Improvement of Photo-sensitivity and Smear Characteristics in a 2.8-μm square Pixel IT-CCD Image Sensor

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Abstract

New technologies for improving photo-sensitivity and smear characteristics to obtain high-performance small-pixel interline-transfer charge-coupled device image sensors (IT-CCDs) have been developed. The photo-sensitivity was increased by creating a new High-Refractive Inner (HRI) microlens, a larger photo-diode (PD) aperture, and a deeper photo-sensitive area in a pixel. To suppress smear noise increased by widening the PD aperture, we also developed a low-smear-noise pixel structure. These new technologies have been applied to our 2.8-μm square pixel IT-CCD, which results in increasing its photo-sensitivity by 35% and reducing its smear noise by 7 dB, compared to a 2.8-μm square pixel IT-CCD manufactured with conventional technologies.

Introduction

The strong demand for smaller image area as well as for improvement in resolution have created the need for pixels smaller than 3.0-μm square. Pixel size reduction, however, results in photo-sensitivity deterioration because it is inevitably accompanied by a decrease in microlens area, photo-diode (PD) aperture area, and photo-sensitive area. While photo-sensitivity can be increased by widening the PD aperture, it is also critical to suppress smear noise at the same time, because the edge position of the PD aperture is consequently set in the vicinity of a Vertical-CCD (VCCD) transfer channel. We have developed several new technologies for IT-CCD image sensors to obtain high photo-sensitivity and low smear noise. The former is achieved by developing technologies to create a high-refractive inner (HRI) microlens and a high-sensitivity PD structure, while the latter is achieved by developing a low smear noise pixel structure optimizing the VCCD and the PD impurity profiles. These technologies have been applied to our 2.8-μm square pixel IT-CCD.

New Pixel Structure

Figure 1 illustrates a cross-section of a new pixel structure perpendicular to the transfer direction. The unit pixel consists of a PD, a VCCD, a transfer-gate (TG) region, and a channel-stop (CS) region. A vertical overflow drain (VOD) barrier is formed at the deep part of the PD to implement blooming suppression and an electronic shutter, and a P^+-layer is formed at the PD surface to reduce the dark current. The differences to the conventional structure [1] are 1) a High-Refractive Inner (HRI) microlens, 2) a larger PD aperture with a low smear noise pixel structure, and 3) a deeper photo-sensitive area in the PD.

Improvement of Photo-sensitivity and Smear Characteristics

Figure 2 illustrates both a conventional inner-microlens structure and the new HRI-microlens structure. The conventional structure incorporates a planarizing layer (n=1.6) just above the concave SiO_2 layer (n=1.45). In contrast, the new structure consists of the convex HRI-microlens (n=2.0) just above the planarizing SiO_2 layer (n=1.45). Figure. 3 shows the simulated photo-intensity distributions for both structures. The wavelength of the incident light was 550 nm. The shape of the top lenses, the concave SiO_2 layer in the conventional structure and the convex HRI-microlens in the new structure, were assumed to be spherical, cosine and parabolic functions, respectively. The top lens curvature of each structure was optimized to obtain maximum photo-intensity at the PD apertures. The figure clearly shows that incident light from the HRI-microlens is focused more sharply at the PD aperture than that of the conventional inner-microlens.

Figure 4 illustrates plan views of the conventional pixel and the new pixel with the larger PD aperture. In the new pixel, the VCCD, the TG region, and the CS region are reduced to widen the PD aperture, resulting in the aperture area becoming 50% larger than that of the conventional one. Widening the PD aperture, however, results in an increase in smear noise because the edge position of the PD aperture is inevitably set close to the VCCD transfer channel. The dominant factor causing smear noise in our 2.8-μm square pixels is diffusion of electrons photo-generated in the surface P^+-layer of the PD and in the P-layer of the VCCD, because the photo-shield is thick enough to make light penetration negligible and the dielectric layer under the photo-shield is made as thin as possible to reduce the wave-guide effect [2]. Thus we have optimally designed the impurity profiles in the VCCD and the PD to improve smear characteristics. Figure 5 shows the simulated photocurrent distributions for the conventional pixel and the new pixel. The simulation results indicate that the photo-sensitivity (photocurrent into the PD), in the new structure increases by 25%, while the smear noise (photocurrent into the VCCD), in the new structure is reduced to 40% of that in the conventional structure. This occurs because we made the N-layer and the P-layer in the VCCD narrower and shallower, and made the surface P^+-layer in the PD shallower than in the conventional pixel.

Figure 6 illustrates the conventional PD structure and the new PD structure with the deeper photo-sensitive area. In the new structure, the VOD barrier is formed at a very deep part of the PD with a sharp impurity profile by using high-energy (>2 MeV) boron ion-implantation and a low-temperature process. Figure 7 shows the simulated photocurrent distributions for both structures. The very deep VOD barrier is formed about 1.6 times deeper than that in the conventional structure, which results in a 25-% increase in the new PD structure's photo-sensitivity.

Device Performance

The new structure includes the technologies to improve photo-sensitivity and smear characteristics. Figure 8 presents measured photo-sensitivity as a function of the f-number for the conventional 2.8-μm square pixel structure and the new 2.8-μm square pixel structure, and it is clear that the photo-sensitivity in the new structure increases across all f-numbers, with a dramatic increase in photo-sensitivity achieved at small f-numbers. This is due to the technologies of HRI-microlens creation and larger PD aperture. Measured photo-sensitivity as a function of wave length is shown in Fig. 9 for both structures, indicating that high photo-sensitivity is obtained for the new structure, especially at wavelengths greater than 450 nm, due to the creation of the deeper photo-sensitive area in the PD.

The device performance is summarized in Table I, measured for the 1/2.5-inch 3M-pixel IT-CCD with the new 2.8-μm square pixels. The smear noise in the new IT-CCD was reduced by 7 dB, while the photo-sensitivity was increased by 35%. The new IT-CCD also achieved a wide dynamic range and low driving voltage in addition to high photo-sensitivity and low smear noise.

Conclusion

New Technologies for improving photo-sensitivity and smear characteristics to obtain high-performance small-pixel IT-CCDs have been developed. We obtained high photo-sensitivity by applying the technologies to create the HRI-microlens, a larger PD aperture, and a deeper photo-sensitive area into our 2.8-µm square pixel IT-CCD. The resulting photo-sensitivity was increased by 35% compared to the 2.8-µm square pixel IT-CCD made with conventional technologies. To suppress smear noise increased by widening the PD aperture, we developed a low smear noise pixel structure by making the N-layer and the P-layer in the VCCD narrower and shallower, and making the surface P^+-layer in the PD shallower. The resulting smear noise was reduced by 7dB in comparison with the conventional structure. These new technologies can greatly improve small-pixel IT-CCD performance and are especially promising for creating new applications that employ such IT-CCDs.

References

[1] Y. Sano, et al., “On-chip Inner-layer Lens Technology for an Improvement in Photo-sensitive Characteristics of a CCD Image Sensor,” J. ITEJ, vol. 50, No. 2, pp. 226-233, 1996.

[2] A. Tanabe, et al., “Dynamic Range Improvement by Narrow-Channel Effect Suppression and Smear Reduction Technologies in Small Pixel IT-CCD Image Sensors,” IEEE Trans. Electron Devices, vol. 47, No. 9, pp. 1700-1706, Sep. 2000.

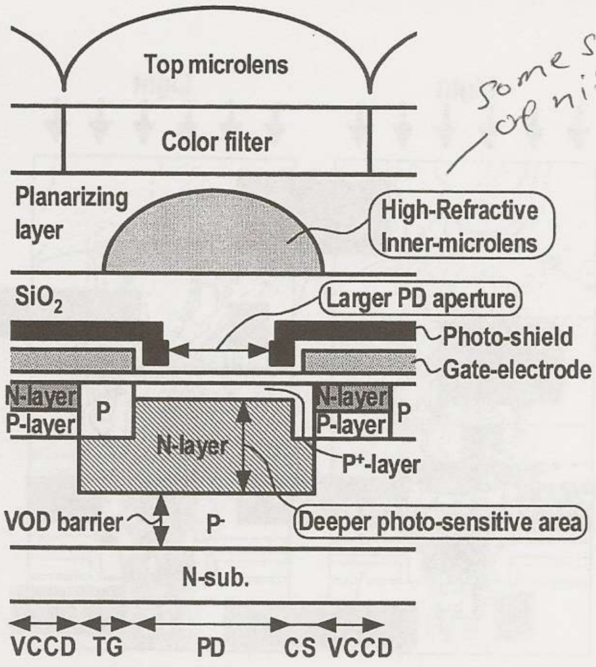

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Fig. 1. Cross-section of the new 2.8-µm square pixel perpendicular to the transfer direction, showing new technologies to improve photo-sensitivity and smear characteristics.

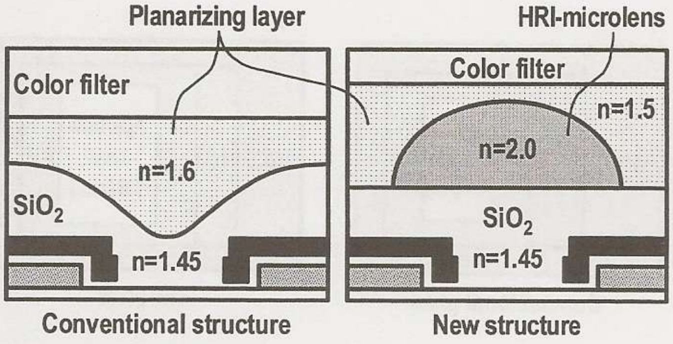

Fig. 2. Cross-sections of inner-microlens structures. The new structure includes the High-Refractive Inner (HRI) microlens.

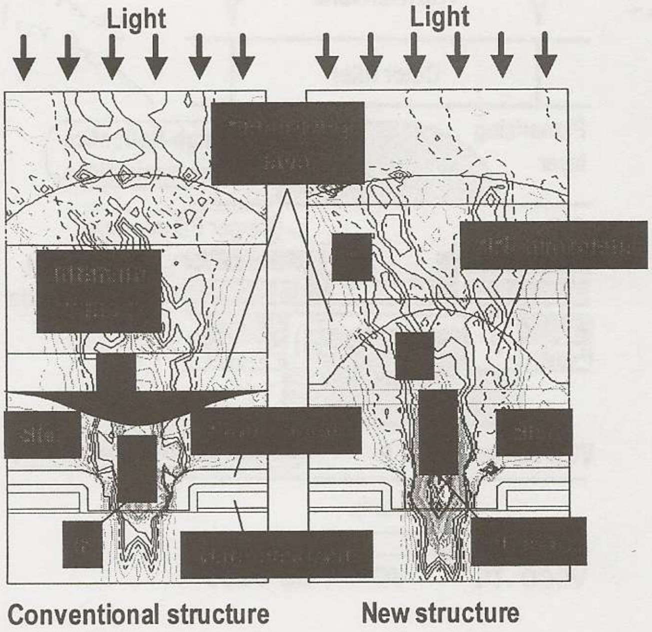

Fig. 3. Cross-sections of simulated microlens structures with photo-intensity distributions. The HRI-microlens focuses incident light more sharply at the PD aperture than does the conventional inner-microlens.

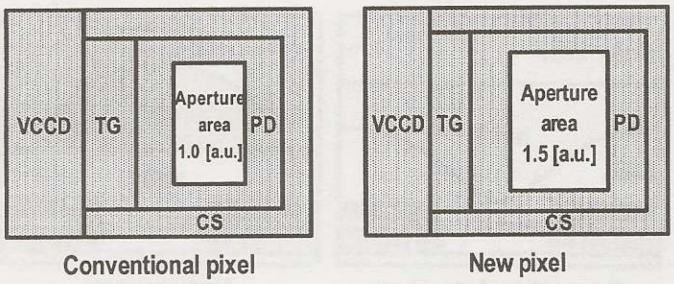

Fig. 4. Pixel plane views. In the new pixel, the VCCD, the TG region, and the CS region are reduced to widen the PD aperture. The resulting PD aperture area in the new pixel becomes 50% larger than that of the conventional pixel.

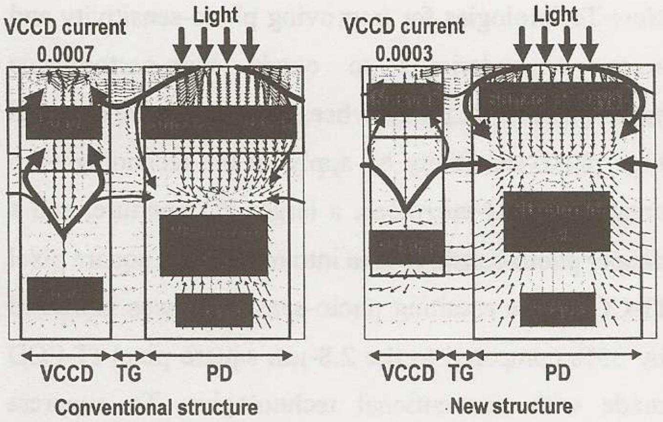

Fig. 5. Simulated photocurrent distributions. The simulation indicates that the photo-sensitivity (PD current) in the new structure is increased by 25% and the smear noise (VCCD current) in the new structure is reduced to 40% of that in the conventional structure, which is due to making the N-layer and the P-layer in the VCCD narrower and shallower, and making the surface P$^+$-layer in the PD shallower.

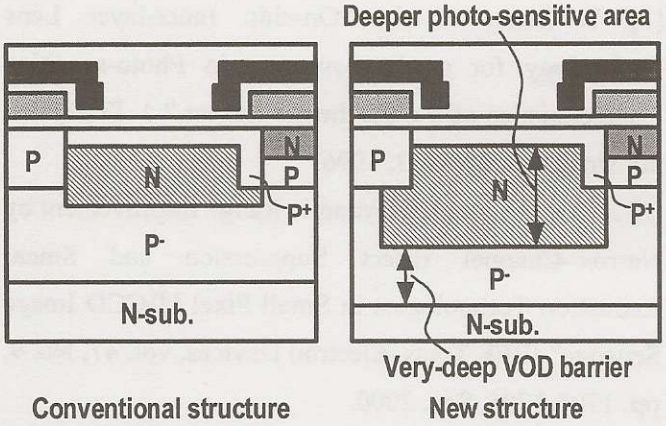

Fig. 6. Cross-sections of PD structures perpendicular to the transport direction. The new structure has a very deep VOD barrier, which can provide a deeper photo-sensitive area.

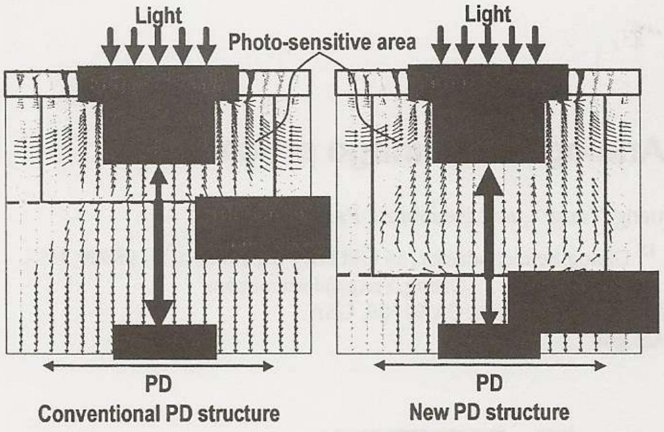

Fig. 7. Simulated photocurrent distributions perpendicular to the transport direction. The VOD barrier in the new structure is about 1.6 times deeper than that in the conventional structure due to the use of high-energy (>2 MeV) boron ion-implantation and a low-temperature process. The resulting photo-sensitivity in the new PD structure increases by 25% compared to the conventional one.

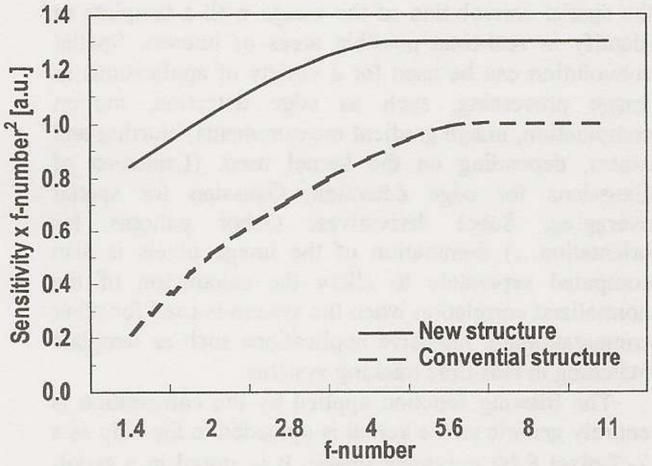

Fig. 8. Measured photo-sensitivity as a function of the f-number. The new structure includes the technologies for improving photo-sensitivity and smear characteristics. Photo-sensitivity in the new structure increases across all f-numbers, and the dramatic increase in photo-sensitivity is achieved at small f-numbers.

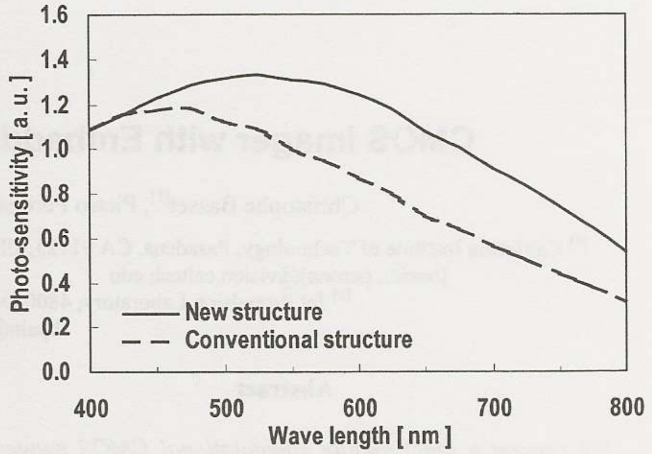

Fig. 9. Measured photo-sensitivity as a function of wavelength. High photo-sensitivity is obtained for the new structure, especially at wavelengths greater than 450 nm.

Table I Device performance measured for the 1/2.5-inch 3M-pixel IT-CCDs with 2.8-μm square pixels.

	Conventional pixel IT-CCD	New pixel IT-CCD
Green sensitivity (F8, 706nt, 1/7.5sec)	230 mV	310 mV
Saturation signal	530 mV	600 mV
Smear noise (V/10)	-84 dB	-91 dB
Dynamic range	64 dB	66 dB
VCCD driving voltage	-8.0 / 0 / 15 V	-7.5 / 0 / 12 V

saturation
15ke⁻