Quantitative Full 3D Blooming Analysis on 1.4um BSI CMOS Image sensor

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***Abstract*—3D TCAD analysis of blooming for 1.4 μm CMOS image sensor (CIS) with two-shared pixel structure has been performed. Its blooming behavior has been modeled and clear design guidelines for potential control inside CIS pixels have been obtained.**

Keywords*—*CMOS Image Sensor; Blooming; TCAD

I. Introduction

To develop recent CIS pixel, it has become common to use 3D process and device simulation for predicting pixel properties such as full-well capacity [1] and image lag [2], [3]. Suppressing blooming is the other key issue for CIS pixel design. Blooming occurs under strong illumination that causes photogenerated electrons inside photodiodes (PD) to overflow to neighboring PD. Lateral overflow drain (LOD) [4], [5] and vertical overflow drain (VOD) [6] have been proposed as effective technology to suppress blooming. However, LOD is unsuitable technology for small pixel because it requires large space and VOD cannot be applied to BSI pixel. Therefore, pixel design that takes account of blooming suppression is necessary for small BSI pixel.

In this work, two shared 1.4 μm backside illumination (BSI) pixels where two PDs share floating diffusion (FD), amp transistor (AMP), and reset transistor (RST), as shown in Fig. 1, have been studied.

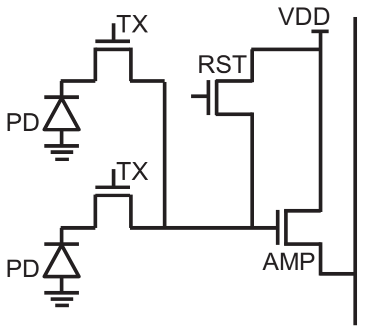

Fig.1. CIS structure studied in this work. The floating diffusion is shared by two pixels.

To suppress blooming, it is necessary to ensure that photogenerated electrons in PDs are drained to power line through transfer transistor (TX), FD, and RST before overflowing to neighboring pixels as shown in Fig. 2. To drain electrons properly, potentials inside pixels should be $\phi ISO<\phi TX<\phi RST$ where ϕISO, ϕTX, and ϕRST are barrier potential between PDs, channel potential of TX and RST, respectively (Fig. 3).

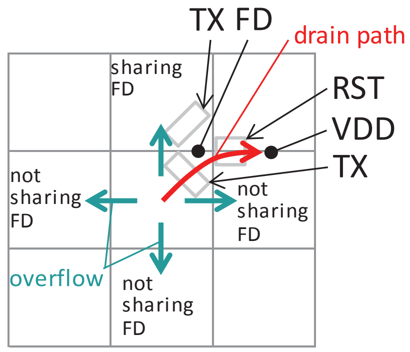

Fig.2. Schematic diagram of electron flow under strong light illumination. Overflowing path to neighboring pixels (green arrow), and drain path to VDD (red arrow) is shown.

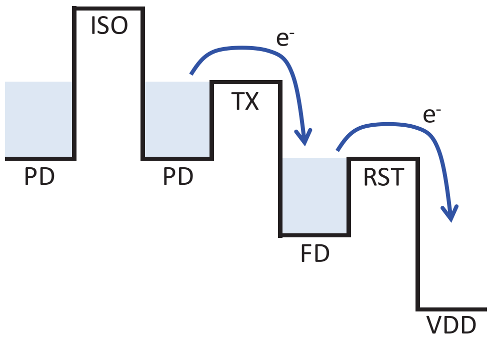

Fig.3. Schematic diagram of potential inside CIS pixel.

In the present work, we have performed 3D process and device simulation to predict blooming. Good agreement with experiments has been confirmed. In addition, design guidelines for potential control inside CIS pixel to meet blooming criteria have been derived.

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II. SIMULATION METHODOLOGY

Fig. 4 shows the results of the blooming experiment. Signal levels (Vsig) of red, green, and blue (R, G, B) pixels vs. exposure time under green light illumination are shown. With increasing exposure time, accumulated electrons in each PD are monotonically increased and G-pixel reaches saturation first. After saturation of G-pixel, increased slope of Vsig on R- and B-pixel is observed. We call the variation of slope before and after the G-pixel is saturated the slope ratio, R_{slope}. This R_{slope} is a good indication of blooming since it reflects overflow of electrons from saturated G-pixel to R- and B-pixels.

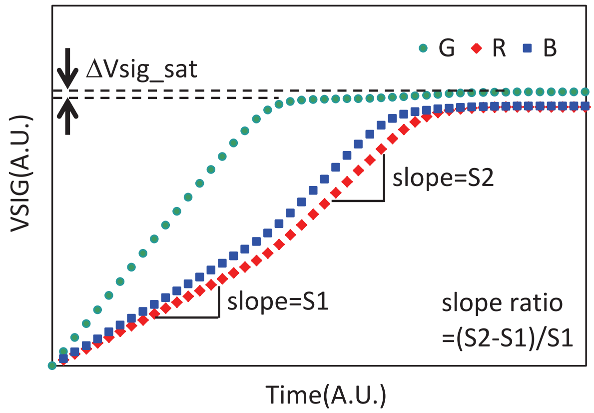
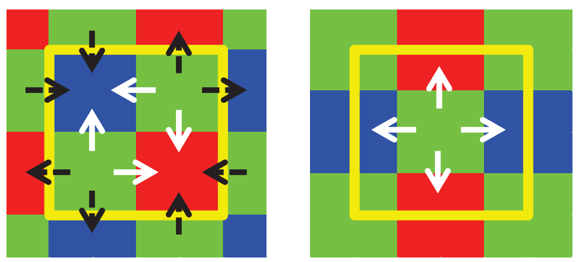


Fig.4. Output signal of RGB pixel with different exposure time under green light illumination. Slope ratio and ΔVsig-sat are the metrics for blooming.

Another signature of blooming is increase of saturation levels (ΔVsig_sat) of G-pixels after R- and B-pixel get saturated.

Fig. 5(a) shows the top view of the pixel arrays. For blooming analysis, adequate simulation domain is 2x2 unit Bayer pattern if periodic boundary condition (PBC) can be used. In this study, however, to avoid the convergence problem, reflective BC is used instead. Therefore, a different simulation domain is adopted (Fig. 5(b)). Center pixel and four nearest neighboring pixels, which are denoted right, left, up, and down, are considered. In addition, FD, TX and RST, which is the drain path, are modeled. By calculating electron current at each neighboring pixel and transistors while generating electrons in center pixel, blooming can be modeled.



(a) (b)

Fig.5. The top views of Bayer RGB pixel arrays, and the preferred simulation domains for periodic boundary condition (a) and reflective boundary condition (b). The latter domain is used in this work.

III. SIMULATION RESULTS

The results of transient analysis with constant electron generation in center pixel are shown in Fig. 6. R_{slope} of neighboring pixels after saturation of center pixel is clearly obtained. In addition, larger R_{slope} of the upper pixel that shares FD with center pixel is confirmed. These results indicate that there are two modes of blooming: direct mode in which electrons flow over barriers between PDs, and indirect blooming mode in which electrons flow through shared FD. The latter mode occurs when ϕRST is not high enough. Overall electrostatic equipotential during blooming is visualized in Fig. 7 (a). Direct and indirect overflow of electrons to neighboring pixels is clearly observed (Fig. 7 (b)). Fig. 8 (a) and (b) show the contour plots of electrostatic potential and electron current density at pixel boundary. Electrons only flow near the potential minimum. Therefore potential is a good metric for blooming.

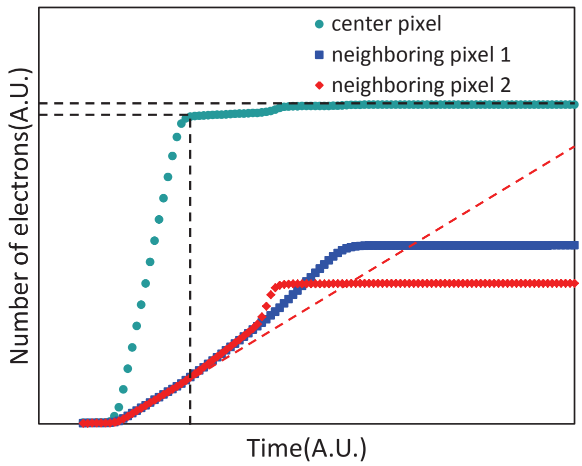
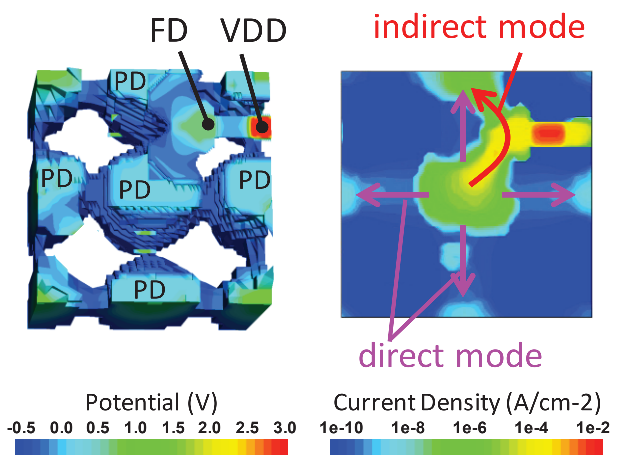


Fig.6. Simulated results of blooming by transient analysis. Enhanced slope ratio is observed on the upper pixel that shares FD with center pixel.



(a) (b)

Fig.7. (a) 3D potential plot of the simulated pixels under blooming condition. Value blanking is applied. (b) The plot of current density under blooming condition. Maximum values are projected to a plane.

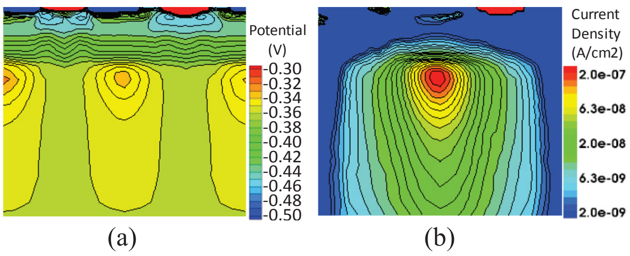


Fig.8. (a) The cross-sectional potential plot at pixel boundary under blooming condition. (b) 2D plot of electron current density at pixel boundary.

For the same structure, we have performed quasistationary analysis with constant electron generation in center pixel while varying process conditions. In this simulation, center pixel has become saturated owing to electron generation. R_{slope} can be expressed as $(I_{left}+I_{right}+I_{down})/I_{gen}$ for direct mode blooming and as I_{up}/I_{gen} for indirect mode blooming, respectively, where I_{left}, I_{right}, I_{down} and I_{up} are current detected in left, right, down and up pixel and I_{gen} is the current generated in center pixel.

The simulated direct blooming results are compared with experiment in Fig. 9. Simulated R_{slope} due to blooming is determined by ϕTX-ϕISO and in good agreement with experiment. From the results, it is necessary to set the difference between ϕTX and ϕISO at more than a certain value that is derived to suppress direct mode blooming. It is also found that R_{slope} is proportional to exp(-q(ϕTX-ϕISO)/kT).

For indirect mode blooming, it is found that R_{slope} is dominated by ϕRST-ϕTX' where ϕTX' is a potential under TX of up pixel that shares FD with center pixel, as shown in Fig. 10. Therefore, for suppressing indirect mode blooming, control of ϕRST is important.

Overall results including both direct and indirect blooming mode are shown in Fig. 11. R_{slope} vs. ϕTX-ϕISO shows bathtub shape. Especially, in the case that ϕRST is not high enough, worsening of blooming becomes remarkable when ϕTX-ϕISO is increased. This simulated tendency is also experimentally observed (Fig. 11). When ϕRST is not high enough (Fig. 12), indirect path through FD becomes significant and leads to blooming.

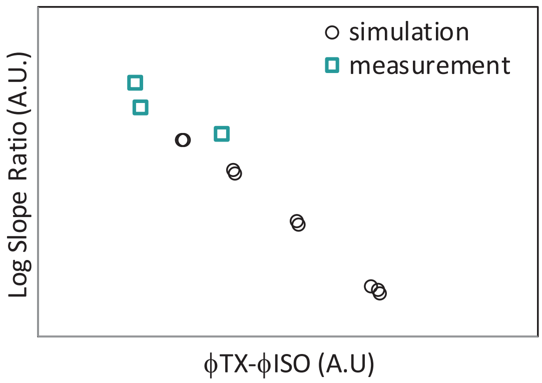


Fig.9. The relation between slope ratio and ϕTX-ϕISO for direct mode blooming.

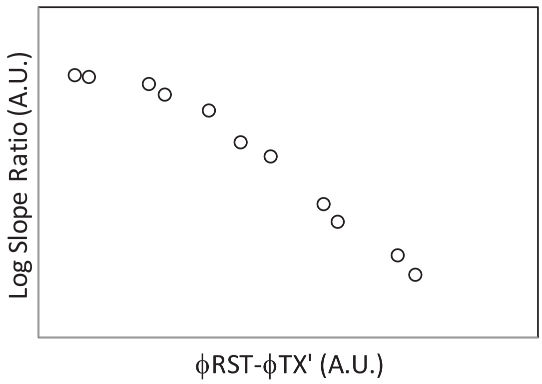


Fig.10. The relation between slope ratio and ϕRST-ϕTX' for indirect mode blooming.

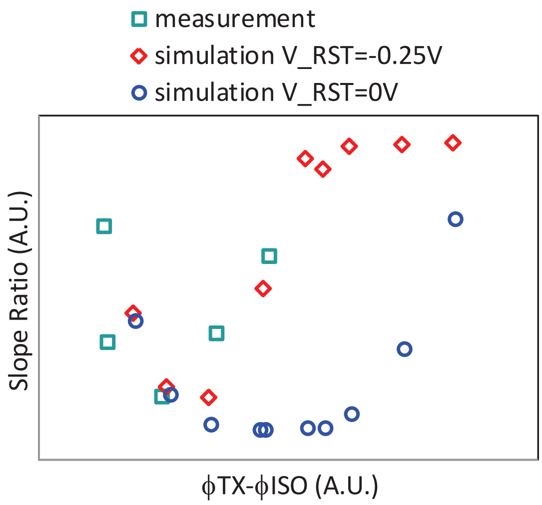


Fig.11. The relation between total slope ratio and ϕTX-ϕISO.

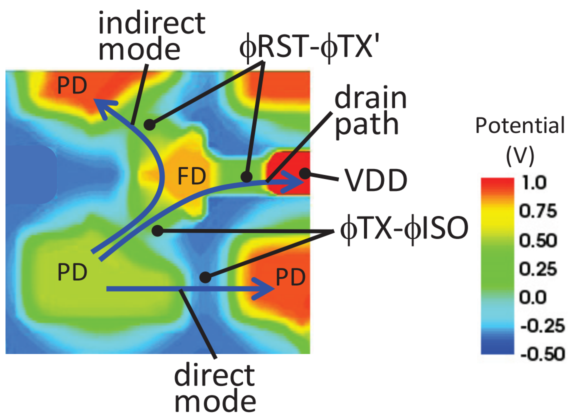


Fig.12. The potential plot of the simulated pixels under blooming condition. Maximum potential is projected to the plane.

Finally, ΔVsig_sat is investigated by transient analysis. It is found that ΔVsig_sat is dependent upon ϕRST-ϕTX. Magnitude of ΔVsig_sat is in good agreement with experiment.

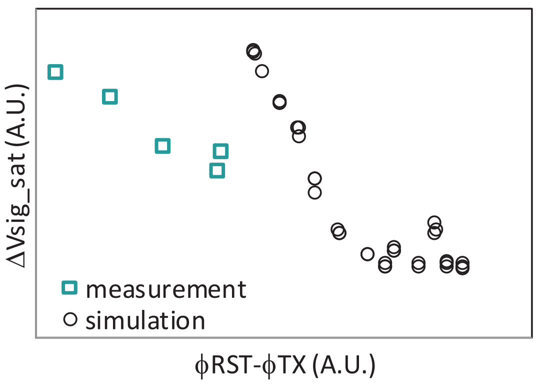


Fig.13. The relation between the change of saturation level (ΔVsig_sat) and ϕRST-ϕTX.

In summary, simulated guidelines for suppressing blooming are obtained. For suppressing R_{slope}, ϕTX-ϕISO>0.2V and ϕRST-ϕTX'>0.2V are required. These extracted guidelines on suppressing blooming are useful when performing CIS pixel design.

IV. Conclusion

3D TCAD analysis of blooming for 1.4 µm CIS with two-shared pixel structure has been successfully performed. Experimental blooming metrics, such as slope ratio R_{slope} and variation of saturation level ΔVsig_sat, are modeled and their agreement with experiment has been confirmed. Clear design guidelines for pixel potential, such as barrier potential between PDs and channel potential of pixel transistors, have been determined.

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