Dimensional effects in CMOS photodiodes

Igor Brouk, Yael Nemirovsky *

Department of Electrical Engineering, Technion—Israel Institute of Technology, Haifa 32000, Israel

Received 20 February 2001; received in revised form 26 June 2001; accepted 16 August 2001

Abstract

CMOS photodiodes with various structures and dimensions were measured and analyzed. The photodiode types under study include structures implemented by: n+ (source implantation)/P-substrate, N-well/P-substrate, and p+ (source implantation)/N-well/P-substrate. Long photodiodes with a narrow width varying between 2-50 μm were studied, in order to consider dimensional effects. For the design under study, a 2-D model is adequate while the overall photodiode size provides sufficient signal for measurement accuracy. The quantum efficiency, dark current and spectral noise behavior were measured and compared with simulations. The good fit between measurements and simulations indicates that the physical mechanisms and the technology parameters, which determine the performance of the CMOS photodiodes, are understood. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Photodiode image sensors; CMOS photodiodes; Quantum efficiency; Dark current; Noise

1. Introduction

Current CMOS image sensors have a performance competitive with charge-coupled device technology, and offer advantages of on-chip functionality, system power reduction, cost and miniaturization [1,2]. Photodiodes are the sensing elements in the passive pixel approach as well as in the active pixel sensor [2,3]. CMOS photodiodes are also used in novel integrated microsystem applications, such as those reported in Refs. [4–6]. Three main photodiode structures such as n+ (source implantation)/P-substrate, N-well/P-substrate, and p+ (source implantation)/N-well/P-substrate, are available using standard CMOS processes.

Photodiodes for CMOS image sensors are characterized by the dark current, dark noise and quantum efficiency (QE). These physical parameters are determined by the photodiode structure as well as dimensions. The present study quantitatively compares the dark current, noise and QE for the three photodiode structures. In addition, photodiodes with different optical window dimensions are compared. The strong dependence of the measured results upon photodiode geometry indicates that dimensional effects should be considered. The measured QE and dark current are compared with simulations, which take into account the above dimensional effects.

2. Design of CMOS photodiodes

The cross-section of the designed three types of photodiode structures is given in Fig. 1. In order to consider dimensional effects, photodiodes with different optical window width Lopt (see Fig. 1) were designed where Lopt is varied between Lopt = 2 μm, Lopt = 5 μm, Lopt = 10 μm, Lopt = 50 μm. All photodiodes have been designed so that access of light to the semiconductor is allowed only through optical windows formed by layer Metal-2. The length of the photodiode optical window
was designed intentionally long and constant for all photodiodes under study. Since the designed length of 1 mm is long relative to either the diffusion length (~300 μm) or the absorption length, a 2-D model is adequate to address the photodiode performance. Thus, geometry effects are taken into consideration while the overall

Fig. 1. The cross-section of the photodiodes under study: (a) n⁺ (source implantation)/P-substrate; (b) N-well/P-substrate; (c) p⁺ (source implantation)/N-well/P-substrate.
photodiode size provides sufficient signal for measurement accuracy.

Although current advanced CMOS processes are characterized by sub-sub-micron technology (~0.18 μm), these processes include shallow trench isolation and exhibit considerable dark noise. Therefore, CMOS processes with LOCOS (local oxidation) isolation are preferred for CMOS image sensors.

Hence devices were fabricated through the MOSIS project,\(^1\) using a 2 μm N-well analog low noise process of Supertex (former Orbit). This process is characterized by an n’/p’ implanted source/drain depth of ~0.2 μm, gate oxide of 400 A and field oxide of ~4000 A. The doping level of the substrate or the epilayer, N-well, and p’/n’ implanted regions is ~7 × 10\(^{15}\), 10\(^{16}\), and 10\(^{20}\) cm\(^{-3}\), respectively. The epilayer is ~15 μm thick, the N-well is ~2 μm and the high-doped bulk is about 500 μm thick. More advanced CMOS processes (0.5 μm technology) utilizing LOCOS isolation are characterized by ~80 A gate oxide, ~2500 A field oxide, ~5 μm thick epilayer, and modified doping levels with non-uniform concentration. The effect of process parameters upon photodiode performance is predicted by the simulations. These predictions indicate that the results presented below can be extended to more advanced CMOS processes.

3. Measured results and simulations

This section presents measured results and simulations of the QE, dark current, and spectral noise density for the photodiodes under study (see Section 2).

3.1. Quantum efficiency

QE is measured with a monochromator SpectraPro-150, consisting of a light source, the monochromator itself, and a computer built-in analog to digital converter, while the photodiode current output is connected to the voltage converter through the low noise current preamplifier SR.570. The system is calibrated by illuminating a calibrated, large-area PIN photodiode connected to an Optical Power Meter 1830-C (NewPort). The purpose of calibration procedure is to measure the dependence of the irradiated light power density (per unit area) coming from the monochromator upon the light wavelength. The QE is defined by [7,8]:

\[ \text{QE} = \frac{h \lambda I_e}{\lambda q P_{\text{opt}}}, \]  

where \( I_e \) is the measured photocurrent, \( \lambda \) is the wavelength, \( h \) is the Plank’s constant, \( c \) is the light velocity, \( q \) is the electron charge, \( P_{\text{opt}} \) is the irradiated power, which is allowed to be absorbed by the measured photodiode through the metal optical window and is given by the light power density multiplied by the optical window area.

Fig. 2 exhibits the measured QE for three types of photodiodes and for four geometries under study. The raw data include the interference waves due to the oxide layers in the optical window, which form an anti-reflection (AR) coating. These layers are the standard field oxide and passivation layers of the CMOS process and hence the AR coating is not optimized. Fig. 2 also shows the smoothed curves, which will be used to compare the measured results to the simulations. In all three types of photodiodes under study, the dependence of the QE upon photodiode geometry is a dominant effect. As the optical window width is reduced, the QE is significantly reduced.

In order to understand this phenomenon, let us consider, for example, an n’/p-sub structure. At wavelengths larger than 400 nm most of the incident photons are absorbed in the neutral regions of the epilayer, thus generating minority carriers that freely diffuse in this layer. Some of them are collected by the active junction, thus contributing to the photocurrent. Some others will recombine within neutral regions, giving no contribution to the photocurrent. Other carriers diffuse laterally, where they may recombine at the surface, or at the ohmic contacts to the corresponding layer. All above carriers do not contribute to the photocurrent. As the width of the optical window is increased, the fraction of photogenerated carriers that is lost laterally becomes less and less significant, thus justifying the occurring of dimensional effects. In other words, as the width of the optical window is increased (increasing the photodiode sensitive area proportionally), the relative weight of the carriers that diffuse into the active junction is increased. These results indicate that dimensional effects should be considered in the simulations.

Fig. 2(c) shows the QE of the double-junction photodiode realized in a N-well CMOS process. The shallow junction photodiode preferentially collects charge generated by shorter wavelength light \( (I_{\text{pump}}) \), while the deeper junction collects the charge generated by longer wavelength light. The total current is measured at the contact to the N-well \( (I_{\text{tot}}) \).

From the comparison of the QE for the photodiodes of the same dimensions and different types, one can see that all photodiode types have approximately the same value of QE, except the photodiode based on the junction p’ implantation—N-well, where the QE is lower.

---

\(^{1}\) Metal Oxide Semiconductor Implementation Service (MOSIS). A multiproject fabrication service run by The Advanced Research Projects Agency (ARPA).
Fig. 2. The measured QE for the three types of photodiodes and for the four geometries under study: (a) n+ (source implantation)/P-substrate; (b) N-well/P-substrate; (c) p+ (source implantation)/N-well/P-substrate. Solid lines—measured QE. Dotted lines—smoothed curves. The photodiodes are operated under applied reverse-bias voltage –2 V. \( I_{p^+\text{-amp}} \) and \( I_{\text{total}} \) are the currents at the p+ contact to the shallow junction and at the N-well contact respectively.

Because of its less effective thickness and the competing deeper junction (see Fig. 1(c)). The similarity between the photodiodes of different types with the same geometry stems from the fact that the QE is determined mainly by the absorption coefficient \( \alpha(\lambda) \) of the photons in silicon [4,9], the dimension of the absorbing layers and the diffusion length of the minority carriers [7].

To understand the measured results, we have performed a 2-D simulation. The model is based on the following assumptions:

- A 2-D current flow. A 2-D model is sufficient since the optical window length is long relative to \( 1/\alpha(\lambda) \) as well as the diffusion length of the carriers.
- Surface recombination velocity (recombination rate of the minority carriers at the surface, \( \text{m/s} \)) is taken into account at all boundaries.
- Degeneration in highly doped implantation regions is neglected.
- Recombination in depletion regions is neglected.
- Reflectance at the optical window is not considered.
- The contribution of the bulk is neglected due to the high surface velocity recombination at the epilayer–bulk interface and due to the reduced lifetime of minority carriers within the bulk.

In the case of the photodiodes implemented by n+ (source implantation)/P-substrate or N-well/P-substrate, the 2-D continuity equations are given for the n- and p-region, respectively by [8]:

\[
\begin{align*}
\frac{\partial}{\partial t}(n_n(x,y) - n_{0n}) + \nabla \cdot \left( \frac{D_n}{\tau_n} n_n \right) &= - \frac{L_n}{\tau_n} n_n e^{\alpha(x,y)} , \\
\frac{\partial}{\partial t}(n_p(x,y) - n_{0p}) + \nabla \cdot \left( \frac{D_p}{\tau_p} n_p \right) &= - \frac{L_p}{\tau_p} n_p e^{\alpha(x,y)} ,
\end{align*}
\]

where \( n_{0n} \) is the concentration of holes in the n-type semiconductor in equilibrium, \( n_{0p} \) is the concentration of electrons in the p-type semiconductor in equilibrium; \( D_n, D_p \) and \( L_n, L_p \) are the diffusion coefficients and diffusion...
lengths for electrons and holes, respectively; \( \alpha \) is the absorption coefficient; \( d \) is the coordinate of the metallurgical junction, \( N_0 \) is the number of photons of wavelength \( \lambda \) entering at the optical window of the device per unit area per unit time.

The boundary conditions for Eq. (2) are given by Boltzmann’s condition at the junction limits and by a balance between minority carriers flowing to the surface by diffusion and carriers recombining at the surface at a rate determined by the surface recombination velocity at the relevant surfaces [8]. Obviously, the above equations and boundary conditions should be carefully formulated for each photodiode structure and geometry.

Eq. (2) provides the values of the excess minority carrier concentration within the volume of the semiconductor. Due to the impossibility to obtain an analytical solution of Eq. (2) for an arbitrary geometry, this equation is solved numerically. The total current collected by the junction is given by integration of the current density along the junction surface:

\[
I_j = I \left[ \int_W (J_n(x, y) + J_p(x, y)) \, dy \right. \\
+ \left. \int_h (J_n(x, y) + J_p(x, y)) \, dx \right],
\]

where \( h \) is the depth of p-n junction, \( W \) is the width of the photodiode, \( I \) is the length of the photodiode, \( J_n \) and \( J_p \) are the electrons and hole diffusion current densities, respectively (depending if n or p doping regions are considered). \( J_n \) and \( J_p \) are calculated by means of numerical differentiation of excess minority carrier concentration:

\[
J_n(x, y) = qD_n \nabla n_n(x, y),
\]

\[
J_p(x, y) = qD_p \nabla p_p(x, y).
\]

![Fig. 3. Comparison between simulated (solid line) and measured (dotted line) QE for the four geometries under study: (a) n+ (source implantation)/P-substrate; (b) N-well/P-substrate; (c) p+ (source implantation)/N-well/P-substrate.](image-url)
Substituting the photocurrent given by Eq. (3) into Eq. (1) the simulated QE is obtained.

Fig. 3 exhibits the simulated QE and the good fit with the measured QE. Table 1 summarizes the simulation parameters. The contribution of the shallow implanted region is limited by the high surface recombination velocities of the simulation. The contribution of the depletion region is limited by the assumed linear graded junction, as discussed below. Fig. 4 exhibits the components of the simulated QE for the photodiode of the type shown in Fig. 1(a). The dominant contribution is from absorption at the p-region of the epilayer. This component is strongly dependent upon dimensions. At the short wavelengths, absorption at the shallow implanted region as well as the depletion region also contribute. These components are independent of the optical window dimensions. The small discrepancies between measurement and simulation results at short wavelengths (<450 nm) are caused by parasitic effects introduced by the monochromator (the light at these wavelengths is not quite monochromatic). The remaining small discrepancies between measured and simulated results are explained by small inaccuracies in the parameters used for the simulation and the assumptions considered during the development of the model.

The good fit is obtained by modeling the depletion region as a linear graded junction rather than a step junction. This is based on the measured results, which show a weak dependence upon the applied bias voltage. The width of the linear graded junction and the step junction depends upon the applied bias voltage \( V_a \), respectively, as \( \sqrt{V_a} \) and \( \sqrt{V_a} \) and hence the former exhibits.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface recombination velocity on the front side</td>
<td>( 4 \times 10^3 ) m/s</td>
<td>Electron diffusion length/life time in P-substrate</td>
<td>( 320 \mu m/30 \mu s )</td>
</tr>
<tr>
<td>Surface recombination velocity on the back side</td>
<td>( 10^3 ) m/s</td>
<td>Hole diffusion length/life time in N-well</td>
<td>( 100 \mu m/9 \mu s )</td>
</tr>
<tr>
<td>Surface recombination velocity of holes on the n(^+)-implanted region boundary</td>
<td>( 10^2 ) m/s</td>
<td>Hole diffusion length/life time in ( n^+ ) region</td>
<td>( 0.05 \mu m/20 ) ps</td>
</tr>
<tr>
<td>Surface recombination velocity of electrons on the p(^+)-implanted region boundary</td>
<td>( 10^2 ) m/s</td>
<td>Electron diffusion length/life time in ( p^+ ) region</td>
<td>( 0.1 \mu m/50 ) ps</td>
</tr>
</tbody>
</table>

Fig. 4. The components of the simulated QE for the photodiode implemented by \( n^+ \) (source implantation)/P-substrate: Dotted line—absorption at the substrate, dashed line—absorption at the shallow implanted region, dashed-dotted line—absorption at the depletion region.
a small voltage dependence, corresponding to the measurements.

3.2. Dark current

The dark current–voltage characteristics of the photodiodes under study can be measured only at forward bias because of the very low value of the dark current at reverse bias. The leakage currents on the chip surface and package are larger than the dark current at reverse bias. At forward bias the current is given by the expression $I \approx I_0 e^{(k/T)}$, where $I_0$ is known as the saturation current, $k$ is the Boltzmann’s constant, $T$ is the temperature, and $\eta$ is a constant ($1 < \eta < 2$). Below we will refer to $I_0$ as the dark current. Fig. 5 shows a typical $I–V$ characteristic in forward bias for the N-well/P-substrate photodiode with dimensions 1000 μm × 50 μm. On a semilogarithmic scale there is only one slope which is determined by $\eta = 1.004$, and $I_0$ is obtained from the intersection with the current axis at $V = 0$. The dark current $I–V$ characteristics of all photodiodes under study exhibits the features of Fig. 5.

Fig. 6 shows the simulated and measured dark current density for the three types of photodiodes discussed above, while the simulated dark current was calculated similarly to the photocurrent, using Eqs. (2)–Eqs. (4b) where $N_0$ is equal to zero. It exhibits that the dark current density increases as the photodiode area decreases. This is due to the relatively more significant contribution from the contacts surrounding the junctions (see Fig. 1). All parameters for the simulation are taken in accordance with Table 1. The n⁺ implantation/P-substrate structure yields the lowest dark current while the p⁺ implantation/N-well/P-substrate exhibits the highest dark current. The best result for the larger photodiode with 50 μm width exhibits $I_0 = 0.06$ nA/cm², while the smallest photodiode with 2 μm width and the same technology exhibits 0.12 nA/cm². The simulated dark current density exhibits good fitting with the measured dark current density. The more significant dark current density obtained for the smaller photodiodes is explained by the contribution to the dark current from lateral currents originating from surrounding surfaces, which are more significant for the smaller photodiodes.

3.3. Photodiode noise

Fig. 7 gives the typical measured noise power spectral density (PSD) of the photodiode. The experimental setup for measuring the current noise spectrum of the photodiode is shown in Fig. 8. The photodiode is illuminated by a LED and connected to a low noise current preamplifier ITHACO 1211 containing a built-in bias voltage supply $V_{bias}$. The dynamic signal analyzer performs the sampling and the fast Fourier transform of the incoming signal. The result of the transform is the PSD of the incoming voltage in the frequency of interest. A PC is used to control the setup of the measurement, the data acquisition and post processing of the measured data. Theoretically, the dominant noise of a reversed-biased junction is shot noise with its PSD of $S_{id} \approx 2qI_i$, but practically, at low frequencies the low-noise preamplifier ITHACO 1211 dominates with its 1/f noise (Fig. 7). Fig. 9 gives the dependence of the noise current PSD taken at a frequency of 1 kHz on the photodiode current, while the whole chip was illuminated uniformly and the photocurrent was generated in each photodiode in accordance with its type and dimensions.
Fig. 6. Saturation current density of the diode structures and geometries under study: (a) n⁺ (source implantation)/P-substrate; (b) N-well/P-substrate; (c) p⁺ (source implantation)/N-well/P-substrate for p⁺ diffusion—N-well junction, (d) p⁺ (source implantation)/N-well/P-substrate for N-well—P-substrate junction.

Fig. 7. Typical noise PSD of the photodiode. Solid line—total noise referred to the transresistance amplifier input. Dotted line—input referred current noise of the transresistance amplifier.

4. Summary

It was found that there is a strong dependence of the QE on the photodiode dimensions, while the effect of the photodiode structure is less significant. The QE of the CMOS photodiodes saturates at ~60% and this value is typical even for large-area photodiodes with an optical window of 500 µm x 500 µm, as reported in Ref.
This is in contrast to the 100% QE obtained in PIN photodiodes. As dimensions are reduced, the QE of the CMOS photodiodes is significantly reduced, which is explained by the fact that the photocarriers are generated in the neutral region of the epilayer and are collected by diffusion. The dark current is strongly affected both by the photodiode structure and the dimensions. The dark current increases as the photodiode width is reduced and is lowest for the structure implemented by n+ implantation/P-substrate. The simulation results are in good agreement with the measurements for both the QE and the dark current, which indicates that the physical mechanisms and technological parameters which determine the performance of CMOS photodiodes are understood. When comparing the above-mentioned diode structures it was found that the n+ implantation/P-substrate diode structure is the preferred one from a point of QE and dark current. As for the photodiode implemented by N-well/P-substrate, its QE and its dark current can be improved to values observed in the n+ implantation/P-substrate structure by decreasing the N-well contact area. The shot noise is the main noise mechanism, which is responsible for noise in all photodiode types.

Acknowledgements

The support of the Israeli Ministry of Science, with Mr. Jo van Zwaren de Zwarenstein, is gratefully acknowledged.

References