CMOS image sensor with pseudorandom pixel placement for jaggy elimination

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CMOS image sensor with pseudorandom pixel placement for jaggy elimination

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Abstract: The pixels in the conventional image sensors are placed at lattice positions, and this causes the jaggies at the edge of the slant line we perceive, which is hard to resolve by pixel size reduction. The author has been proposing the method of reducing the jaggies effect by arranging the photo diode at pseudorandom positions, with keeping the lattice arrangement of pixel boundaries that are compatible with the conventional image sensor architecture. In this paper, the author discusses the design of CMOS image sensor with pseudorandom pixel placement, as well as the preliminary evaluation of the fabricated CMOS image sensor.

Keywords: CMOS image sensor, jaggy, displacement, Vernier accuracy

Classification: Integrated circuits

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1 Introduction

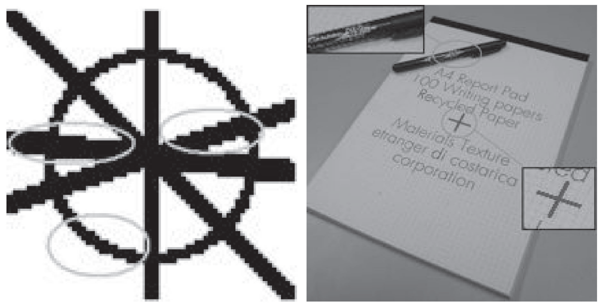

Fig. 1. Example of jaggies at the edge of the slant line.

The image sensors have been developed for enhancing the quality of the image representation, with the trend of pixel size reduction in conjunction with the other technologies. The pixels in the conventional image sensors are placed at lattice positions, and this causes the jaggies at the edge of the slant line as shown in Fig. 1. The reduction of pixel size also decreases the size of jaggies, however, it is hard to completely eliminate the jaggies "perceived" by our eyes, since our eye system has a high sensitivity for perceiving the small steps forming jaggies, so called the Vernier accuracy [1, 2].

The author has been proposing the method of reducing the jaggies by arranging the effective area (photo diode) at pseudorandom positions, with keeping the lattice arrangement of pixel boundaries that are compatible with the conventional image sensor architecture [3]. The author has indicated that the pseudorandom pixel placement has the effect of eliminating "perceived" jaggies compared with the conventional lattice pixel placement with the same pixel size [4, 5].

In this paper, the author discusses the design of CMOS image sensor with pseudorandom pixel placement, as well as the preliminary evaluation of the fabricated CMOS image sensor.

2 Pseudorandom pixel placement

The concept and the example of pseudorandom pixel placement for jaggies reduction are shown in Fig. 2. The white box and black box represent the pixel boundary and the photo diode (PD) area, respectively. Here we call the PD area as the active area, which effectively contributes to the image acquisition. Since the PD occupies a part of pixel area, we can generate several pixels with different active

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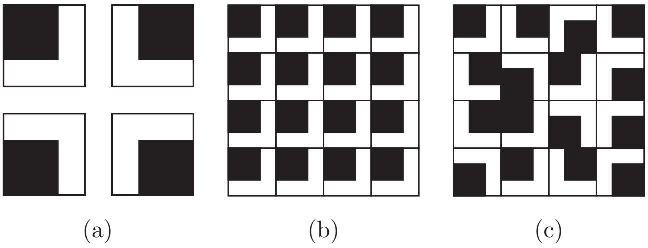

Fig. 2. Pixel structure and the active area arrangement. (a) Four types of pixels, (b) Conventional lattice placement, and (c) Pseudo-random pixel placement.

area positions. The four types of pixels are shown in Fig. 2(a). We obtain the conventional pixel placement by placing one of these pixels at lattice positions, as shown in Fig. 2(b). By placing randomly-chosen one of the four pixels at lattice position, we obtain the randomly-placed active areas, as shown in Fig. 2(c), which we call pseudorandom pixel placement. Note that since the circuit configuration and physical electric terminals of the four type pixels are identical, we can design the image sensor with pseudorandom pixel placement by placing the pixels as the conventional image sensor design with the additional random choice procedure. It is also notable that the variety of the pixels can be more than four, for example, nine or sixteen, however, the variety of four types results the good performance in terms of the spatial spectrum, jaggy elimination effect, and the circuit design [6].

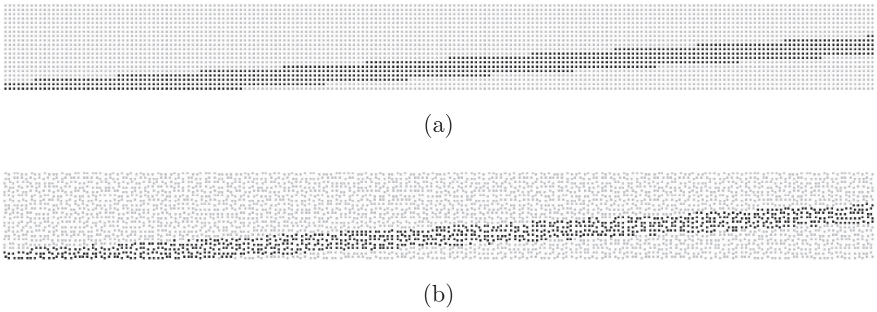

Fig. 3. Examples of the slant line representation. (a) Conventional lattice placement, and (b) Pseudorandom pixel placement.

The pseudorandom pixel placement has the jaggy elimination effect as shown in Fig. 3. There are periodical steps at the edge of the slant line in Fig. 3(a), which we perceive the jaggies. Since the spatial frequency of the jaggy exists in the range we strongly perceive and we have higher sensitivity for the steps in jaggies, it is hard to eliminate the jaggy by pixel size reduction. Note that the jaggy frequency is dependent on the angle of the line.

In the line representation with the pseudorandom pixel placement in Fig. 3(b), there are small random steps at the edge of the line, and the appearance of these random steps is independent on the angle of the line. Since the spatial frequency of these random steps is higher than that of the jaggies, we don't strongly perceive these random steps, and can be easily eliminated by the pixel size reduction. Note that the displacement of the active area requires the reduction of the active area size,

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resulting in the decreased fill factor and the decreased photo sensitivity. The jaggy elimination effect by the pseudorandom pixel placement has the possibility of enhancing the image quality overcoming the photo sensitivity reduction [7].

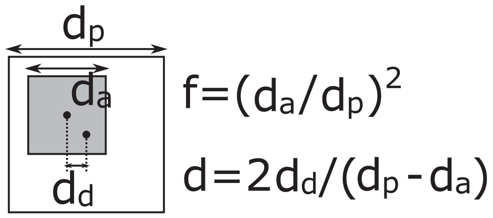

Fig. 4. Definition of the pixel design parameters.

There are the design parameters in the pixels used in the pseudorandom pixel placement as shown in Fig. 4. The ratio of the active area to the pixel area, f, or the fill factor, is corresponding to the photo sensitivity. The displacement ratio of the active area in the pixel area, d, defines the spatial characteristics of the pseudorandom pixel placement. The smaller d will reduce the jaggy elimination effect by the pseudorandom pixel placement, while the larger d will result in the strong step appearance at the edge of the line. Note that $d = 0$ corresponds to the lattice placement, while $d = 1$ corresponds to the case the active area's edge fits the pixel boundary. It is also notable that d of approximately 0.6 will result in the best jaggy elimination effect [5].

3 Design of CMOS image sensor with pseudorandom pixel placement

We designed the CMOS image sensor with pseudorandom pixel placement for evaluating the jaggy elimination effect in the captured image by the physical CMOS image sensor. It is possible to design four types of pixels with the different positions of the phot diodes, with keeping the identical physical electric terminals [3]. However, it is difficult to keep the large photo diode area under the physical design restriction to realize these pixels. For example, the pixel under this design strategy has the fill factor of 25% [3]. We started the image sensor design using the conventional CMOS image sensor. We employed a pixel with LOFIC capacitor for dynamic range enhancement [8, 9, 10] using CMOS 0.18 µm, five metal layers image sensor process. The pixel size is 7.8 µm × 7.8 µm with the photo diode of 6.26 µm × 5.06 µm, where the fill factor is 51.8%.

Here, we designed the photo shield as shown in Fig. 5(a) to implement the four types of pixels for the pseudorandom pixel placement. The boundary box size is equal to the size of the photo diode aperture of the pixel. Fig. 5(b) shows the four types of the photo shield generated by rotating the photo shield. We can obtain the four types of pixels with the different "effective" photo diode positions by overlapping them to the original pixel (Fig. 5(c)) as shown in Fig. 5(d). The fill factor is 35.7%, and the displacement radio d is 0.384.

Fig. 6 shows the whole layout of the designed CMOS image sensor using the pixels in Fig. 5(c). The chip size is 5 mm × 5 mm, and the number of pixels is

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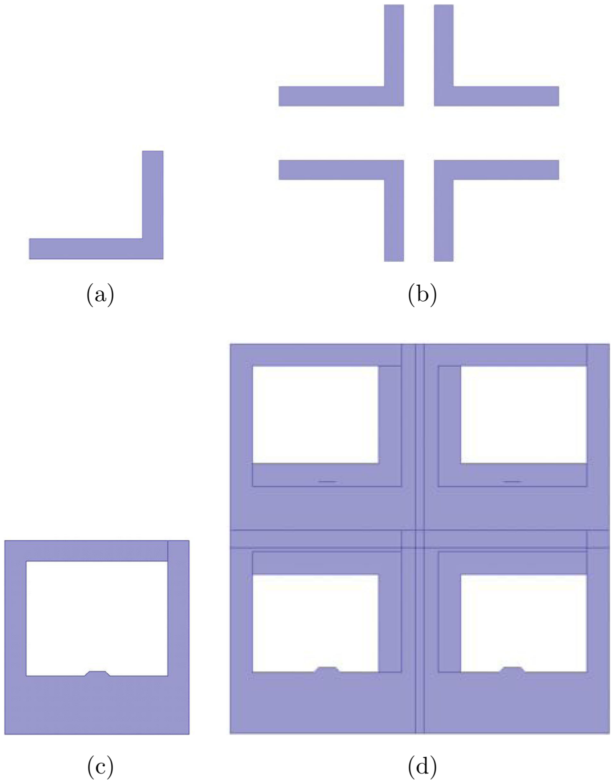

Fig. 5. Partial photo shield (a), four types of photo shields (b), the top metal layout of the original pixel (c), and the four types of pixels with different photo diode positions (d).

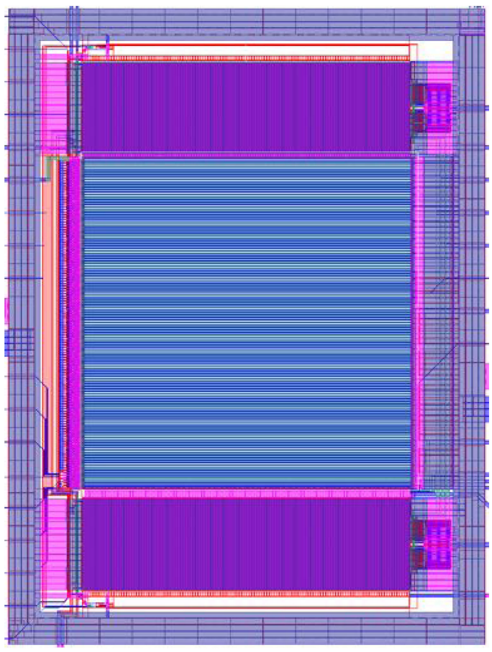

Fig. 6. Layout of the designed CMOS image sensor with pseudorandom pixel placement.

128×128. The upper half 128×64 pixels are designed without photo shields (lattice plain), while the lower half 128×64 pixels are designed with randomly chosen photo shield (pseudorandom plain), as shown in Fig. 7.

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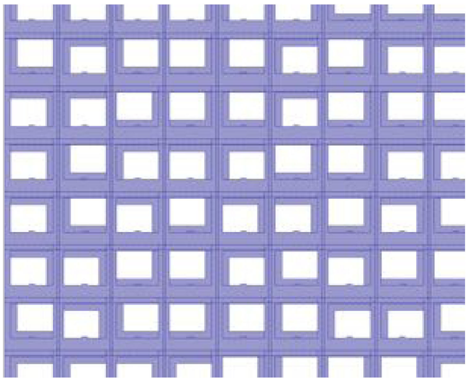

Fig. 7. Layout of the pseudorandom pixel part.

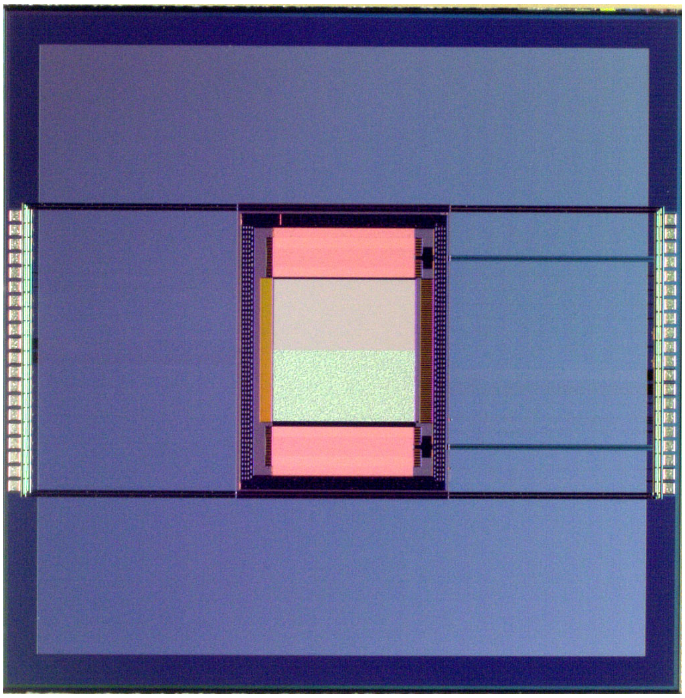

Fig. 8. Photograph of the fabricated CMOS image sensor

4 Evaluation of the fabricated CMOS image sensor

Fig. 8 shows the photograph of the fabricated CMOS image sensor. The magnified photographs of the pixel region are shown in Fig. 9 for both the lattice and the pseudorandom plain.

We carried out the evaluation of the fabricated CMOS image sensor using the designed evaluation system as shown in Fig. 10. The control signals are generated by FPGA (Xilinx XC6SLX45-2FGG484C), and the signals are acquired by 16 bit A/D converters and transferred to PC.

Fig. 11(b) shows the the captured image for the target in Fig. 11(a). Here, the pixels are represented at the lattice positions for both the lattice and the pseudorandom plain. It is confirmed that the photo sensitivity for pseudorandom plain is lower than that for the lattice plain, since their fill factors are different.

Fig. 12 shows the digitized binary image generated from the captured image in Fig. 11(b). Note that the different thresholds in digitize are applied for the upper

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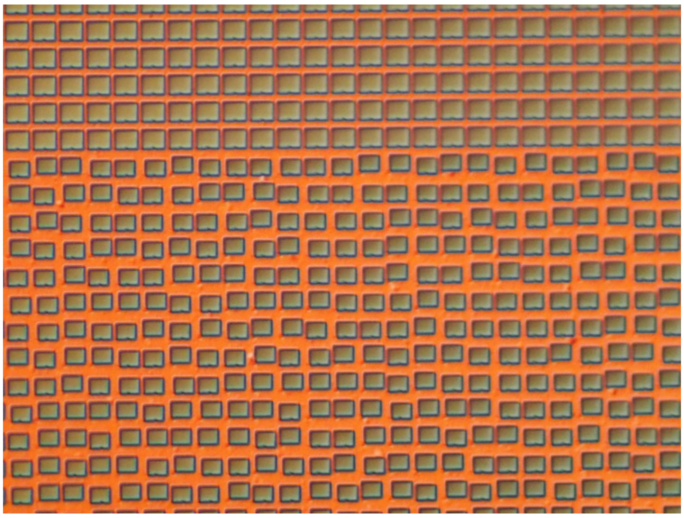

Fig. 9. Magnified photographs of the pixel plains. (The upper area is lattice plain, and the lower area is pseudorandom plain.)

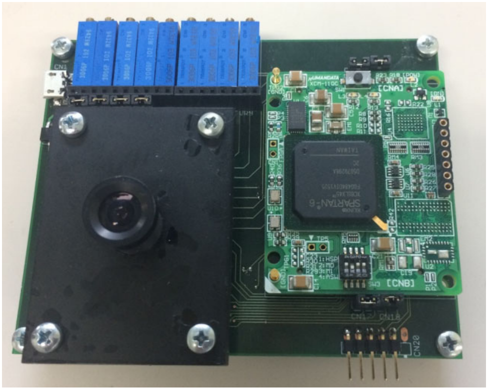

Fig. 10. Designed evaluation system.

half (lattice) plain and the lower half (pseudorandom) plain, since the photo sentivities for the pixel in each area are different. The thredhold is manually adjusted so as to obtain the same line width. Here, the pixels are represented based on the physical pixel parameters for both the lattice and the pseudorandom plain. One physical pixel is represented by 10×10 pixels, where the pixel value is represented by the active area whose sizes are 7×7 and 6×6 pixels, respectively, with the displacement of 1 pixel, as shown in Fig. 13.

It is confirmed the jaggies appearance are dependent on the angle of the slant line edge in the lattice plain. For example, there are no jaggies for the vertical line edge, while a large jaggy at the slant edge with small angle, and a small jaggy at the slant edge with large angle. The jaggies appearance dependency on the line angle is one of the factors to image quality degradation [7].

We can confirm that the jaggies appearance are independent on the angle of the slant line edge in the pseudorandom plain. There are small random steps for all the line edges in pseudorandom plain, which can be easily eliminated by the pixel size reduction.

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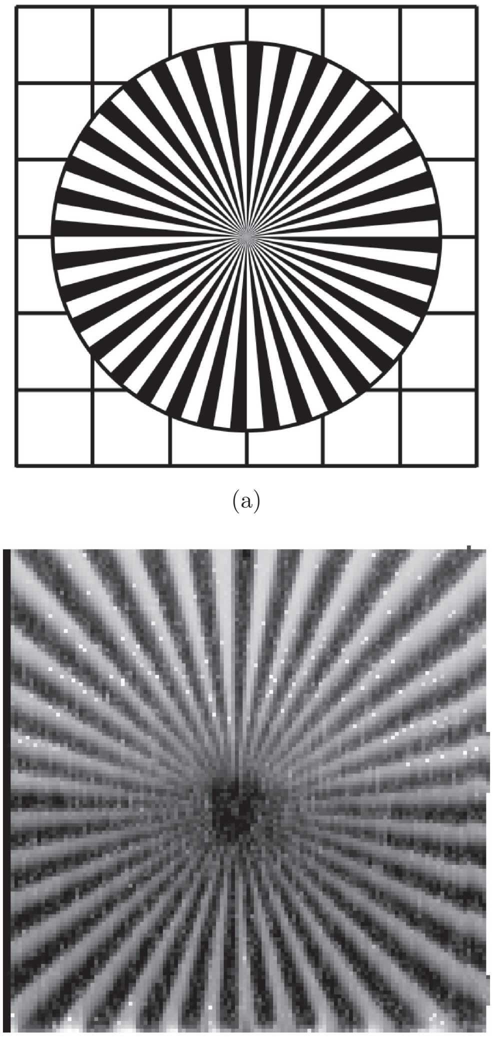

(a)

(b)

Fig. 11. Target object (a) and the captured image (b).

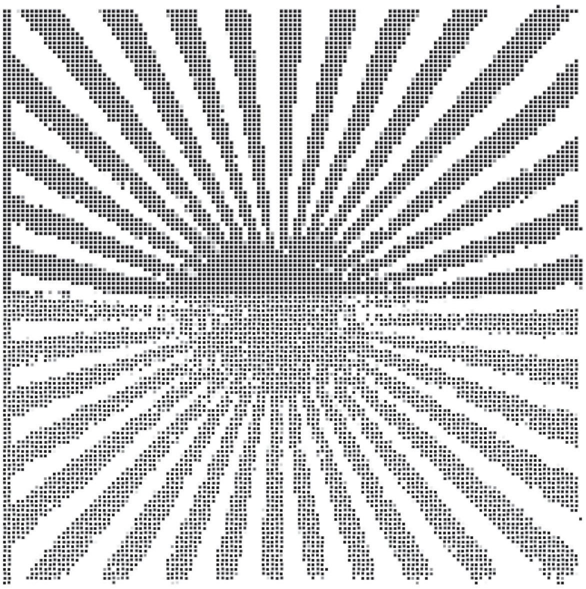

Fig. 12. Digitized binary image generated from the captured image.

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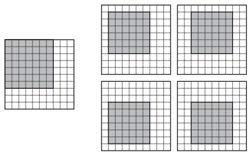

(a) (b)

Fig. 13. Pixel presentation for one physical pixel. (a) For the lattice plain, and (b) For the pseudorandom plain.

5 Conclusion

In this paper, we demonstrated the design and the evaluation of the CMOS image sensor with pseudorandom pixel placement, comparing with the conventional lattice placement. We can design the pseudorandom pixel placement based on the practical CMOS image sensor using the additional partial photo shield. Although the pseudorandom pixel placement has the decreased fill factor and the photo sensitivity compared with the conventional ones, jaggies elimination effect has the possibility on image quality enhancement. We continue to evaluate the image quality by the pseudorandom pixel placement in term of the perceiving how we see.

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