CMOS PHOTODIODE MODEL USING VHDL-AMS

Nur Sultan Salahuddin
Fakultas Ilmu Komputer dan Teknologi Informasi, Universitas Gunadarma
Jl. Margonda Raya No. 100 Depok 16424
Sultan@staff.gunadarma.ac.id

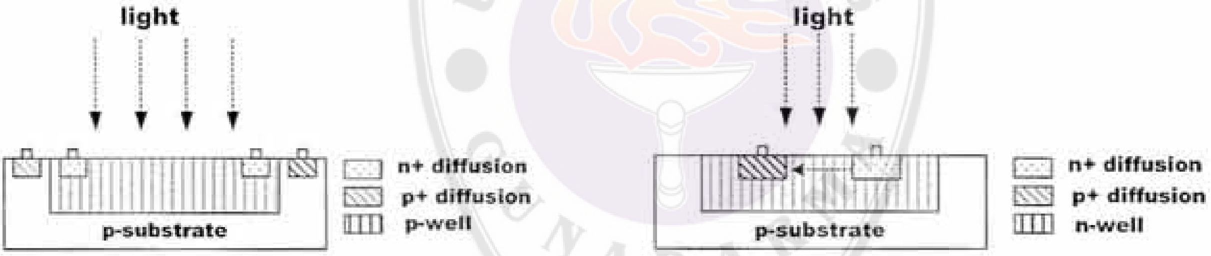
ABSTRACT

The objectives of this research is to designed and simulated CMOS photodiodes models using VHDL-AMS with the ADVance-MS (ADMS) simulation tool of Mentor Graphics. The Photodiode models show a logarithmic response in illumination and are capable of detecting blue or green light emitting diode. The result is fast and thorough design verification before the expense of fabrication.

Key Words: light, diffusion, substrate, drift

INTRODUCTION

In a standard CMOS process several parasitic junction can be used as photodiode either p-well or n-well (Jin, et al., 1997). Two pixels different structure as shown in Figure 1 have been realized using a photodiode formed n+ diffusion in the p-well (vertical photodiode) and n+ and p+ diffusion in the n-well (lateral photodiode). The photodiode is forward biased, and when incoming photons are absorbed, a photocurrent proportional to the intensity of light flows through the photodiode. This current is converted to output voltage value using current mirroring integration readout circuits (Nur Sultan, 2004).



(a) (b)

Figure 1. Two Photodiode structures on p-type substrate, (a) partly hollowed n+ diffusion in p-well (vertical photodiode), (b) partly hollowed n+ and p+ diffusion in n-well (lateral photodiode).

CMOS Photodiode Model

Photocurrent happens because incident light incites electron-hole pairs. When a potential applied on two sides of a photodiode separates the electron-hole pairs, the photo current is generated. Two major sources of photo current are (1) from the diffusion current due to an imbalance of carrier concentration outside of the depletion region; (2)from the drift current due to the separation of electron-hole pairs within the electric field of the depletion region. The vertical (Reginald and Arora, 1996) and lateral (Moini, 1997) photodiode model is developed by analyzing the steady-state response (in one dimension) of the n-p junction diode shown in figure 2 to optically induced excess charge.

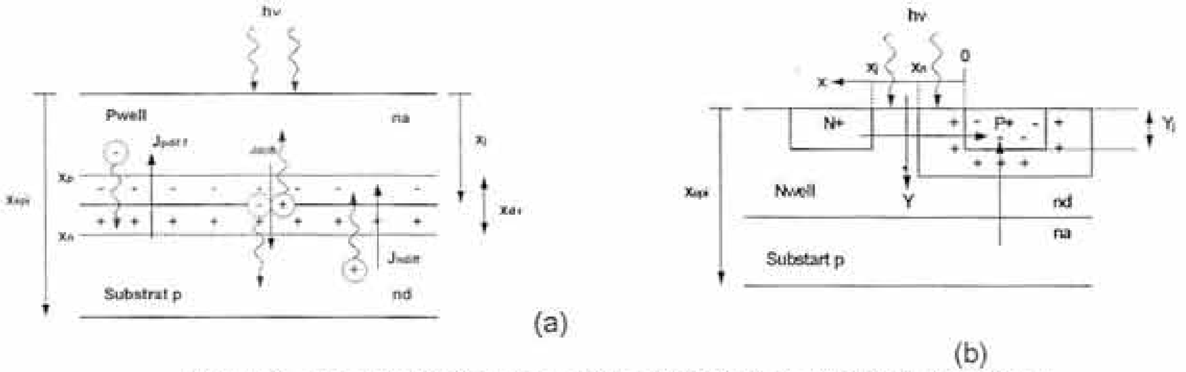


Figure 2. One Dimension n-p junction photodiode: (a)Vertical, (b) Lateral .

The analysis is based on an ideal solution to the drift-diffusion semiconductor device equations as outlines in (Schroder, 1990) and (Sze, 1980). It assume that (1) the electric field is zero outside the depletion region, (2) excess minority carrier concentration at all depletion region boundaries are zero (i.e. $\Delta n = \Delta p = 0$),(3)the optical source monochromatic, and (4) low-level injection conditions exist.

The drift current in depletion region Figure 1a is:

$$J_{Drift} = -q \int_{x_j - x_n}^{x_j + x_p} G(x)\,dx \quad (1).$$

Where G(x) is the carrier generation rate due to the optical radiation, ϕ_0, in a semiconductor with an absorption coefficient of α ,and is given by

$$G(x) = \phi_0 e^{(-\alpha x)} \qquad (2).$$

Hence,

$$J_{Drift} = \frac{q\phi_0}{\alpha} e^{-\lambda x_j}\left(1 - e^{-\lambda x_{dr}}\right) \qquad (3).$$

The diffusion current outside the depletion region is calculated using Equation (5) through (10). The total current is the summation of the drift and diffusion current, as shown in Equation (11).

$$J_{diff\_Pwell} = \frac{q\phi_0 L_n}{(\alpha L_n)^2 - 1}\left[\alpha L_n\, e^{-\alpha x_j} + \sinh\left(\frac{x_j}{L_n}\right) + A(\alpha, x_j, L_n)\cosh\left(\frac{x_j}{L_n}\right)\right] \qquad (5).$$

$$J_{diff\_sub} = \frac{q\phi_0 L_p}{(\alpha L_p)^2 - 1} e^{\alpha(x_j + x_{dr})}\left[A\left(\alpha, x_{epi} - (x_{dr} + x_j), L_p\right) + \alpha L_p\right] \qquad (6).$$

$$x_{dr} = \sqrt{\frac{2\varepsilon_{si}(\phi_{bi} + V_d)}{q}\left(\frac{1}{na} + \frac{1}{nd}\right)} \quad , \varepsilon si = 11.8\varepsilon_0 \qquad (7).$$

$$\phi_{bi} = V_t \ \ln\left(\frac{na\ nd}{ni^2}\right), \quad Vt = \frac{kT}{q} \qquad (8).$$

$$A(\alpha, x, L) = \left(\frac{e^{-\alpha x} - \cosh\left(\frac{x}{L}\right)}{\sinh\left(\frac{x}{L}\right)}\right) \qquad (9).$$

$$\begin{aligned} D_p &= V_t\mu_p, D_n = V_t\mu_n \\ L_p &= \sqrt{D_p\tau_p}, \quad L_n = \sqrt{D_n\tau_n} \end{aligned} \quad (10).$$

$$J_{total} = J_{drift} - J_{diff\_pwell} - J_{diff\_sub} \quad (11).$$

the structure of lateral photodiode Figure 1b, assume that only the area between the two fusion is exposed to the light. Because erwise, there will be a large contribution from vertical bipolar component formed by p-fusion/n-well/p-substrate. We also assume that the effective depth of the device is only y_j. The drift current in the depletion region is:

$$J_{tr} = -q\phi_0 G(y)x_n \quad (12).$$

And the diffusion current is:

$$J_{diff} = \frac{-qD_p\left(p_{n0} - \tau_p G(y)\right)}{L_p \sinh\left(\frac{x_j - x_n}{L_p}\right)}\left[1 - \cosh\left(\frac{x_j - x_n}{L_p}\right)\right], \; p_{n0} = \frac{n_i^2}{na} \quad (13).$$

e total current can be obtained by integrating addition of the drift and diffusion components across the depth and width of the device.

$$\begin{aligned} J_{total} &= \int_0^{y_j} -A + BG(y) - q\phi_0 G(y)x_n \\ &= -Ay_j + \left(B - q\phi_0 x_n\right)\phi_0\left(e^{-\alpha y_j} - 1\right) \end{aligned} \quad (14).$$

ere

$$A = \frac{qD_p p_{n0}\left(1 - \cosh\left(\frac{x_j - x_n}{L_p}\right)\right)}{L_p \sinh\left(\frac{x_j - x_n}{L_p}\right)} \quad (15).$$

$$B = \frac{qD_p\tau_p\left(1 - \cosh\left(\frac{x_j - x_n}{L_p}\right)\right)}{L_p \sinh\left(\frac{x_j - x_n}{L_p}\right)} \quad (16).$$

$$x_{dr} = \sqrt{\frac{2\varepsilon_{si}\left(\phi_{bi} + V_d\right)}{q}\left(\frac{1}{na} + \frac{1}{nd}\right)} \quad (17).$$

Implementation in ADMS

This photodiode model has been implemented in VHDL-AMS with the Advance-MS simulation tool of Mentor Graphics. We defined entity and architecture of photodiodes, to simulate the response to a monochromatic light. Entity photodiode is:

```
          generic (T :Real :=298.0 ;
               ni :Real :=1.45e10 ;
               ....
                    xj :Real :=2.5e-4 ;
                    xepi :Real :=4.5e-4 ;
                    Nd :Real :=145.0e15 ;
                    Na :Real :=52.0e15) ;
               port(terminal anode,cathode
:electrical) ;
          End entity photodiode ;
```

Architecture vertical of photodiode is:

```
               constant vtx :Real :=0.0258 ;–Vt=K*T/q
                         ....
                         constant esi :Real :=11.8*eo ;
                         quantity vd across anode to chatode ;
                         quantity alpha :Real ;
                         ....
                         quantity jtr :Real ;
                         quantity jpdiff :Real ;
                         quantity jndiff :Real ;
                    Begin ....
                         alpha==(((84.732)/lamda)-79.417)**2 ;
                         jtr==qg0*(exp(-alpha*xj))-cosh(xj/Ln))/sinh(xj/Ln) ;
                         jpdiff==qg0*Lp*(Ap+alpha*Lp)*(exp(-alpha*DRB))/
                         (1.0-(alpha*Lp)**2) ;
                         jndiff==qg0*Ln*(alpha*Ln*exp(-
               alpha*xj))+cosh(xj/Ln)
                         *An+sinh(xj/Ln))/(((alpha*Ln)**2)-1.0) ;
                         jtotal==jtr-jpdiff-jndiff ;
          End Architecture caisson–n ;
```

Architecture photodiode_test of test_bench is:

```
terminal vin,vout :electrical ;
     Begin
          vo :entity work.Vdc(continue)
               generic map (amplitude→5.0)
               port map (p→vin,m→electrical_ground ;
          Ro :entity work.resistor(simple)
               generic map (r→5.0)
               port map (vpos→vout,vneg→electrical_ground ;
          PD :entity photodiode(vertical)
               generic map (xj→2.5e-4,
                              xepi→4.5e-4,
                              Nd→145.0e15,
                              Na→52.0e15,
                              lamda–min→0.4,
                              lamda–min→1.0)
               port map (vpos→vout,vneg→electrical_ground
     End Architecture photodiode_test ;
```

o validate our model, we simulated the spectral ensibilities of vertical and lateral photodiode hown in Figure 3. These curves are obtained y scanning the wavelengths. The photodiodes as to be reverse biased and a direct voltage ource is therefore needed. It is defined as an ntity and architecture. These elements photodiode and voltage source) were implemented in the test-bench in order to simulate this simple test circuits. To obtain a dynamic response, we have been defined an electrical model associated to the component shown in figure 4 (Reginald and Arora, 1996). A photodiode is a PN junction, it can thus be represented by a diode with its junction capacitance $C_{junction}$.

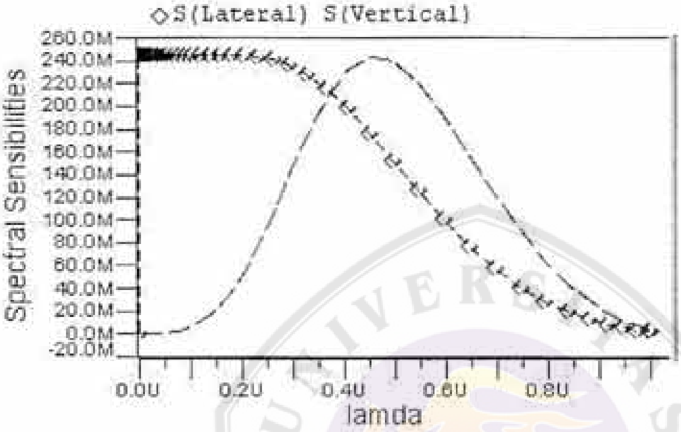


Figure 3. Spectral sensibilities of vertical and lateral photodiode.

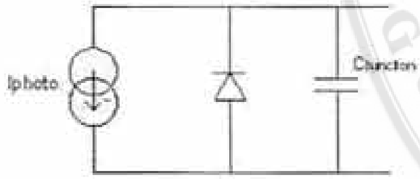
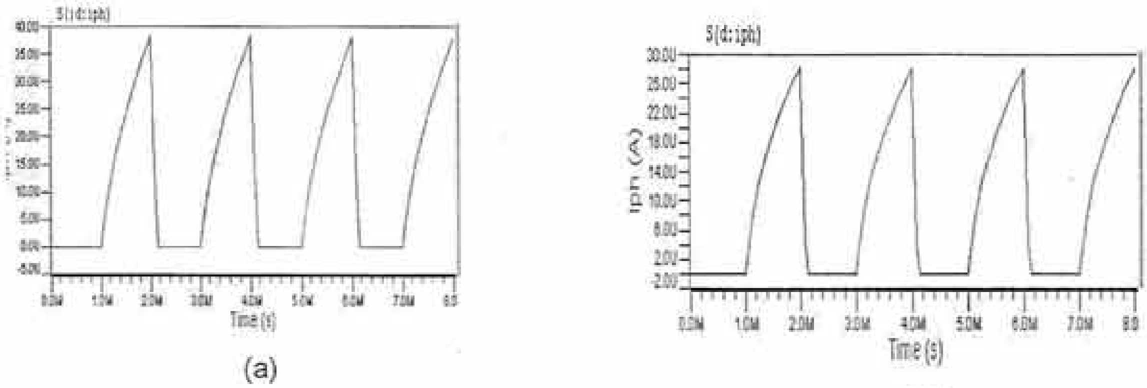


Figure 4. Electrical model of photodiode.

And to validate the model of the capacitance, dynamic simulation was performed. A generator of pulses was applied across the photodiode and resistance was associated with the circuits. The period of the signal was chosen to let the time constant of the circuits appear, the results shown in figure 5. The parameters used in the simulation are those given by AMS foundry for the CMOS 0.6 µm technology.



(a)

(b)

Figure 5. Dynamic characteristic of the photodiode: (a) Lateral and (b) Vertical.

CONCLUSIONS

The CMOS photodiode model has been simulated using (ADMS) simulator. The Simulation results show that this sensor is capable of detecting very low blue lights emitting diode The result is fast and thorough design verification before the expense of fabrication.

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