Image Lag Analysis and Photodiode Shape Optimization of 4T CMOS Pixels

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***Abstract*— A good charge transfer efficiency is very important for high-speed application CMOS image sensors. This paper presents a method to optimize the pinned-photodiode (PPD) shape, which is implemented in the 4T CMOS pixel for reducing the image lag of large area photodiode pixels. The new design allows combining a better light sensitivity with a good charge transfer. A CMOS image sensor test chip is designed for verifying the performance of the proposed pixel design. Comparing the performances of different PPD shape designs, the chip measurement results prove that the proposed "W" shape PPD achieves 1/27 image lag of traditional rectangular shaped PPDs. And with about 80% area of the rectangular shape, the light sensitivity of the proposed "W" shape PPD is comparable with the rectangular shape.**

I. INTRODUCTION

The pixel is the most important CMOS image sensor's component. It detects the optical signal and converts it to an electric signal. In recent years, with the fast development of the CMOS image sensor technology and more and more various applications, the pixel size scaling evolves in two opposite directions: very small and very big. Both of them bring big challenges for pixel designers. For high-speed applications and low light imaging, a larger photodiode is needed. On one hand, the light sensitivity can be increased because more photons are projected on a large pixel. On the other hand, transferring all the photon-generated electrons from the photodiode to the floating diffusion can become an issue in a large pixel. This insufficient transfer results in image lag. It retains information from one frame to the next frame. A lot of Many work [1] has been reported in the field of image lag and the optimization method [2][3] to lower it.

In this paper, first we will analysis the different origins of the image lag, and then based on the different origins, different optimization methods for image lag will be discussed. Secondly, by investigating how the photodiode shape can affect the image lag, a new photodiode shape optimization for reducing large photodiode image lag will be proposed. It combines a better light sensitivity with a good charge transfer. Finally, the test chip implementation and the image lag measurement method will be introduced. The experimental measurement results will be presented to prove the proposed pixel shape optimization design.

II. IMAGE LAGE ORIGINS AND OPTIMIZATION

The 4T pixel structure is consisting of the PPD, transfer gate (TG), floating diffusion (FD) and three transistors. The basic working principle of a 4T pixel is as follows: first the photodiode converts the incident photons to electrons; this process converts the optical input signal to an electric signal in the charge domain. Then, opening the transfer gate will transfer all the photon-generated electrons from the photodiode to the floating diffusion. The signal in the charge domain was converted to the voltage domain, which is easy for signal processing and measurement. Due to physic limitations of the photodiode and the transfer gate structure, complete depleting all the electrons from the photodiode is very hard especially for large photodiodes.

From the potential diagram of a pinned photodiode (in Fig. 1), it can be found that there are two main origins causing the image lag. The first one is a potential barrier and/or a potential well around the intersection of the TG and PPD (1 in Fig. 1). It will hamper the electron transfer to the FD. This potential barrier and/or well are created by the technology and the position of the TG. The image lag can be minimized when optimal values of the PPD and the TG mask distances are chosen. The second origin, which can affect the image lag, is the reversed pn junction (2 in Fig.1). At the edge of the PPD, there is a reversed pn junction formed by the n-doping of the photodiode and the surrounding p-well. The electrical field will speed up the photon-generated electrons to pass the TG. The value of this electrical field is decreasing with the distance to the n-doping edge and only exists in the depletion region.

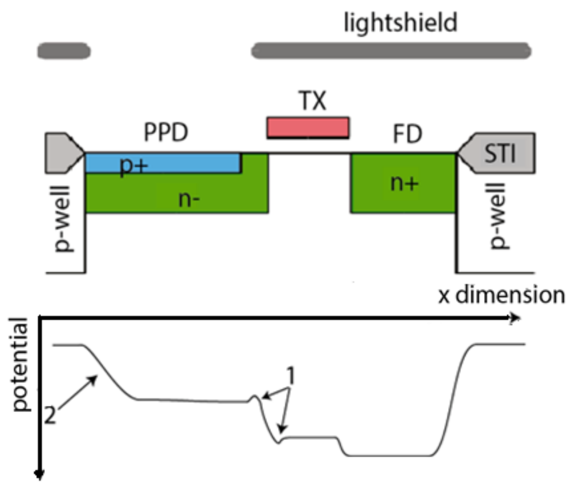


Figure 1. Cross section of PPD structure and corresponding

Considering these two origins together, when the electrons do not have enough energy/speed to pass through the transfer gate within a certain time, the image lag is popping up.

According to the analysis of these two origins of the image lag in a pixel, they need to have different optimization methods to decrease image lag for 4T CMOS image sensor pixels, such as:

- Technology optimization method [4]: both doping concentration in the TG channel and in the pinned photodiode part (surface p-layer and buried n-layer) can be optimized for the image lag by minimizing the potential barriers near the TG and enhance the electrical field in the transfer direction. But this method is not that easy to implement and adjust in individual designs. And the doping adjustment will affect other pixel performance dramatically as well.
- Pixel operation optimization: a longer transfer time and a higher TG voltage can effectively reduce the image lag, but also more noise will be introduced by TG hot carrier effect [5].
- Pixel design optimization: when tuning the distance between the TG to the n-layer of photodiode, the distance between the TG and the surface p-doping layer, and the TG voltage, the size and the location of the potential barrier and pocket will be influenced. Then the image lag can be reduced when the optimal value of these mask distances are achieved. The PPD shape is also determining the fringing fields around the PPD, which are needed for speeding up the electrons transfer. In this paper, we will focus on how to optimize the image lag by changing the PPD shape.

Different PPD shapes will form different electrical fields in the photodiode. At the edge of the PPD, the direction of electrical field, which is formed by the pn junction, is always perpendicular to the edge of the

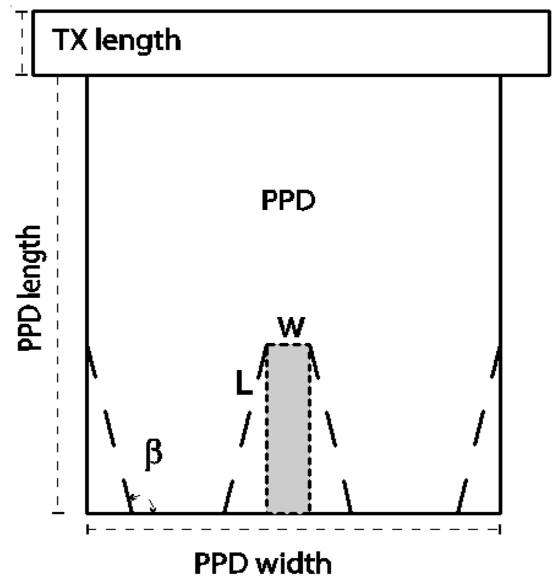


Figure 3. Photodiode shape optimization

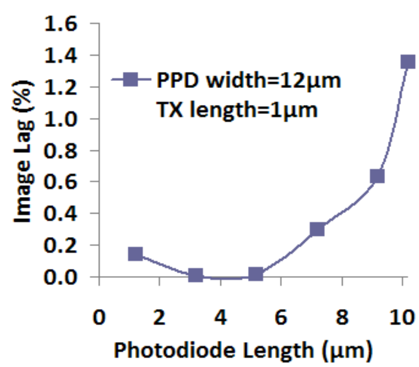


Figure 2. The image lag vs. PPD length

photodiode. And the value of the electrical field in the PPD is inversely proportional to the distance to the n-doping edge and only exists in the depletion region. Based on these boundary conditions, it can be deduced that when the length of the PPD exceeds some technology advised limit, the image lag will dramatically increase with the PPD length. This is proved by our test chip measurement results in Fig. 2. In Fig. 2, the image lag is increasing with the length of pixel, except for a very short pixel length. But if we just simply reduce the length of the photodiode to remove the image lag, the full well and the light sensitivity of the photodiode will also be decreased with the length of the photodiode, but this is not acceptable for large pixel pitch applications like high speed imaging. To minimize the large photodiode image lag and also to minimally sacrifice the light sensitivity and full well, starting from a rectangular shaped PPD, we make a rectangular opening in the lower part of the PPD (the dotted line, "bridge" shaped PPD in Fig. 3), and replace this part by the p-well. Then the center of the original rectangular shape is becoming much closer to the pn

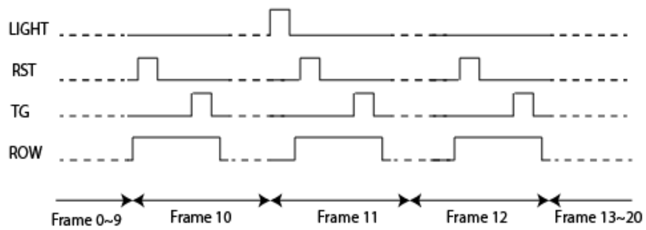


Figure 4. Image lag measuremnent timing

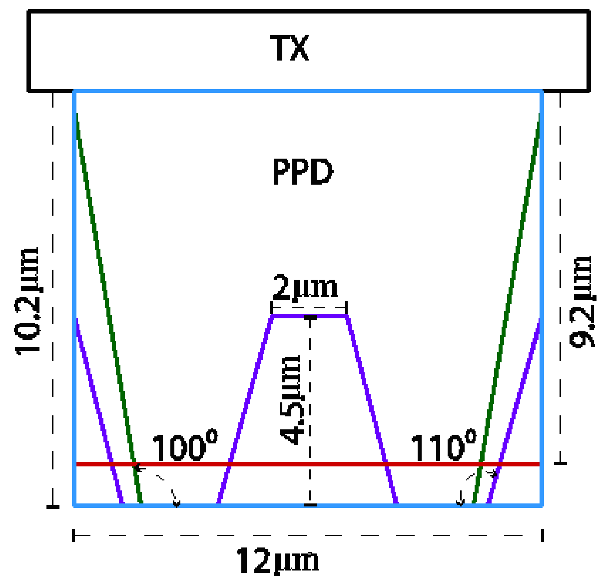
junction-formed fringing field in the bridge shaped photodiode. The electrical field in the PPD center will be increased. Further, based on the electrical field direction analysis and the reference [2] for triangular shaped photodiodes, we can modify the 4 corners of the lower border to the obtuse angle β (in Fig. 3) to further reduce the image lag. In this paper we will compare the image lag performance and light sensitivity performance of the proposed "W" shaped PPD 4T pixel with other shapes of the PPD design.

III. MEASUREMNT AND RESULTS

In this project, we designed a test sensor to verify our analysis of the image lag for different pixel designs. The designed chip is implemented in a TSMC 0.18μm process. The chip contains an 80x80 pixel array. And there are 80 different pixel designs contained in the test chip. The readout circuit contains a sample and hold circuit which is used to realize the correlated double sampling (CDS). The image sensor is working in a rolling shutter mode. Different pixel design implementations, for the proposed "W" shaped PPD design are included, for which three parameters are changed to find the optimized photodiode shape (W, L, β) (in Fig. 3).

To measure the image lag, we recorded the raw data of 20 frames. Keep the sensor in dark during 10 frames, then during the time between frame 10 and frame 11, a LED flash is given to make sure all the pixel in different rows achieve the same input light level and exposure time. The timing diagram is shown in Fig. 4. Then frame 11 will contain the illuminated image data. The light flush time length is tuned to make sure the pixels achieving about 90% of their saturation level. The signal readout from frame 12 will come from the electrons left in the PPD after the charge transfer in frame 11 (=image lag of frame 11). Using the value of the raw data in frame 12 divided by value of the raw data in frame 11 (after compensation with the dark frame), we can define the (left-over signal/light signal) x 100% as the image lag.

By comparing the results of designs with different W, L, β values, we can conclude that getting a small W, large L and large β all can reduce the image lag. Fig.5 compares the image lag performance of four different pixel designs. The purple line belongs to the optimized proposed "W" shape PPD (W=2μm, L=4.5μm, β=110°). The green line belongs to the inverted trapezoid shape having β= 100°



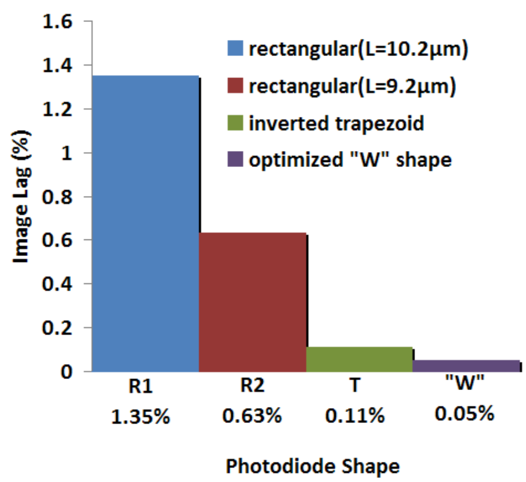


Figure 5. The image lag vs. different shaped photodiodes

and without the extra opening. The blue line presents the traditional rectangular photodiode pixel (PPD length = 10.2μm), which has the same PPD length as the "W" shaped and inverted trapezoid shape. The red line belongs to the 9.2μm photodiode length. The result shows (in Fig. 5), that the optimized "W" shape photodiode pixel (purple) achieved 1/27 of the image lag of the normal rectangular shape (blue), and about 1/2 of the image lag of the inverted trapezoid shape (green). This image lag value is very low and actually its characterization is already limited by the readout noise of the sensor. The value measured for the "W" shape diode is comparable to the image lag performance with a normal size rectangular shape PPD of 5.2μm.

Due to the extra opening of the proposed "W" shaped PPD, and the modified corner (obtuse angle β), the remaining area of this "W" shape is only about 81% of the rectangular shaped photodiode (same PPD length). In the

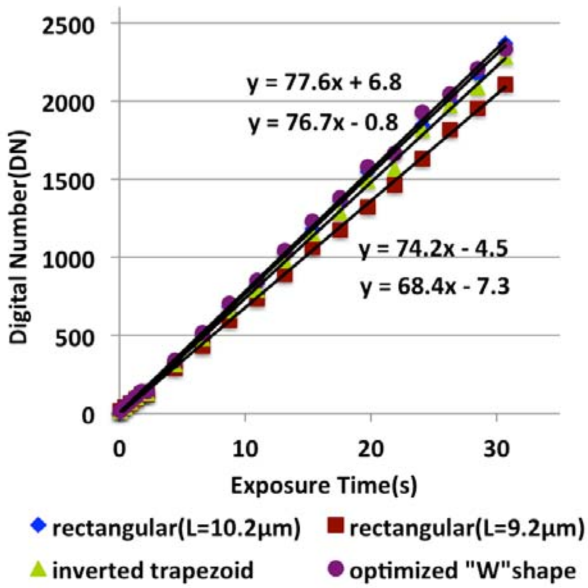


Figure 6. Light sensitivity comparision

light sensitivity measurement (Fig. 6), under a constant light illumination level, and by changing the exposure time, the slope of the signal response can reveal the pixel light sensitivity (DN/s). The result shows that the proposed "W" shape PPD pixel and the normal rectangular shaped one got nearly the same light sensitivity. The removed area to get a better image lag does not sacrifice the light sensitivity, which in its turn is a crucial parameter for large PPD applications.

In summary, the measurement results prove that the proposed "W" shaped PPD 4T pixel indeed can improve the transfer efficiency, and drastically decreases the image lag for large PPD pixel. And this new PPD shape can provide an equivalent large light sensitivity for the pixel that is of crucial importance for using large PPD in pixel.

IV. CONCLUSION

To deal with the image lag problem in a large photodiode pixel present in a normally rectangular shaped photodiode, we propose a new shape, which increases the electrical field in the center of the photodiode. The high electrical field can speed up the electron transfer from the photodiode to the floating diffusion. For verifying the proposed pixel design, a test image sensor was designed and implemented. The chip measurement results show that the proposed "W" shaped PPD can decrease the image lag to 1/27 of normal large rectangular photodiode.

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