High-Efficiency Dielectric Structure for Advanced CMOS Imagers

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Abstract

Air-gap-in-situ-microlens (AGML) above each pixel has been successfully developed to dramatically improve the optical crosstalk and pixel sensitivity. Combining light concentrated by dielectric microlens with light totally reflected by air-gap-guard-ring (AGGR), the pixel crosstalk can be suppressed more efficiently. On the other hand, investigations of optical effect on backend dielectrics show proper film thickness that can result in higher transparency. Adopting both proper dielectric thickness and AGML technology, at least 92% optical crosstalk and 152% photosensitivity improvements have been shown on 2.8um square pixel under 10° incident angle. And the pixel size can be further scaled to less than 2.8um square and maintain good performance.

Introduction

Recently, CMOS image sensor (CIS) has been widely applied to digital still camera (DSC), optical mouse, security camera and mobile phone. Since the strong demands for small chip size and high resolution of CIS applications, the pixel size has to be shrunk continuously [1-2]. Pixel size reduction, however, results in crosstalk and photosensitivity deterioration because it is inevitably accompanied with the decreases in photodiode aperture area and microlens area. Several special technologies such as air-gap-guard-ring (AGGR) and thinner backend (TB) processes have been proposed to improve the optical crosstalk [3-4]. For further improving the optical performance, in this paper, the simulations of quantum efficiency (Q.E.), which show the relations between spectral response and dielectric film structures, have been done and then lead to proper film thickness for pixel with higher transparency. Moreover, a more efficient optical structure, air-gap-in-situ-microlens (AGML), is proposed and combined with TB process to significantly improve the pixel crosstalk and photosensitivity. Especially, there is only one additional process and without extra mask in comparison with AGGR formation. Based on the experimental results, the pixel size can be scaled to 2.8um square with excellent optical performance.

Technology and Design

The test chips were prepared by typical 0.18um CMOS logic technology including shallow trench isolation (STI), borderless contact (BLC), retrograde channel doping, self-aligned silicide gate and source/drain (S/D). Special process modifications such as non-salicided S/D and double diffusion S/D implantation inside pixel array were used to improve the pixel performance [5-6]. The "Optical Device Advanced Application Module" of the software "Medici" was used to simulate the spectral response of the photodiodes with different dielectric structures [7]. Furthermore, the AGML structure was made on each pixel as seen in Fig.1, where (a) and (b) are the schematic layout diagram of AGGR and the tilted cross-sectional SEM photograph of AGML, respectively. The processes for AGML are compatible with standard CMOS logic processes and listed as follows: (a) First, define a taper dielectric trench around each pixel by using AGGR mask just after top inter-metal-dielectric (IMD) planarization; (b) Then, deposit dielectric film to seal the opening of the trench; (c) Finally, deposit the passivation film which has higher refractive index (RI) than that of the dielectric film in step (b). The most significant difference between AGGR and AGML is the step (a). Because we made a taper trench, the shape of a lens would be formed after the deposition of following dielectric film. Then a high RI dielectric film, such as SiN for passivation, was deposited to enhance the ability of the microlens to focus the incident light. Moreover, the measurement system consists of a parallel light source and a rotating stage. The chip test-board is fixed on the rotating stage to precisely simulate the variable incident angles.

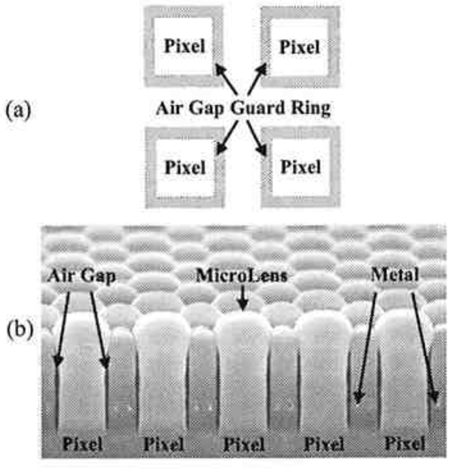

Fig.1 (a) Schematic layout of the AGGR; (b) Tilted cross sectional SEM photograph of the pixel with AGML

Experimental Results

Figure 2 shows the measured Q.E. of NW/Psub diode with two dielectric structures: (a) passivation (SiN)/ ILD (SiO_2)/ SiON/ Si, (b) passivation (SiN)/ ILD (SiO_2)/ SiON/ STI (SiO_2)/ Si, while the ILD (inter-layer-dielectric SiO_2) represents all backend oxide layers and the SiON is used as the contact-etch-stop layer in BLC process. The refractive index (R.I.) of SiN, SiO_2, SiON and Si are 2.01, 1.46, 1.97 and 3.44, respectively. Because the destructive interference occurs between SiON/ STI (SiO_2)/ Si (hi R.I./low R.I./high R.I.) interfaces, sample (b) shows the worse spectral response than that of sample (a), especially under blue light (420nm~480nm) [6]. That means the photodiode under Si has better spectral response than the photodiode under STI.

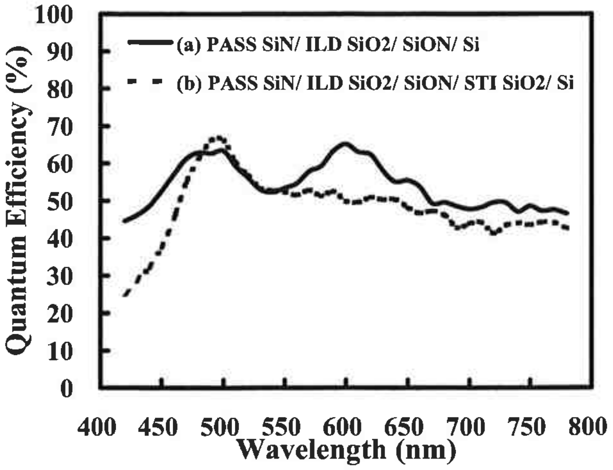

Fig.2 Measured Q.E. for two dielectric film structures.

In order to find out other factors in relation to the spectral response, Q.E. of the photodiode with different dielectric film thicknesses are simulated. Fig.3 shows the simulated Q.E. for different passivation (SiN) thickness. As increasing SiN thickness, the peaks of spectral response shift toward short wavelength region and show little degradation. The ILD SiO_2 thickness has nearly no impact on the simulated spectral response as shown in Fig.4. In Fig.5, increasing SiON thickness reduces the Q.E. of short wavelength (<500nm). Consequently, proper choice of dielectric film structure and thickness can result in higher transparency of backend stack.

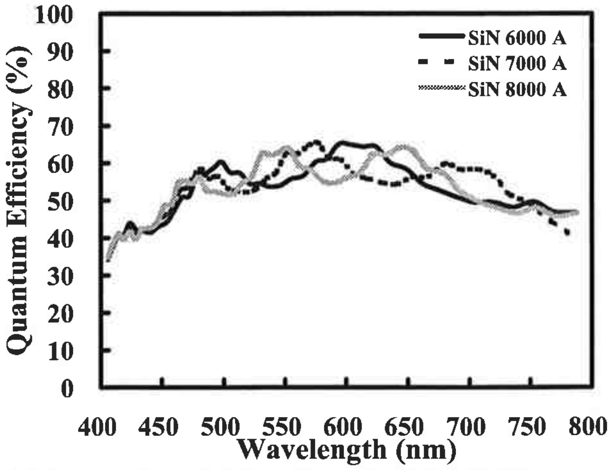

Fig.3 Simulated Q.E. for different PASS SiN thickness.

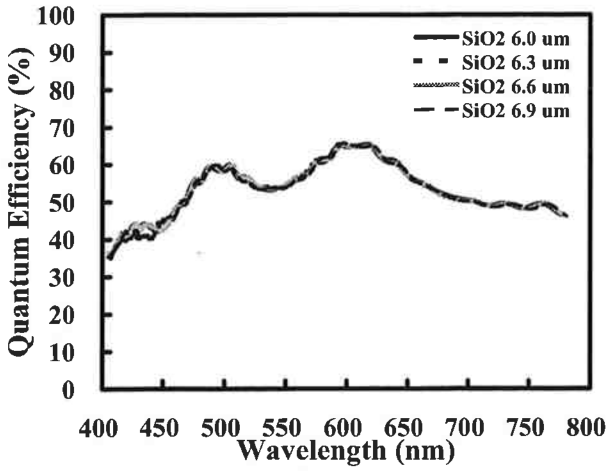

Fig.4 Simulated Q.E. for different ILD SiO_2 thickness.

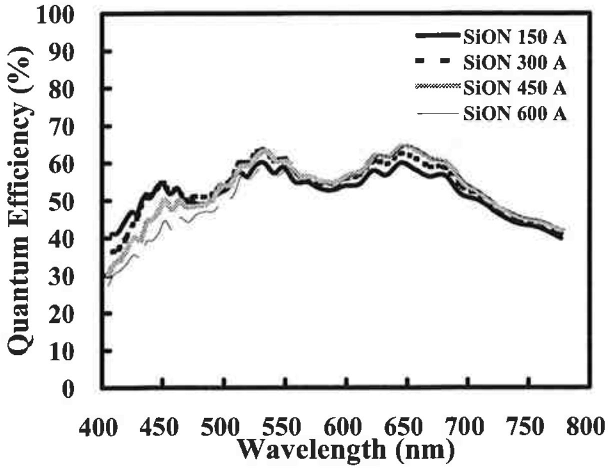

Fig.5 Simulated Q.E. for different SiON thickness.

Combining the AGGR structure with TB processes has been reported to alleviate optical crosstalk by incident light total reflection [4]. For further improvement of the photosensitivity by collecting more incident light, we add an additional dielectric microlens on AGGR for each pixel, and call it air-gap-in-situ-microlens (AGML). This novel AGML structure can collect more incident light, thus, enhance pixel sensitivity and reduce crosstalk significantly. Fig. 6 presents the crosstalk versus the incident angles (θ) of collimated light for standard (STD), TB+AGGR and TB+AGML structures on 2.8um square pixel, where the crosstalk (%) is defined as the signal of pixel "1" or "-1" divided by that of the pixel "0". The insert is the diagram of the crosstalk test structure, where the top metal was adopted to define targeted (pixel "0") and nearby (pixel "1" and "-1") pixels. As seen in the figure, TB+AGML pixel structure has the least crosstalk. At 0° incident angle, pixel with TB+AGML shows 68% and 39% crosstalk reduction compared with that of STD and TB+AGGR structures, respectively. The crosstalk (%) is reduced while the signal is enhanced for pixel "0". This is mostly attributed to the incident light focused by the dielectric microlens. At 10° incident angle, the crosstalk of TB+AGML shows 92% and 32% optical crosstalk reduction compared with that of STD and TB+AGGR structures, respectively. The optical crosstalk means the measured crosstalk excluded the electric crosstalk at 0°incident angle where the electric crosstalk is mainly caused by minority carrier diffusion. Consequently, pixel with TB+AGML structure provides significant optical crosstalk improvement due to the good combination of AGGR and an additional dielectric microlens.

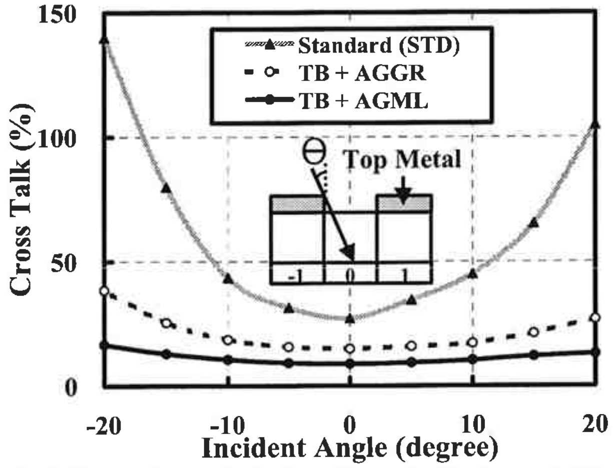

Fig.6 Crosstalk v.s. incident angle with STD, TB+AGGR and TB+AGML structures on 2.8um square pixel.

Figure 7 is the pixel sensitivity versus the light incident angles (θ) for standard (STD), TB+AGGR and TB+AGML structures on 2.8um square pixel. As seen, the photosensitivity is decreased while the light incident angle is increased. However, pixel with TB+AGML structure provides the best photosensitivity due to the light is focused by the additional microlens and totally reflected by the AGGR. At 0° incident angle, there is 25% and 17% sensitivity enhancement compared with that of STD and TB+AGGR structures, respectively. While the incident angle is increased to 10°, there is also 152% and 35% photosensitivity improvement compared with that of STD and TB+AGGR structures. Furthermore, the sensitivity of TB+AGML at 20°is larger than that of STD pixel at 5° incident angle. That means the chief angle of the sensor array could be efficiently enlarged.

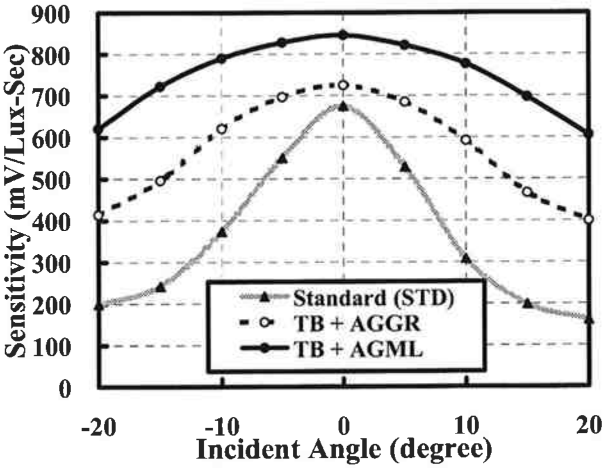

Fig.7 Sensitivity v.s. incident angle with STD, TB+AGGR and TB+AGML structures on 2.8um square pixel.

Figure 8 plots the crosstalk at 10°incident angle for standard (STD), TB+AGGR and TB+AGML structures on 4.0um square to 2.8um square pixels. In standard structure, the crosstalk is dramatically rising as pixel size shrinks. This becomes a great challenge for CIS to develop smaller size pixels. Adopting TB+AGML shows more efficient crosstalk resistance than using either STD or TB+AGGR structures, especially for the smaller pixel. The pixel size can be further downscaled to less than 2.8um square and provide lower crosstalk than 4.0um square pixel with standard structure. Therefore, TB+AGML structure indeed offers a powerful solution for solving the problem of optical crosstalk.

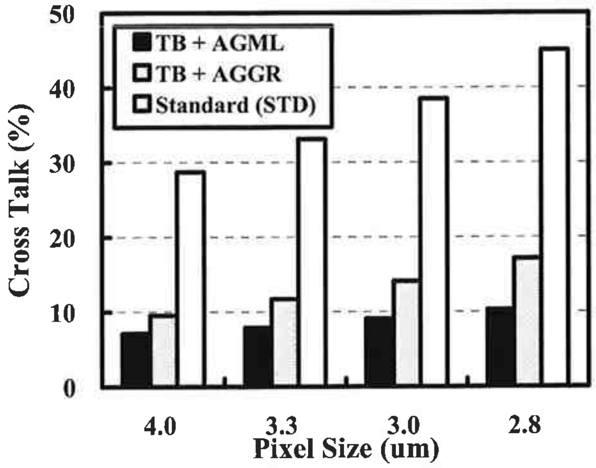

Fig.8 Crosstalk under 10° incident angle with standard, STD+AGGR and TB+AGML structures on 4.0um, 3.3um, 3.0um and 2.8um square pixels.

Conclusion

The optical effects of dielectric film structure have been investigated. Proper choice of the dielectric film thickness is necessary to gain the better quantum efficiency of the sensor. A highly efficient optical structure, air-gap-in-situ-microlens (AGML), has also been successfully developed with 0.18um CMOS image sensor technology. Combination of AGGR with an additional dielectric microlens, dramatic improvements of the optical crosstalk and pixel sensitivity have been demonstrated for small size pixel. By using thinner backend scheme with AGML technology, the pixel size can be further downscaled to smaller geometry with good optical performance.

Acknowledgement

The authors would like to thank the members of MTD in Taiwan Semiconductor Manufacturing Co., Ltd., for technical supports and valuable discussions. The work was supported by the National Science Council under Contracts NSC93-2215-E-006-005.

References

[1] E. R. Fossum, “CMOS image sensors: electric camera on a chip,” IEEE Trans. Electrons Devices, vol. 44, pp. 1689-1698, Oct. 1997.

[2] H. Wong, “Technology and device scaling considerations for CMOS imagers,” IEEE Trans. Electrons Devices, vol. 43, pp. 2131-2142, Dec. 1996.

[3] D. N. Yaung et al, “Air-gap guard ring for pixel sensitivity and crosstalk improvement in deep sub-micron CMOS image sensor,” IEDM Tech. Dig., pp 401-404, Dec. 2003

[4] C. H. Tseng et al, “Crosstalk improvement technology applicable to 0.14um CMOS image sensor,” IEDM Tech. Dig., pp 997-1000, Dec. 2004.

[5] S. G. Wuu et al, “A high performance active pixel sensor with 0.18um CMOS color imager technology,” IEDM Tech. Dig., pp 555-558, Dec. 2001.

[6] H. C. Chien et al, “Active pixel image sensor scale down in 0.18 spl mum CMOS technology,” IEDM Tech. Dig., pp 813-816, Dec. 2002.