Novel non-metallic pixel isolation technology for high sensitivity in CMOS image sensors with submicron pixels

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Abstract

Demand for high-resolution multiple cameras leads to competition to decrease size of pixels, and image sensor products with submicron-sized pixel coming to the market. Technologies of CMOS Image Sensor (CIS) have been developed to produce high quality images even with small pixel size and being limited area of image sensor [1]. Based on 3D finite-difference time-domain (FDTD) simulations including color filter properties and device spectrometry, we concluded that major light loss was caused by the metallic grid structure (71.4%) and developed non-metallic pixel isolation structure that eliminates optical losses for high performance in the world's highest resolution image sensors for mobile applications. By this sensitivity maximization technology, image quality in high resolution camera using small pixels and non-metallic pixel isolation increases SNR (+0.7dB) and sensitivity (+15%) compared with pixel isolation with hybrid grid. This innovative technology will be used in smaller pixel generations in order to provide superior image quality.

Introduction

Recently, smartphones have been hiring high-resolution multiple cameras and demand for small pixel size are required to implement more pixels into limited area. As pixel size is decreasing continuously, it is very difficult to maintain sensitivity due to reduction of photons that goes through microlens and limitations of light diffraction [2]. In order to reduce the light loss but avoid crosstalk to adjacent pixels, the total reflection structure was designed by introducing the difference in refractive index between color filter and new grid [3]. New technologies increased sensitivity and signal-to-noise ratio (SNR) to enhance image quality of pixels, especially for small pixels. Based on the FDTD analysis and experiments, it is concluded that light absorption by metallic grid is still a key to reduce light loss and a non-metallic pixel isolation technology for high sensitivity was proposed.

Simulation and Theoretical Analysis

In the previous research, factors of light loss from microlens to the bottom of Si are examined by FDTD simulation, and the most dominant part above back-side of Si is grid structure which occupies 71.4% of total loss compared with microlens (3.8%), color filter (21.4%), and anti-reflective layer (3.3%) in 0.8um pixel [3]. In spite of microlens shape is well designed to help incident light focused on Si surface, it is inevitable that beam size is overlapped with grid as pixel size decreases. There are two reasons: (1) In the semiconductor manufacture, there is physical limit of width of grid and ratio of grid area to total APS area gets higher in small-sized pixels and (2) beam spot size can't be reduced as pixel shrinks. To reduce beam spot size on silicon surface from microlens is key to avoid light loss by adjacent metal grid. For minimum spot size, small effective focal length (EFL, focal length(f)/lens diameter(D)) and large refractive index(n) are preferred.

$$\text{Diffraction limited spot size} = 2.44 \times \frac{\lambda}{n} \times \frac{f}{D}$$

In FDTD simulation with 1.4, 1.0, 0.7um pixels, portion of metal grid increases from 9% to 32% (Figure 1) and light loss ratio by metal grid also significantly increases [4]. Therefore, transparent low refractive index material was proposed to decrease optical loss and more than 30% loss is reduced and Y-SNR is increased by >0.4dB. Transparent material reflects more light and absorbs less light compared with metal (Tungsten) grid. However, new material-based grid structure still has thin metal layer below for metal-shield auto-focus in FDTI structure. By shielding a half of photodiode by metal under grid, signals from left and right are calculated and compared for phase detection. Because of this, hybrid grid had metal layer at the bottom of grid structure. However, tons of technologies have been developed for small pixels, and new technology named 'Super PD (Figure 2)' which uses dual PDs and guides incident light into two pixels for auto-focus has come and it allowed image sensor to be free from metal. For the optimized structure, effect of thickness of metal grid on pixel performance is simulated and it is found that sensitivity and Y-SNR increase linearly as ratio of metal from total grid is decreased.

Fabrication and Experiments

The schematic view and cross-sectional TEM image of ‘ISOCELL’ technologies are described in figure 3. From metal grid to hybrid grid and non-metallic grid structure, low refractive index material was developed to replace metal grid to increase light source efficiency. Various ratio of metal to grid height were simulated and fabricated to verify FDTD simulation and modeling. Figure 4 shows simulated results are well matched with Si results and both indicate that SNR will be increased when using thinner metal or non-metal. Highest sensitivity and SNR were achieved with non-metal grid structure. In 0.7um pixels, +15% sensitivity and +0.7dB Yi SNR at 20lux are obtained by eliminating optical loss from metal grid structure and by optimizing color filter processes. Normalized Quantum Efficiency (QE) of non-metallic grid and hybrid grid is described in Figure 5. It is found that max peak of blue, green and red color filter is increased while crosstalk is suppressed.

Smaller pixel like 0.64um also adopted metal-free grid to generate 123% efficiency and +1.2 Yi SNR compared with conventional grid structure (hybrid grid) and it is even bigger jump while 0.7um metal-free grid generates 15% more sensitivity and +0.7dB Yi SNR improvement. Performance of 0.8um, 0.7um and 0.64um are summarized in Table 1 and it is showed that pixel performance overcomes one-generation with two-step technology (from metal grid to metal-free grid). In this way, ‘more pixel’ trend continues by overcoming physical limitation with the new structure with less light loss.

Another benefit of non-metallic structure is improved performance at binning mode at low light condition. Special modes such as tetra(4-) mode and nona(9-) mode are adopted to utilize light source effectively. A sum of four small pixels or nine small pixels should compete with bigger pixels however, cross-shaped grids between same color pixels are occupying considerable physical area and blocking incoming light. Due to this, a sum of pixels is not able to perform one big pixel’s performance at binning mode before this technology. However, when pixel integration uses metal-free grid, 0.7um at binning mode with four pixels performs the same SNR as 1.4μm big pixel.

Real images taken by hybrid grid and metal-free grid are in Figure 6. Metal-free grid uses more incident light source efficiently and produce more vivid image with reduced noise. With enhanced light sensitivity, we never lose finer details and color reproduction. More pixel strategy with small size will be more powerful with this novel technology.

Conclusions

For detailed, high quality image, sensitivity maximization technology is very important. In this paper, high resolution camera using metal-free grid increases SNR and sensitivity with non-metallic pixel isolation, compared with hybrid grid. Metal-free grid technology isolates each pixel with reflective barrier to utilize more light with suppressed crosstalk between pixels. This cutting-edge new technology will be used in smaller pixel generations in order to provide superior image quality.

REFERENCES

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Figures.

Figure 1. Schematic diagram (Top) and optical absorption by metal grid of 1.4, 1.0, 0.7µm pixel (Bottom) and cross-sectional image of FDTD Simulation (Right)

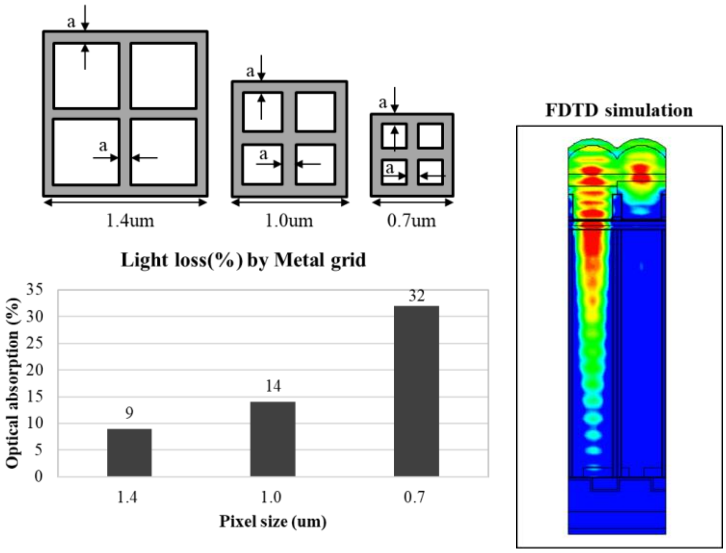


Figure 2. Schematic image of Metal-shield AF and Super PD

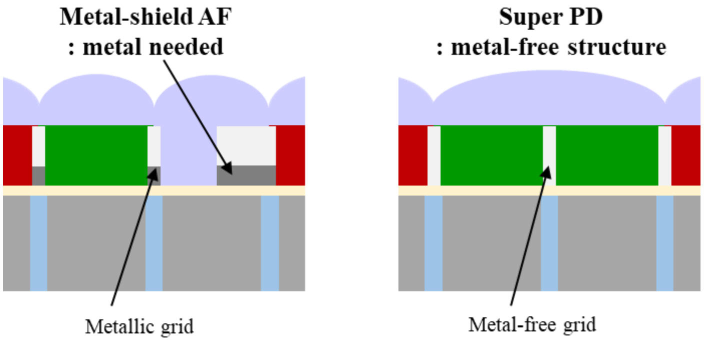


Figure 3. (Top)Schematic view of generation of technologies (metal grid, hybrid grid and metal-free grid) and (Bottom) Cross-sectional TEM image of the optical stack.

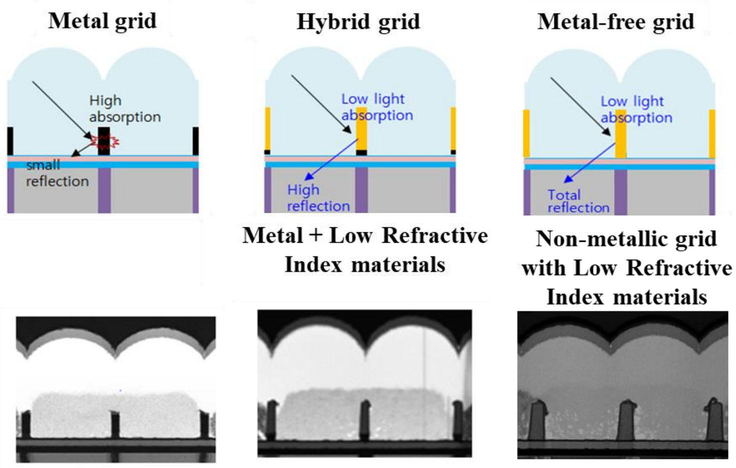
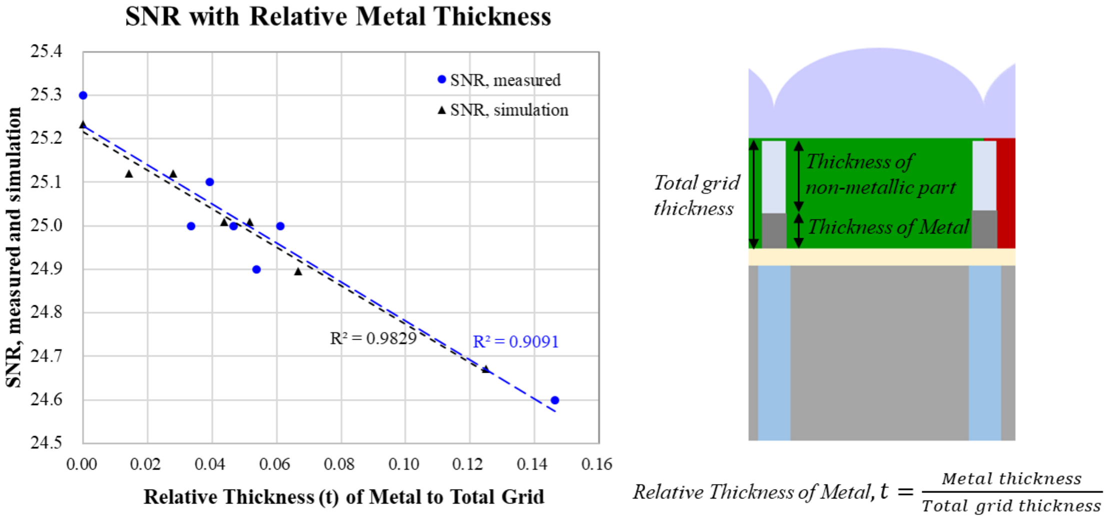
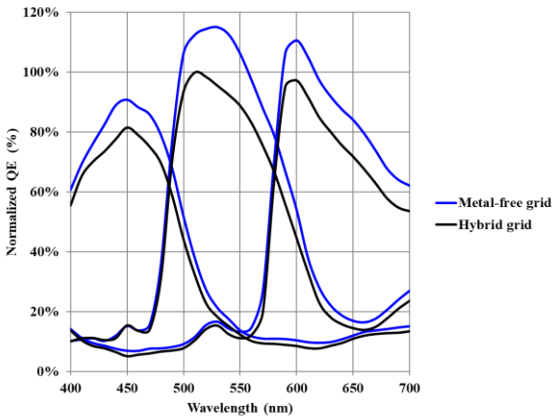


Figure 4. Effect of metal thickness on pixel performance: Comparison of Si and Simulation result (Left) and schematic view of sensor (Right)



$$\textit{Relative Thickness of Metal},\ t = \frac{\textit{Metal thickness}}{\textit{Total grid thickness}}$$

Figure 5. Quantum efficiency of hybrid and metal free grid (Left) and comparison of pixel performance with metal, hybrid, metal-free grid (Right)



	Pixel size	Metal grid	Hybrid grid	Metal-free grid
SNR	0.8um	25.6	26.0 (+0.4dB)	26.3 (+0.3dB)
	0.7um	-	24.6	25.3 (+0.7dB)
	0.64um		*confidential*	+0.7dB
Sensitivity	0.8um	2000	2200 (+10%)	2400 (+9%)
	0.7um	-	1650	1900 (+15%)
	0.64um		*confidential*	+23%

Figure 6. Comparison of images with hybrid and metal-free grid