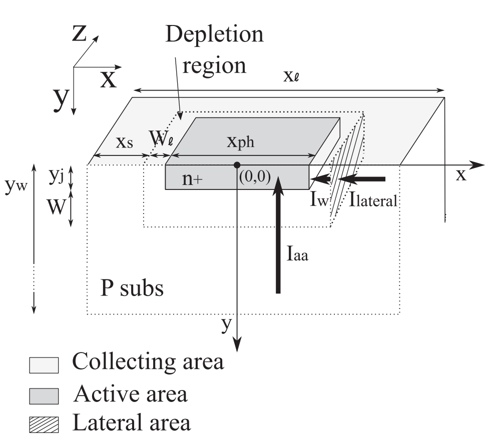

Fig. 1. Cross section of the photodiode 3D structure.

$$D_n \frac{\partial^2(n_p - n_{p0})}{\partial y^2} - \frac{n_p - n_{p0}}{\tau_n} + G(y) = 0 \tag{1}$$

where n_p and n_{p0} are the electron concentration and its equilibrium value, respectively, D_n and τ_n are the electron diffusion coefficient and lifetime, and $G(y) = -\partial\Phi/\partial y$ is the optical generation rate, i.e. the number of photogenerated electron–hole pairs per unit volume and time (where Φ is the photon flux). According to Beer's law, Φ decreases exponentially with the depth in Si, y, $\Phi(y) = \Phi_0 e^{-\alpha y}$, where α is the absorption coefficient and Φ_0 is the photon flux penetrating the silicon surface. The latter can be written as $\Phi_0 = P_{opt} T\lambda/hc$, where P_{opt} represents the incident optical power, T the transmission coefficient, h Plank's constant, λ the impinging radiation wavelength and c the speed of light. The procedure is similar for holes in the n^+ region

$$D_p \frac{\partial^2(p_n - p_{n0})}{\partial y^2} - \frac{p_n - p_{n0}}{\tau_p} + G(y) = 0 \tag{2}$$

Eqs. (1) and (2) are solved subjected to the boundary conditions

$$\left.\begin{aligned} &p_n(0) = p_{n0} + \frac{D_p}{S_p} \left.\frac{\partial(p_n - p_{n0})}{\partial y}\right|_{y=0} \\ &p_n(y_j) = p_{n0} e^{qV_{PD}/KT} \\ &n_p(y_j + W) = n_{p0} e^{qV_{PD}/KT} \\ &n_p(y_w) = n_{p0} \end{aligned}\right\} \tag{3}$$

where V_{PD}, S_p, K, and T are the reverse-biased voltage of the photodiode, surface recombination velocity of holes, Boltzmann constant and temperature, respectively. In the depletion region carriers mainly move by drift. The high electric field inside this region moves charges out to neutral regions before they can recombine. Consequently, the photogenerated current density in the depletion region can be found by integrating the generation rate over the whole region. The total current can be calculated as sum of drift and diffusion currents at the edges of the depletion region multiplied by the active area

$$I_{aa} = q x_{ph}^2 \left(\int_{y_j}^{y_j+W} G(y)\,dy + D_n \left.\frac{\partial n_p}{\partial y}\right|_{y_j+W} - D_p \left.\frac{\partial p_n}{\partial y}\right|_{y_j} \right) \tag{4}$$

Regarding the lateral depletion region, the photogenerated current can be found by integrating the generation rate over the whole region:

$$I_W = 4\,q \int_{-x_{ph}/2}^{x_{ph}/2} \int_0^{W_\ell} \int_0^{y_j+W} G(y)\,dy\,dx\,dz \tag{5}$$

The corners of the depletion region have been neglected in the calculation since their influence on the p–n junction device is low in comparison with the lateral regions.

However, the most challenging task is to model the lateral current density through the device, $I_{lateral}$. The surroundings of the photodiode form four lateral p–n junctions in the x and z directions. Consequently, the steady-state two-dimensional continuity equation has to be solved,

$$\frac{\partial^2(n_p - n_{p0})}{\partial x^2} + \frac{\partial^2(n_p - n_{p0})}{\partial y^2} - \frac{n_p - n_{p0}}{\tau_n D_n} + \frac{G(y)}{D_n} = 0 \tag{6}$$

For this purpose we apply the following boundary conditions at the borders of the lateral region:

$$n_p\left(\frac{x_\ell}{2}, y\right) = n_{p0}, \quad n_p\left(\frac{x_{ph}}{2} + W_\ell, y\right) = 0 \tag{7}$$