Characterization of crosstalk between CMOS photodiodes

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Abstract

The crosstalk in CMOS photodiodes has been measured, at two wavelengths of 543 and 633 nm, by an experimental structure containing several types of photodiodes with varying dimensions. The role of the design of the junction in reducing crosstalk is studied. The measurements indicate that to reduce crosstalk it is essential to optically shield the gap between junctions and to reverse bias the adjacent junctions. Crosstalk is significantly reduced in double-junction photodiodes, but at the cost of lower quantum efficiency. The results indicate that with properly designed layout, the crosstalk may be small. However, there is a tradeoff between small crosstalk, reduced fill factor and quantum efficiency. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Recently, there has been much interest in photodetectors and imagers realized in standard CMOS fabrication processes for military and civilian application such as motion detection and solid-state cameras (Ref. [1], and references therein). The imager usually consists of a matrix of photodiodes (sensors) with various configurations of the readout circuitry, mostly in the form of active pixel sensors (APS). CMOS APS technology is emerging as an alternative solid-state imaging technology to charge coupled device (CCD) technology that has significant advantages in terms of low power dissipation, scaling to high resolution formats, and compatibility with camera system integration [1,2]. The important issues which need to be considered while designing the silicon imager are: quantum efficiency, dark current, noise, leakage current within each pixel, and crosstalk between pixels. The first four phenomena have been thoroughly analyzed in several works [2–5]. However, the issue of crosstalk has not been addressed adequately to CMOS photodiodes in the open literature. The effect of crosstalk on the acquired image would be limited resolution as the sharp edges would be “blurred”. In Ref. [6], the crosstalk between pixels of CMOS camera has been estimated to be within the range of 10–20% in a design, which is used to increase the fill factor, but no data is provided on actual measurements.

In the present work we have tested a special configuration of CMOS photodiodes allowing evaluating the influence of the surrounding pixels on the photocurrent of the device under test. Different types of junctions have been tested including: n+(source implementation)/P-substrate, N-well/P-substrate, p+(source implementation)/N-well/P-substrate. Our test results indicate that photodiodes with a single junction (the first two types) exhibit similar behavior and the crosstalk may be considerable (above several percent). In contrast, the photodiodes with a double junction (the third type) exhibits the highest immunity to crosstalk, which is reduced to
the order of ~0.1%. Numerical simulations have also been performed to elucidate the mechanisms that produce these observed differences.

2. The crosstalk mechanism

Optical coupling between arrays of photosensors is known as crosstalk [7–10]. Holloway [7] has calculated the dependence of the crosstalk value on a number of parameters of arrays of photosensors, which are used in thermal imaging. The crosstalk value has been measured by using a laser between silicon U-grooved-isolated photodiode array [9] and silicon diffused photodiodes [10].

There are two physical mechanisms that may cause the crosstalk. Optical crosstalk results from the multiple reflection, refraction and scattering of radiation between different surfaces within the chip (such as interfaces between insulators, silicon, epi-layer, and also exterior surfaces of the chip and its packaging). Electrical crosstalk within the photodiodes is the phenomena whereby photons generate carriers within the nominal absorption/collection region of a particular element of the pixel array, but the minority charge carriers undergo diffusion to be collected by another element.

Crosstalk is generally managed at the fabrication process level by controlling the epilayer and poly-silicon thickness (i.e. optical crosstalk), and the doping concentration of the substrate to limit the diffusion length of minority carriers, and optimizing the pixel structure such as providing channel stops between pixels to absorb free carriers (i.e. electrical crosstalk). However, neither of these options is available in standard CMOS technology for image sensor design, and as a result, it has not been addressed adequately in the available literature.

This paper focuses on the first mechanism, electrical crosstalk by diffusion of photogenerated minority charge carriers in the silicon substrate, which is more fundamental and the more significant in the case of CMOS image sensors.

3. The test structure and measurement methodology

The test chip, which consists of several rows of photodiodes with varying dimensions and different types has been fabricated in 2 μm analog n-well low noise process [11] and is presented in Fig. 1(a). There are three types of photodiodes, each of them implemented in a different structure: n^+ (source implantation)/P-substrate, N-well/P-substrate, and p^+ (source implantation)/N-well/ P-substrate. The cross section of the first type is shown in Fig. 1(b). Metal 2 defines the optical windows for the illumination above the photodiode junction and above the gap between junctions. The photocurrent of the central photodiode in a row is measured while the photodiode is reverse biased to 2 V. The photodiodes adjacent to the device under test are also reverse biased to 2 V while the further photodiodes have been left floating in order to test various cases. The measurements are performed in the following manner: The photocurrent of the diode under test (the middle one in each of the rows) is measured, while the light beam scans along the row of pixels. By focusing the light of a monochromator through an optical fiber using a suitable lens, we obtain an illumination spot with a diameter of ~15 μm. The result of the procedure is the measured photocurrent as a function of the distance of the illuminated point from the measured photodiode.

The scanning has been performed in two directions. In the first case (scan along the row of sensors) the influence of adjacent pixels (biased and floating) and interpixel gap has been tested. The second case (scan in the direction perpendicular to the row of sensors) allows assessing the significance of the surface recombination velocity vis-a-vis the diffusion length of carriers in CMOS chips. The measurements have been performed for two wavelengths: 543 and 633 nm.

To explain the mechanism that produces the observed crosstalk between pixels for the different photodiode configurations, the measured photocurrent profiles have been compared with numerical simulations using DAVINCI [12], a finite element based semiconductor device modeling package.

4. Results

Fig. 2(a) exhibits the quantum efficiency of the measured central photodiode as a function of the point of illumination, for n^+/p-substrate junctions. When the illumination spot coincides with the optical window of the measured photodiode, the quantum efficiency is maximal. The value of ~56% on the wavelength of 633 nm corresponds to the measured quantum efficiency of uniformly irradiated CMOS photodiodes with similar structure and dimensions, which is reported in Ref. [2]. When the illumination is focused on the metallic contact surrounding the junction and defining the optical window, the quantum efficiency drops because the illumination is reduced by the opaque metallization. When the illumination is focused on the gap (opening) between the central photodiode and the adjacent photodiode, the quantum efficiency is reduced to ~30% indicating a crosstalk of ~50%. This crosstalk can be avoided by using an additional metallization layer to optically shield the gap between adjacent photodiodes. When the illumination is focused on the optical window of the adjacent biased photodiode, the quantum efficiency is
reduced to $\sim0.2\%$ and the crosstalk, which is estimated by $(0.2/56) \times 100$ is significantly reduced to $\sim0.35\%$. The significant reduction is due to the fact that the photocarriers are mainly collected by the illuminated junction. The crosstalk increases again when the illumination is focused on the gap (opening) between the further photodiodes ($x \geq 400 \mu m$). In this case the quantum efficiency is $\sim2\%$ and the crosstalk is $\sim3.5\%$. Similar crosstalk is observed when the illumination is focused on the optical window of the edge photodiode,
Fig. 2. The measured quantum efficiency of the central photodiode in a row (see insert) as a function of the point of illumination. A circular spot of 15 μm diameter provides illumination and the point of illumination is defined by the center of the spot. The dimensions of the optical window of the central photodiode used for measuring responsivity are 60 × 60 μm². The measuring photodiode as well as the adjacent photodiodes to the right and to the left are reverse biased at 2 V (see insert). The photodiodes at the ends (left as well as right) are not biased and are floating. The photodiodes are implemented by: (a) n⁺ (source implementation)/P-substrate, (b) N-well/P-substrate, (c) p⁺ (source implementation)/N-well/P-substrate. The quantum efficiency is measured at the shallower p⁺/N-well junction, (d) p⁺ (source implementation)/N-well/P-substrate. The quantum efficiency is measured at the deeper N-well/P-substrate junction.

which is floating. In this case the photocarriers diffuse in all directions and are collected by the biased photodiodes and hence when the light spot is at x ≈ 500 μm, the observed quantum efficiency is nearly the same as in the former case.

It should be noted that the photodiodes on the left side of the measured photodiode (negative x) have larger dimensions compared to the photodiodes on the right (positive x). As the photodiode area increases, the observed crosstalk is smaller because the adjacent photodiode (between the floating photodiode and the measured photodiode) has higher quantum efficiency and thus collects more efficiently the diffusing photocarrier. Similar results are observed when the illumination wavelength changes from red (633 nm, solid line) to green (543 nm, dashed line). The quantum efficiency of CMOS photodiodes is always lower at 543 nm compared to 633 nm as reported in Ref. [2–5]. However, the crosstalk pattern is nearly the same.

The measured crosstalk for photodiodes defined by N-well/p-substrate is nearly the same for the n⁺/p-substrate type of photodiodes, as indicated by the results of Fig. 2(b), which are very similar to the results of Fig. 2(a). In both types of photodiodes, the minority carriers are electrons, and the diffusion length is much larger in state-of-the-art silicon than the typical vertical dimensions of the location of the junction (~0.3 μm in the former case and ~0.2 μm in the latter case).

Fig. 2(c) exhibits the measured quantum efficiency in the case of photodiodes with double junctions of the
Fig. 3. Simulated photocurrent flux spatial maps in 2D for an array of three photodiodes, with the laser at three different scan positions. Maps are shown for (a) single junction n⁺ (source implantation)/P-substrate devices all reverse biased at 2 V, and (b) deeper junction N-well/P-substrate of the double structure p⁺ (source implantation)/N-well/P-substrate devices all reverse biased at 2 V. The graph shows photocurrent flux maps, with the spacing between flux lines inversely proportional to the actual photocurrent density at each point.

The measured photocurrent is obtained from the shallow junction between the p⁺ (source implantation)/N-well. When the illumination spot coincides with the optical window of the measured photodiode, the quantum efficiency is ~28% on the wavelength of 633 nm. This lower quantum efficiency compared to the former cases, is a result of the competing deeper junction, as reported in Ref. [2]. When the illumination spot is displaced beyond the optical window of the measured photodiode, the quantum efficiency drops by approximately three orders of magnitude and the crosstalk is practically negligible. This is because the reverse-biased deeper junction effectively collects all photocarriers that are generated by photons, which are not illuminated through the optical window of the measured photodiode.

Fig. 2(d) exhibits the measured quantum efficiency of photodiodes with double junctions but in contrast to Fig. 2(c), the measured photocurrent is obtained from the deeper junction between the N-well/P-substrate. Fig. 2(d) is very similar to Fig. 2(b).

Flux maps, showing the flow of photogenerated current, were simulated in 2D DAVINCI [12], and are shown for an array of three photodiodes all reverse biased at ~2 V. The structures simulated represent the three middle devices in the five device arrays used for the experimental measurements. Fig. 3(a) is for the n⁺ (source implantation)/P-substrate, and Fig. 3(b) is for the deeper junction N-well/P-substrate of the double structure p⁺ (source implantation)/N-well/P-substrate. The graphs are shown for three different laser positions, for an incident wavelength of 633 nm. The flux maps represent the magnitude of the photogenerated current flowing through the structure, with the spacing between flux lines inversely proportional to the magnitude of the current at that position. The double junction structure shows both an increase in the flux density near the photogeneration region, and a reduction in the flow of current to adjacent photodiodes (i.e., reduced flux density away from the photogeneration region), compared to the single junction structure.

Fig. 4 exhibits the measured quantum efficiency as a function of the illumination distance between the light spot and the measured photodiode along the free silicon, namely in an axis perpendicular to the row of photodiodes (y-axis in Fig. 1(a)). The measurements have been performed for two wavelengths: 543 nm (dashed line) and 633 nm (solid line). When the illumination spot coincides with the optical window of the measured photodiode (in the case of photodiodes implemented by n⁺/P-substrate), the quantum efficiency is maximal with the value of ~58%. The quantum efficiency decreases
monotonically to $\sim 1\%$ at a distance of $\sim 800 \mu m$. Thus, the estimated crosstalk is $\approx (1/60) \times 100 \approx 1.66\%$. This result can be explained in light of the long diffusion length of electrons in state-of-the-art silicon wafers, which is of the order of $\sim 300 \mu m$ [13–15]. The measured crosstalk for photodiodes defined by n-well/p-substrate is nearly the same for the n$^+$/p-substrate type of photodiodes, as indicated by the results of Fig. 4(b), which are very similar to the results of Fig. 4(a). In both types of photodiodes, the minority carriers are electrons, and the diffusion length is much larger in state-of-the-art silicon than the typical vertical dimensions of the location of the junction ($\sim 0.3 \mu m$ in the former case and $\sim 2 \mu m$ in the latter case). In contrast, in Fig. 4(c), the quantum efficiency drops by approximately three orders of magnitude at a distance of $\sim 150 \mu m$, again indicating the efficiency of the deeper junction to reduce the crosstalk in the case of photodiodes with double junctions.

Fig. 5 exhibits the simulated photocurrent (for a wavelength of 633 nm) as a function of the illumination distance between the light spot and the measured photodiode along the free silicon, similar to that shown in Fig. 4. Results are shown in Fig. 5(a) for the n$^+$ (source implantation)/p-substrate, and in Fig. 5(b) for the deeper junction N-well/p-substrate of the double structure p$^+$ (source implantation)/N-well/p-substrate. The plot shows a significant reduction in the crosstalk generated in the double junction structure when the laser is positioned outside the optical window of the photodiode, when compared with the single junction device. This is due to the additional electric field of the reverse-biased p$^+$/n shallow junction, which is driving minority carriers away from the deeper n/p photocarrier collection junction and into the silicon substrate bulk region, where they undergo recombination before contributing to the photocurrent.
5. Summary

The optically induced electrical crosstalk in CMOS photodiodes has been experimentally characterized, by an experimental structure containing several types of photodiodes with varying dimensions. In the present setup, the smallest photodiode is $\sim60 \times 60 \ \mu m^2$, since the diameter of the light spot is $\sim15 \ \mu m$. In order to characterize state-of-the-art CMOS image sensors, which typically include $\sim4 \times 4 \ \mu m^2$ photodiodes, a light spot less than the photodiode area is required. However, since the diffusion length of electrons in modern state-of-the-art silicon is $\sim300 \ \mu m$, which is much longer than the dimensions discussed above, the results presented here are expected to be relevant even for the smaller photodiodes. The role of the design of the junction in reducing crosstalk has been illustrated. The measurements indicate that to reduce crosstalk it is essential to optically shield the gap between junctions and to reverse bias the adjacent junctions. Optical crosstalk is significantly reduced in double-junction photodiodes but at the cost of lower quantum efficiency. In more advanced CMOS processes, gradients in dopant concentrations may be incorporated. Such gradients induce electric fields, which enhance the role of the transport of carriers by drift and reduce the role of diffusion. Properly designed electric fields will restrict the region from which carriers are collected and further reduce the crosstalk. It can be concluded that for properly designed layout, the optical crosstalk may be small, even in CMOS image sensors with small photodiodes corresponding to high spatial resolution. However, there is a tradeoff between small crosstalk and reduced fill factor as well as quantum efficiency.

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