Rigorous Three-dimension Electromagnetic Simulations and Optimization for CMOS Image Sensor pixels

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Abstract: The size of pixels in complementary metal-oxide-semiconductor image sensor has steadily decreased during the last decade, which leads to a challenge on maintaining the pixels’ optical performance. The diffraction effects result in increased spatial crosstalk and decreased optical efficiency, so rigorous simulation and optimization are important. FDTD method is used to simulate the optical performance and a diffuse-like source is used to reproduce real conditions. A commercial tool from Lumerical Solutions is used to do three-dimension FDTD simulation. The diffuse-like sources are simulated by the uniform sum of several focused beams characterized by a given f-number of the objective len. The typical 1.75µm, 1.45µm and 1.1µm pixels are simulated and analyzed. The results show that the optical efficiency of the pixels decreases dramatically when the pixels size scaling down. Several approaches to produce better device performance for sub-2um pixels are analyzed. Micro-lens optimization, dielectric stack height reduction can decrease the optical power loss and optical confinement realized by an air-gap can reduce the spatial crosstalk. The results show that the optical performances of the optimized 1.1µm pixel are comparable to those of conventional 1.75µm pixel.

1. Introduction
CMOS image sensors are experiencing exponential market growth due to the increasing demands of digital still and video cameras, security cameras, webcams, and mainly mobile cameras. Complementary Metal Oxide Semiconductor (CMOS) technology has shown competitive performance but also many advantages in on-chip functionality, power consumption, pixel readout, and cost, so that it has become more and more important in the Image Sensor Industry. Market trend for higher pixel density leads to smaller and smaller pixel size. Thus the photodiode area shrink. On the other hand the thickness of interconnect layers scales less than the planar dimension, light has to travel through a narrower path to reach the photodiode which cause the problem of light collection. Thus optical simulation[1] is of great importance to characterize the sensor and optimize its performance such as Quantum Efficiency and Crosstalk. Figure 1 shows the structure of CMOS image sensor.
As diffraction effects can substantially affect light propagation when the pixel size is comparable to the wavelength of light waves, we chose an electromagnetic simulation tool based on Finite Difference Time Domain (FDTD)\(^4\)\(^5\), available from Lumerical Solutions, to do 3-D simulation for light propagation and photon collection inside the pixels. Figure 2 shows the typical 3-D structure for CMOS image sensor.

Fig. 2. 3-D structure for CMOS image sensor

The imaging performance of the 1.75-, 1.4-, and 1.1- \(\mu\)m pitch pixels is simulated by the FDTD methodology in this paper respectively. A rigorous light source is used to simulate the real light from the objective lens. A set of new techniques for the pixel architecture optimization is proposed by analyzing the characteristic parameters. Finally, a comparison between the performance before and after optimization for the 1.1- \(\mu\)m pitch pixel is made and also a performance contrast between the optimized 1.1- \(\mu\)m pitch pixel and the conventional 1.75- \(\mu\)m pitch pixel is done.

2. Design and Methodology

2.1. Pixel geometrical architecture.

Figure 2 shows the cross-section projection view of a typical conventional front-side-illuminated image sensor structure. It consists of the microlens, the color filters, dielectric stacks, metal interconnection, and the substrate. A gapless microlens array with an elliptic parabolic surface is used, and the CFA and the silicon substrate are simulated as absorptive materials. Ideal red–green–blue filters are used, and the metal in the dielectric stacks is treated as a perfect electrical conductor. The
dielectric properties of materials are described by refractive indexes or dielectric constants obtained from Palik\cite{2,3}. We assume a fill factor of 50% and the photosensitive area is located at the center of the pixels.

![Diagram of a four-pixel unit cell](image)

**Fig. 3.** Vertical structure projection of the four-pixel unit cell

### 2.2. FDTD
Perfectly matched layer conditions are used at the structure’s boundaries. The simulation grid spacing is set to 25 nm for a fast simulation and approximately 10 nm for a detailed simulation. The z components of the Poynting vector available from the resulting fields, are integrated to obtain the total optical power delivered to the photodiode. Complete conversion of photons to electrons, i.e., quantum efficiency of 100%, is assumed when the light incidents on the photodiode area at the silicon interface. The plane-wave illumination with the wavelength of 650 nm is adopted as an incident light source located just above the microlens surface. The simulation area covers a square 2-by-2 pixel array.

### 2.3. Defuse like light source
In order to correctly evaluate pixels optical performances we must simulate a product-like illumination. But the lens is hundreds of times bigger than the pixel. So it is difficult to simulate the objective-lens and pixels together because the computation will consume very large resources.

In Lumerical software, a source called “thin lens” allows the simulation of such an objective lens with a given f-number and chief ray angle. Figure 4 below shows a schematic representation of the light source seen by the pixel array.

![Diagram of light source](image)

**Fig. 4.** A schematic representation of the light source seen by the pixel array.
The f-numbe is assumed to be 2.8. Sources with a spacing of 0.5μm are employed to illuminate uniformly the microlens. The simulation result shows that this is sufficient to simulate the real conditions.

3.Result and optimization

3.1.simulation result

Optical efficiency and optical spatial crosstalk are introduced to characterize the pixel imaging performance. The pixel optical efficiency is defined as the ratio of optical power received by the photodiode at the silicon substrate to that incident on the pixel surface. Assuming that quantum efficiency of 100%, spatial crosstalk (CTK) is defined as the average ratio of optical power received by the photodiodes of the adjacent pixels (generally four-adjacent pixels) to that of the source directly incident on the pixel surface.

The electric field intensity through the middle of the Green - Blue pixels are shown in the simulation result. The figures show high transmission through the green pixels and low transmission through Blue pixels.
3.2. Optimization

3.2.1 Dielectric stack height reduction. The pixel performance greatly depends on the height of the dielectric stack layer as the pixel size shrinks. A Cu process with 0.13-μm design technology can be used to reduce the total pixel height by 20% through the thicker metals and interlayer materials compared with those of Al [6-9]. Figure 6 shows the simulation result of the pixel which the dielectric stack height was reduced by 1 μm.

![Figure 6: Simulation result of the pixel with dielectric stack height reduced.](image)

3.2.2 Microlens optimization. In this case, the microlens is optimized for the 1.05-μm pixel. Effective optical efficiency at three locations with a microlens radius from 0.5 to 30 μm is measured and curved utilizing the simulation results (shown in Fig. 7). The microlens height is kept constant at 500 nm, and the illumination is incident normal to the photodiode. Seen from Fig. 7, the optimal microlens radius of curvature is between 1 and 1.5 μm, a microlens radius of 1.1 μm is used in later simulation for an optimal 1.1-μm pixel to concentrate more light onto the photodiode.

![Figure 7: Simulation results of microlens optimization.](image)
3.2.3 optical confinement method. Diffraction resulting in increased spatial optical crosstalk. Optical confinement methods for guiding incident light from the microlens down to the photodiode. These techniques rely on total internal reflection (TIR) at the boundary between dielectric media of different refractive indices.\(^{[10-13]}\). Figure 8 shows an example calculation for the 0.2 \(\mu\)m air gap thicknesses for light with normal incidence angle.

![Figure 7: Curves of optical efficiency versus the microlens radius](image)

**Fig.7. curves of optical efficiency versus the microlens radius**

**Fig.8: pixels with air gap**

4. Comparison

Figure 9 (a) shows the Poynting Vector on the active layer before optimization and Figure 9 (b) shows the Poynting Vector on the active layer after all the optimization is done. It is obvious that the optical crosstalk is reduced dramatically. The air gap play an important role in light confinement.
5. Conclusion

We have investigated the optical performance of sub-2-μm pixels using FDTD method. Three kinds of approaches are introduced to optimize the pixel architecture according to the simulation results. The performance improvements for the 1.1-μm pixel after optimization are shown. The optimization in microlens radius can concentrate more light to the photosensitive area. The combination of the dielectric stack height reduction and the air gap structure can maximize the optical efficiency and minimize the spatial crosstalk. By employing all these optimization methods, the optical performance of the 1.1-μm pixel after optimization are comparable to those of the larger 1.75-μm pixel.

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