Extended Abstracts of the 2006 International Conference on Solid State Devices and Materials, Yokohama, 2006, pp. 664-665

P-7-16

Photodiode Model for CMOS Image Sensor SPICE Simulation

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1. Introduction

With the rapid development of CMOS image sensor (CIS), a pixel model capable of predicting the optical behavior of the photo-detector is essential for accurate simulation of the pixel operation. Unfortunately, no accurate pixel model is currently available for the optical responses of CIS active pixel sensors (APS) [1]-[3]. In general, the photodiode in a conventional APS is modeled as a current source with a parallel capacitor as plot in Fig.1. The simplified description is often not sophisticated enough to simulate those circuits whose performance depend critically on the photodiode characteristics. Therefore, the purpose of this work is to establish a close-form photodiode model, providing both accurate electrical and optical responses for the CIS pixel circuit simulation.

2. Dark current and Photocurrent of a Photodiode

Fig. 2 shows the dc equivalent circuit of a MOSFET adopted by BSIM3.3 model [4]. For a photodiode with the source/drain (S/D) parasitic junction diode, the dark current can be expressed as

$$I_{dark} = JS \times AS + JSSW \times PS + GMIN \times V_{BS}$$

Where *JS* and *JSSW* are the S/D leakage current density and S/D sidewall leakage current density. They are functions of operating temperature, and related to fabrication process. *AS* and *PS* are area and perimeter of the junction. *GMIN*, without any physical meaning and set to $10^{-12}\ \Omega^{-1}$ by default, is added to help convergence of numerical solution computation. V_{BS} is the junction reverse bias.

When the junction is illuminated by photons with $h\nu > E_g$, the photocurrent is generated (Fig.3). It can be described as

$$I_{photo} = J_{photo} \times AS\ ;\ J_{photo} = J_{dn} + J_{drift} + J_{dp}$$

$$J_{drift} = -q\int_{x_{jn}}^{x_{jp}} G(x,\lambda)dx = q\Phi_0 e^{-\alpha x_{jn}}\left(1-e^{-\alpha x_d}\right)$$

is the drift current generated in the space charge region. It is a function of absorption coefficient, reflection rate and excess minority carrier generation rate of Si and intensity and wavelength of incident light. J_{dn} and J_{dp} are the photocurrents generated in the N and P-type neutral regions.

Once the parameters of the junction are known, circuit designers can simulate the pixel characteristics with different pixel structures, photodiode sizes and wavelengths under various light intensity levels [5].

3. Sample Fabrication

The samples used for verifying this model are fabricated by the silicided 0.35μm 2P4M standard CMOS logic process. The test circuits, as list in Tab. 1, are conventional 3-T APS pixels with resist protection oxide (RPO) masked N+/P-sub photodiodes.

4. Experimental Results and Discussions

Fig. 4 presents the schematic of the proposed photodiode model. It consists of a diode, D_{photo}, an independent voltage source, V_{photo}, for setting of light intensity and a voltage controlled current source, I_{photo} for generating of photocurrent.

The un-illuminated measurement results and simulation data with the original BSIM3.3 model are shown in Fig. 5. The simulations do not coincide with the measurements due to the influence of *GMIN*, *JS* and *JSSW*. In this work, we replaced the *JS* and *JSSW* with *JS'* and *JSSW'* because of that the values of *JS* and *JSSW* extracted by the conventional method do not agree well the measurement results. While the areas and perimeters of the junction in standard devices are much different from those of the photodiode, the simulation results are naturally not agreed with the measurement data. In addition, we reset the *GMIN* to $10^{-21}\ \Omega^{-1}$ to suppress the effect of the non-physical meaning item in the dark signal simulations. Fig. 6 shows the simulation results with the replaced values of *GMIN*, *JS'* and *JSSW'*. It demonstrates that the revised dark signals match the measurements much better than the original simulations.

When we simulated the lighting situation, the V_{photo} was set to meet the corresponding Lux value. Then, the photocurrent was generated in I_{photo} according to the values of V_{photo} and wavelength. Tab. 2 shows the calculated RGB photocurrents for several illuminations. Comparing the simulations with the measurements plotted in Fig. 7 and Fig. 8 shows that the characteristics of the photodiode model are very similar to the actual optical responses measured on a pixel.

5. Conclusions

In this work, we proposed a photodiode SPICE model for both electrical and optical simulations of CIS pixels. The experiment results demonstrate that the model can predict the pixel characteristics very well and can provide a more accurate tool for performance optimization and system-on-chip simulation on various CIS applications.

Reference

[1] W.J. Liu, et al., IEEE-BMAS, pp. 102-105, 2001
[2] I. Shcherback, et al., SPIE-Opt. Eng., Vol. 41, Issue 6, pp. 1216-1219, 2002
[3] D. Passeri, et al,.Nucl. Instr. and Meth. in Phy. Res. Sec. A, Vol. 511, Issues1-2, p. 92-96, 2003
[4] W. Liu, MOSFET Models for SPICE Simulation, Including BSIM3v3 and BSIM4, 2001
[5] L. Ravezzi, et al., Microelectronics Journal, Vol. 31, Issue 4, p. 277-282, 2000

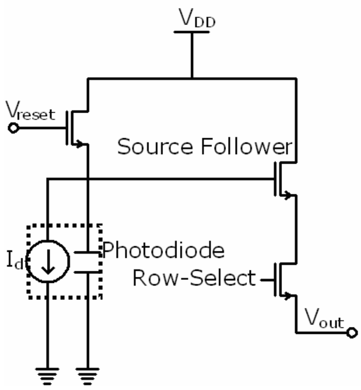


Fig.1. Photodiode is general modeled as a current source with a parallel capacitor.

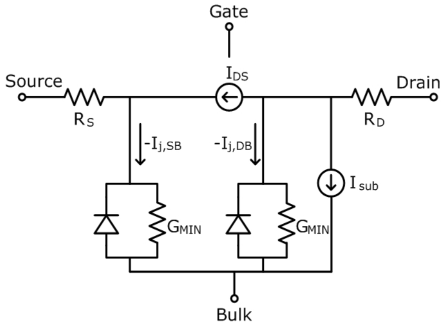


Fig.2. The dc equivalent circuit of a MOSFET adopted by BISM3.3 model.

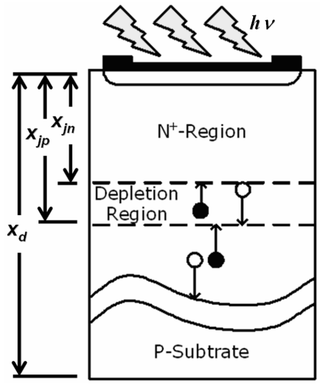


Fig.3. When the junction is illuminated by photons with $h\nu > E_g$, photocurrents are generated.

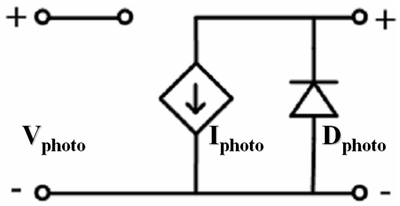


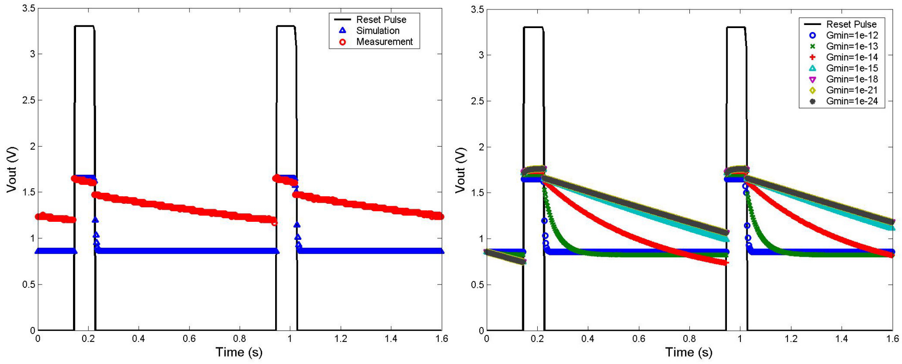
Fig.4. The equivalent schematic of the proposed photodiode model

	Area (cm^2)	Periphery (cm)
Pixel_1	4.204×10^{-8}	14.954×10^{-4}
Pixel_2	6.50985×10^{-8}	15.934×10^{-4}
Pixel_3	9.289043×10^{-8}	17.14×10^{-4}
Pixel_4	12.339442×10^{-8}	19.566×10^{-4}
Pixel_5	16.716676×10^{-8}	22.604×10^{-4}
Pixel_6	21.337377×10^{-8}	25.55×10^{-4}
Pixel_7	26.584435×10^{-8}	28.543×10^{-4}

Tab.1. Test circuits of photodiodes with various areas and perimeters.

Photocurrent (A)	Red (690nm)	Green (550 nm)	Blue (480nm)
1 lux	7.4714×10^{-15}	8.5307×10^{-15}	1.1672×10^{-14}
3 lux	2.2414×10^{-14}	2.5592×10^{-14}	3.5017×10^{-14}
5 lux	3.7357×10^{-14}	4.2653×10^{-14}	5.8361×10^{-14}
7 lux	5.2300×10^{-14}	5.9715×10^{-14}	8.1706×10^{-14}

Tab.2. Calculated photocurrents for some kinds of illuminations and wavelengths.



(a) (b)

Fig.5. (a) The simulations do not coincide with the measurements under no illumination; (b) The value of *GMIN* influence the simulation of dark signal.

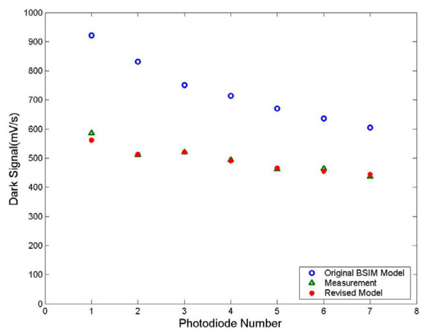


Fig.6. The revised dark signals match the measurements much better than the original simulations.

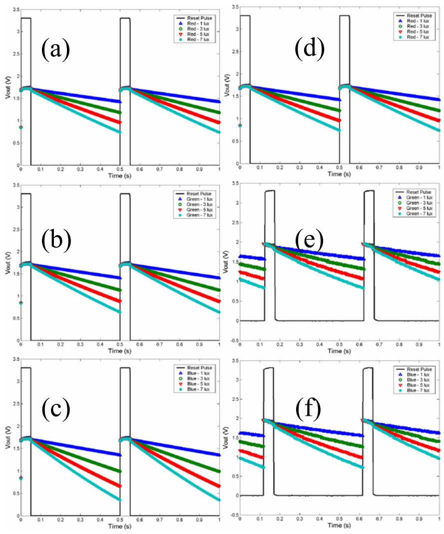
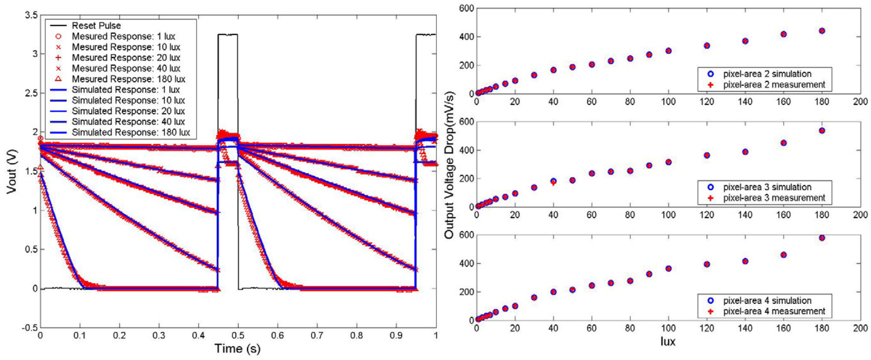


Fig.7. (a)-(c): Simulated outputs with red, green and blue light source under different intensity; (d)-(f): Measured responses with red, green and blue light source under different illuminations.



(a) (b)

Fig. 8. (a) Simulated and measured waveform for various illuminations in the same wavelength; (b) Simulated and measured data versus light intensity.