3D Modeling of CMOS Image Sensor and Aperture Size Effect

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***Abstract* — Three-dimensional (3D) modeling is reported for CMOS active pixel image sensor with microlens and color filter layer. Process simulation is performed by Crosslight CSuprem while the optical effect is simulated by finite difference time domain technique and the electronic response by 3D drift-diffusion software APSYS. The opto-electronic responses are presented versus various power intensity and illumination wavelength. The aperture size of the isolated metal layer is also discussed. Whereas the microlens is shown to improve the sensitivity, the aperture size of the isolated metal layer should be optimized to avoid sensitivity loss. The presented results demonstrate a methodological and technical capability for 3D modeling optimization of complex CMOS image sensor.**

I. Introduction

The complementary metal oxide semiconductor (CMOS) active pixel sensor (APS) has attracted increasing interest due to demand for miniaturized system-on-chip capability, low-power, and cost-effective imaging systems during the past two decades [1-2]. Efforts including several photodiode structures such as the pinned photodiode (PPD) [3] have been explored to enhance the sensitivity without compromising the resolution. These include the 3D integration of photodiode and the optimization of metal layer distribution to maximize the sensitive area. However, the plano-convex microlens routinely fabricated on top indicates that 3D modeling together with finite difference time domain (FDTD) technique for optical modeling is indispensable [4]. In this work, based on Crosslight CSuprem and APSYS [5], we present 3D modeling of an APS unit. The results are also discussed on the effect of the aperture size of the isolated metal layer.

II. 3D APS Development by CSuprem

The schematic APS unit structure is similar to Ref. [1-3,6,7] including a PPD, a transfer (TX) gate, and a reset (RST) gate. The whole 3D APS unit is process-built and simulated by Crosslight CSuprem with structure mesh, material together with doping exported and interfaced to Crosslight APSYS. To reduce mesh size, we assume 5-μm-thick p-type starting substrate. The detailed unit component deployment (as generated by Crosslight MaskEditor with 9 mask layers) is schematically shown in Fig. 1. The fully process simulated structure with microlens is shown in Fig. 2 with 2D net doping concentration for one typical region (PPD and TX) presented in Fig. 3.

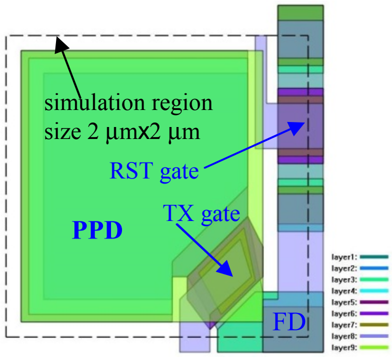

Fig. 1. Schematic APS unit deployment.

III. 3D Opto-Electronic Modeling by APSYS

Taking the exported file from CSuprem, 3D modeling of opto-electronic responses is performed by APSYS software based on drift-diffusion theory. The optical modeling is done by FDTD technique [4] with all the important material index data converted to the Lorentz dispersion coefficients as described by Eq. (1) below. The color filter array (CFA) layer is assumed with an imaginary permitivity and then fitted with Eq. (1), as shown in Fig. 4.

$$\varepsilon(\omega,\mathrm{x})=\varepsilon_\infty(\mathrm{x})+\sum_n \frac{\omega_n^2\Delta\varepsilon_n}{\omega_n^2-\omega^2-i\omega\gamma_n} \quad (1)$$

The FDTD optical modeling indeed observed the focusing effect of the microlens [6,7].

The illumination and APS unit operating bias clock is shown in Fig. 5. The evolution of the potential on the floating drain (FD) versus time is shown in Fig. 6(a) where the illumination overshot effect can be seen when the power intensity is high. In Fig. 6(b), the potential difference (relative to dark case) on FD at the transfer (TX) stage is also shown versus wavelength. The enlarged potential difference near 0.52 μm is believed due to the Lorentz dispersion terms of the CFA layer used for FDTD modeling. A flat APS unit without microlens has also been simulated for comparison. The potential difference (relative to dark case) on the FD after TX stage versus optical power intensity is shown in Fig. 7(a) by comparing between the microlens and the flat cases. The pixel unit with microlens apparently shows improved response for a wide range of optical power intensity. The opto-electronic response is also simulated versus the aperture size of the isolated metal layer in the APS structure with microlens. The potential difference on FD after TX stage is also shown in Fig.

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7(b) by comparing the cases of large and small apertures of the isolated metal layer, respectively. It indicates that inappropriate aperture for the isolated metal layer may actually lead to sensitivity loss (e.g., the small aperture case with more metal blocking). More modeling work is needed on CFA and cross-talk issues [4].

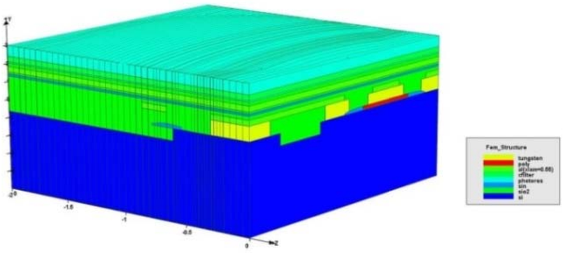

Fig. 2. 3D APS developed by CSuprem (microlens on top).

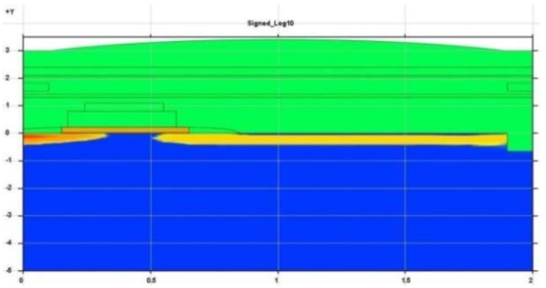

Fig. 3. 2D net doping profile around PPD and TX.

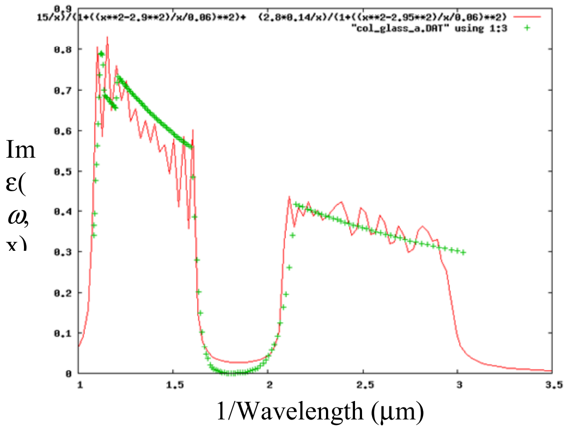

Fig. 4. Fitting of color filter array (CFA) layer.

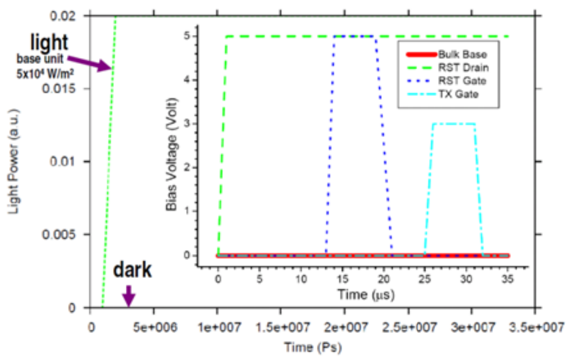

Fig. 5. Illumination & APS unit operating bias clock (inset).

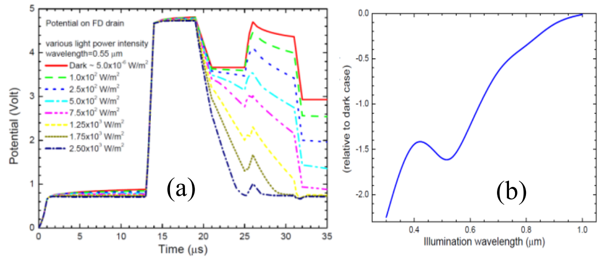

Fig. 6. (a) Potential on FD versus time with various optical power intensity with microlens, and (b) potential difference (TX stage) vs. wavelength.

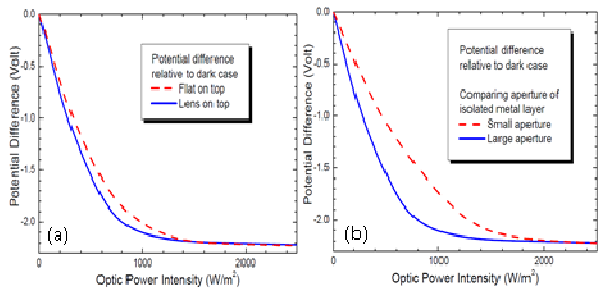

Fig. 7. Potential difference (after TX stage) versus optical power intensity: (a) comparison between flat and lens cases, and (b) comparison between small and large aperture of the isolated metal layer in the APS structure.

IV. Conclusion

The 3D modeling of CMOS APS with microlens is presented. The microlens is shown to improve the sensitivity, but the aperture size of the isolated metal layer should be optimized to avoid sensitivity loss. The results demonstrate a methodological and technical capability for 3D modeling optimization of complex CMOS image sensor.

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