Journal of Sensor Science and Technology
Vol. 20, No. 1 (2011) pp. 14-18
DOI : 10.5369/JSST. 2011.20.1.14
pISSN 1225-5475/eISSN 2093-7563

Analytical Pinning-Voltage Model of a Pinned Photodiode in a CMOS Active Pixel Sensor

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Abstract

An analytical pinning-voltage model of a pinned photodiode has been proposed and derived. The pinning-voltage is calculated using doping profiles based on shallow- and exponential-junction approximations. Therefore, the derived pinning-voltage model is analytically expressed in terms of the process parameters of the implantation. Good agreement between the proposed model and simulated results has been obtained. Consequently, the proposed model can be used to predict the pinning-voltage and related performance of a pinned photodiode in a CMOS active pixel sensor.

Keywords : CMOS active Pixel Sensor, Pinning-Voltage, Pinned Photodiode, Analytical Model, Low voltage Operation

1. INTRODUCTION

Pinned photodiode(PPD)-based pixels are widely used in CMOS active pixel sensors(CAPSs) due to their low noise level and high sensitivity[1-7] performances. During the operation of the PPD-based pixels, the performance strongly depends on its pinning-voltage(V_P) level, which directly affects the charge-transfer process by the transfer-gate[2,3]. It is mainly because PPD-based pixels have shown some problems in pixel operation, especially at a low supply-voltage, due to an incomplete charge-transfer and the difficulty of full depletion arising from a high level of V_P, resulting in a high random noise-level[3-5]. Hence, it should be required to measure the V_P. However, it is difficult to measure V_P, so that an accurate prediction of V_P is very important to improve device performance in advance, using an analytical model. A simple analytic model for V_P was introduced in which the abrupt junction approximation is assumed[6]. However, this model is only valid for uniform doping profiles of a PPD.

In this work, an analytical V_P model of a PPD has been proposed. To derive the analytic model, shallow- and exponential-junction approximations are employed for Gaussian doping profiles based on the LSS(Lindhard, Scharff, Schiott) theory[8-10]. In order to verify the proposed V_P model, comparisons between the new model and the simulation data have been made using a two-dimensional device simulator(SIL-VACO). In the following sections, the pinning voltage model is derived, verified, and discussed.

2. MODEL DEVELOPMENT

A schematic cross sectional view of the PPD is illustrated in Fig. 1(a), which is composed of both P_o/N_W junction and N_W/P_{epi} junction. In Fig. 1(a), a definition for the voltage pinning condition can be expressed by

$$t_{Nw} = W_{N1}(V_P) + W_{N2}(V_P) \quad (1)$$

In addition, the pinning-point is located at the middle of N_W, as shown in Fig. 1(a). To calculate the depletion width(W_{N1}, W_{N2}) at V_P, we begin with a Poisson's equation as follows:

$$\frac{dE(x)}{dx} = -\frac{d^2V(x)}{dx^2} = \frac{\rho(x)}{\varepsilon} \approx \frac{q}{\varepsilon}(n(x) - p(x)) \quad (2)$$

where E(x) is an electric field, V(x) is the potential, ρ(x) is the charge density, n(x) is ionized donor density, p(x) is ionized acceptor density, ε is the permittivity of the silicon, and q is the magnitude of an electron charge. For n(x), the PPD shows Gaussian profiles of N_W(x) by the

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(Received : Jul. 31, 2010, Revised : Dec. 9, 2010, Accepted : Dec. 17, 2010)

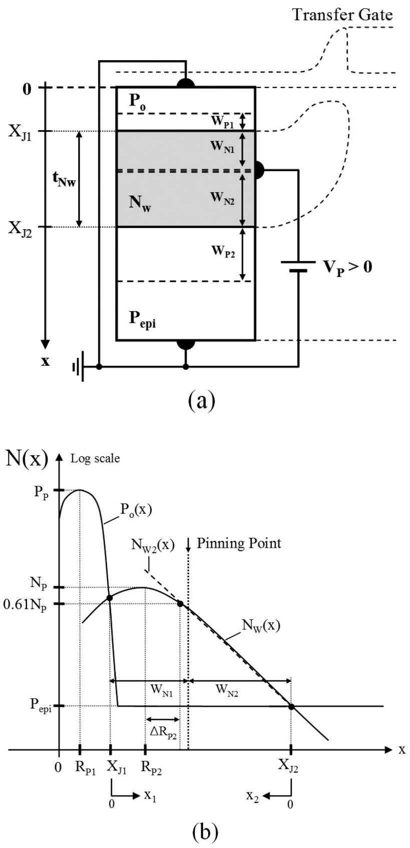

Fig. 1. (a) A schematic diagram in cross-sectional view and (b) doping profiles based on the Gaussian distribution of the PPD (where t_{Nw} is the junction thickness of the N-well, W_{N1} is the depletion width in the N-well region at the junction of the N_W/P_o, and W_{N2} is the depletion width in the N-well region at the junction of the N_W/P_{epi}).

implantation process[8,9], as shown in Fig. 1(b). However, it is difficult to solve the Poisson's equation based on the Gaussian function analytically. Thus, the Gaussian function can be transformed to the parabolic function in the log-scale[8-10]. In addition, the parabolic function can be expressed by a linear function in the range of $x > (R_{P2}+\Delta R_{P2})$, and the linear function in the log-scale is transformed into an exponential function in the linear-scale[10]. Therefore, $N_{W2}(x)$ based on the exponential junction approximation are employed[8, 9], as shown in Fig. 1(b). We can then solve the Poisson's equation and derive an analytical expression for V_P. The detailed derivation of the proposed V_P model is as follows. As shown in Fig. 1(b), we may obtain p(x) and n(x) based on the Gaussian distribution as in (3) and (4):

$$p(x) = P_o(x) = P_P \exp\left(-\frac{(x-R_{P1})^2}{2\Delta R_{P1}^2}\right) + P_{epi} \tag{3}$$

$$n(x) = N_W(x) = N_P \exp\left(-\frac{(x-R_{P2})^2}{2\Delta R_{P2}^2}\right) \tag{4}$$

where P_P is the peak density of $P_o(x)$, ΔR_{P1} is the projected range of $P_o(x)$, ΔR_{P1} is the normal straggle of $P_o(x)$, N_P is the peak density of $N_W(x)$, R_{P2} is the projected range of $N_W(x)$, and R_{P2} is the normal straggle of $N_W(x)$. After the annealing, ΔR_P is redefined by both the annealing time (t) and the dopant-diffusivity (D) at the annealing temperature[8, 9]. At the junction X_{J1}, we can write (5) for a charge density of $\rho(x_1)$ based on the shallow junction approximation:

$$\rho(x_1) \approx \begin{cases} qN_P, & 0 < x_1 < W_{N1} \\ -qP_P, & -W_{P1} < x_1 < 0 \end{cases} \tag{5}$$

By solving (2) using $\rho(x_1)$ and the boundary conditions that relate the balance of the charge requirement and depletion approximation[10], we may obtain

$$W_{N1} = \sqrt{\frac{2\varepsilon(V_P + V_{bi1})}{q}\frac{P_P}{N_P(N_P+P_P)}} \tag{6}$$

For junction X_{J2}, we can write (7) for charge density $\rho(x_2)$ based on an exponential junction approximation:

$$\rho(x_2) \approx q\left(N_{W2}(x_2) - P_{epi}\right) \tag{7}$$

where

$$N_{W2}(x_2) = P_{epi}\exp(\alpha x_2) \quad \text{and} \quad \alpha \equiv \frac{\ln(0.61N_P/P_{epi})}{X_{J2} - R_{P2} - \Delta R_{P2}}$$

By solving (2) using charge density $\rho(x_2)$ and boundary conditions that relate the balance of the charge requirement and depletion approximation[10], we may obtain (8) assuming $\exp(\alpha W_{N2}) \gg 1 \gg \exp(-\alpha W_{P2})$:

$$W_{N2}(V_P) \approx \frac{1}{2\alpha}\ln\left(\frac{2\varepsilon\alpha^2}{qP_{epi}}(V_P + V_{bi2})\right) \tag{8}$$

From (1), (6) and (8), we can obtain the analytical expression for V_P as follows:

$$t_{Nw} = \sqrt{\frac{2\varepsilon(V_P+V_{bi1})}{q}\frac{P_P}{N_P(N_P+P_P)}} + \frac{1}{2\alpha}\ln\left(\frac{2\varepsilon\alpha^2}{qP_{epi}}(V_P+V_{bi2})\right) \tag{9}$$

where $t_{Nw} = X_{J2} - X_{J1}$,

$$P_P = \frac{Q_P}{\sqrt{2\pi}\Delta R_{P1}},\quad N_P = \frac{Q_N}{\sqrt{2\pi}\Delta R_{P2}},$$

$$X_{J1} = \frac{\left(\begin{aligned}&R_{P1}\cdot\Delta R_{P2}^2 - R_{P2}\cdot\Delta R_{P1}^2\\ &+\Delta R_{P1}\cdot\Delta R_{P2}\sqrt{(R_{P1}-R_{P2})^2 + 2(\Delta R_{P2}^2-\Delta R_{P1}^2)\cdot\ln(P_P/N_P)}\end{aligned}\right)}{\Delta R_{P2}^2 - \Delta R_{P1}^2},$$

and

$$X_{J2} = R_{P2} + \Delta R_{P2}\sqrt{2\ln\left(\frac{N_P}{P_{epi}}\right)}$$

Finally, we have an analytical expression for V_P, as shown in (9). The derived pinning-voltage model is analytically expressed in terms of the parameters of the implantation(N_P, P_P, R_{P1}, R_{P2}, ΔR_{P1}, and ΔR_{P2}), which are associated with the implant dose(Q_P, Q_N) and implantation energy(E_P, E_N)[8,9]. Therefore, V_P can be expressed and calculated by the process parameters of the implant dose and implant energy.

Table I. Implantation and related process conditions of the PPD for typical cases

Region	Value			
P_{epi}	5×10^{14}cm^{-3}			
N_W	Implantation Parameters			
	Dose		Dopant	Energy
	Case 1	1×10^{12} cm^{-2}	Phosphorus	100 keV ~ 200 keV (Step = 25 keV) for each case
	Case 2	2×10^{12} cm^{-2}		
	Case 3	3×10^{12} cm^{-2}		
	Case 4	4×10^{12} cm^{-2}		
	Case 5	5×10^{12} cm^{-2}		
P_o	1×10^{13} cm^{-2}		Boron	30keV
Annealing	T = 1025 ℃, t = 10 sec			

3. RESULT AND DISCUSSION

In order to verify the accuracy of the proposed model, the simulation results are used for comparison with our model. The typical process conditions for the PPD are used for both the proposed model and simulation, as shown in Table 1. The calculation of V_P has been performed using the proposed V_P model, as shown in (9). For the calculation of the proposed model, the implant parameters(ΔR_{P1}, R_{P1}, ΔR_{P2}, and R_{P2}) are determined by using the plots based on the LSS theory[8, 9]. Fig. 2 shows the calculated V_P in comparison with the SILVACO simulation results. Good agreement between the proposed model and simulation results has been obtained, as shown in Fig. 2. In addition, it has been found that V_P shows very sensitive characteristics for the N-well implant conditions

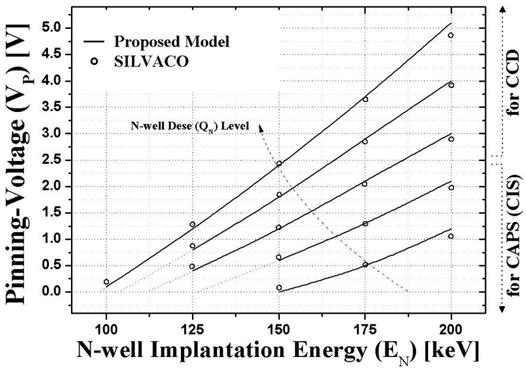

Fig. 2. Plot of the Pinning-voltage(V_P) vs. N-well implantation energy(E_N) of the proposed model in comparison with the simulated results for various cases of N-well Dose(Q_N = 1 × 10^{12} cm^{-2}, 2 × 10^{12} cm^{-2}, 3 × 10^{12} cm^{-2}, 4 × 10^{12} cm^{-2}, and 5 × 10^{12} cm^{-2}). Other conditions(Q_P, E_P, P_{epi}) are fixed.

of Q_N and E_N. This is mainly because the dominant parameters(N_P and X_{J2}) are determined by the combination of Q_N and E_N.

On the other hands, the proposed model is based on a 1-Dimensional Poisson's equation so that it is difficult to consider some non-ideal effects, such as breakdown characteristics and parasitic element-related effects. In other words, the proposed model is only valid for a shallow junction, which is fabricated by using a low energy implantation, operating at a low voltage. There are some reasons why a 1-Dimensional model was employed in our analytical model. First, the PPD is normally operated at a low voltage below 1.8 V. Moreover, the p-type substrate and the epi-layer(P_{epi}) play a role as a resistor to suppress the diode breakdown, though the pinning voltage is below 1 V. Second, a shallow junction can be approximated to a 1-Dimensional structure, which is also one of the reasons why our model is more fit to the simulation results at lower implantation energy below 150 eV, as shown in Fig. 2.

Consequently, the proposed model has been verified and can be used to predict V_P for typical cases of implantation conditions(Q_N, E_N) of the PPD process.

4. CONCLUSION

This paper presents an analytical model for the pinning-voltage of a pinned photodiode. In order to verify the proposed model, comparisons between the proposed model and simulation results have been made. It is shown that excellent agreement has been obtained. Although the developed model is valid for the Gaussian doping profile based on the LSS theory and suitable for a shallow junction device by low energy implantation, it can be used to predict a typical case of the pinning voltage in a CMOS active pixel sensor.

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