A CMOS image sensor with pseudorandom pixel placement for clear imaging

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A CMOS Image Sensor with Pseudorandom Pixel Placement for Clear Imaging

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***Abstract*—The picture element (pixel) in conventional image sensors, such as CCD or CMOS imager, are placed in the form of a lattice for ease of implementation. Lattice placement of pixels intrinsically has directional dependency on the clarity of image representation; in other words, the image clarity is significantly dependent on the directions of the objects in the image, such as lines. For example, horizontal lines are perfectly represented by lattice pixels, while slanted lines have jagged edges.**

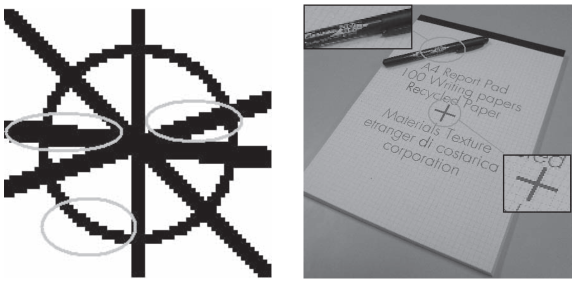
In this paper, we propose a pseudorandom pixel placement architecture for clear imaging with solving the directional dependency problems. We also discuss our evaluation of its characteristics based on the designed layout of CMOS image sensor with pseudorandom pixel placement, as well as its implementation.

I. Introduction

Numerous image sensors, such as digital cameras, video cameras, mobile phones' cameras, are a part of our daily lives. The common ultimate purpose of the image sensors can be summarized as that of representing objects clearly, realistically. One of the most remarkable directions in developments of image sensors to achieve this purpose, as well as display systems, is to increase the resolution of imaging systems[1], [2], as well as other approaches; wider dynamic range, lower noise, for instance.

However, the 'clarity' of the images are not completely evaluated by PSNR (peak signal-to-noise ratio), since we often perceive 'jaggies' at the edge of the objects in the images, as shown in Fig.1, that PSNR can not deal with. The jaggies are composed of the certain pair of the pixels at the edge of the slant lines, and they are intrinsically caused by the lattice placement of the pixels; in other words, pixel placement with no 'noise' or 'randomness.' The jaggies cannot be completely eliminated by the increase of the pixels, or the reduction of the pixel size, since the size of the jaggies are the certain times of the pixel size, which is often larger than the lower limit of our eye's perceive, and we sensitively perceive the step along the line. In addition, the appearance of the jaggies depend on the slope of the lines, or the spatial frequency of the jaggies; in other words, there is the directional dependency in the clarity of the images, and we also sensitively perceive jaggies in the moving objects, since our eye has the higher sensitivity in perceive for motion.

In this paper, we propose a pseudorandom pixel placement architecture for clear imaging with solving the directional dependency problems. We also discuss our evaluation of its characteristics based on the designed layout of CMOS image sensor with pseudorandom pixel placement, as well as its implementation.



(a) (b)

Fig. 1. Examples of jaggies and its directional singularities on the clarity of image representation. (a) Illustration and (b) Photo, where jaggies appear within the indicated ellipses.

II. Pixel Placement and Image Representation

A. Lattice placement and directional dependency

Almost all image sensors employ the lattice layout of pixels; the pixel circuit has a square shape. Some researches have reported using a hexagonal layout pixel to equivalently increase the vertical resolution[3], but the pixels in all image sensors are placed regularly on the focal plane. The basic direction of development in image sensors aims at increasing the resolution, or the number of pixels, in order to represent a clearer image.

However, the images represented by the imaging systems, including image sensors and displays, are ultimately 'seen' by human beings. We see the images with our eyes, particularly the retina in our eyes. The photoreceptor cells on the retina are not placed regularly. The layout of photoreceptors on the retina is approximately hexagonal, but the detailed positions are in random displacement from a regular position with higher density at the center of the retina and lower at the edge[4]. Because of this fact, human perceive the pixel placement of the conventional imaging systems as a 'lattice' by us.

The clarity of the represented images using the lattice placement intrinsically depends on the direction of the objects in the image. For example, horizontal or vertical lines are perfectly represented as lines, while the slanted lines are represented with jaggy edges derived from the lattice approximation of slant lines. For the slant lines with smaller slope, the interval of the jaggies becomes large, or the spatial frequency of the

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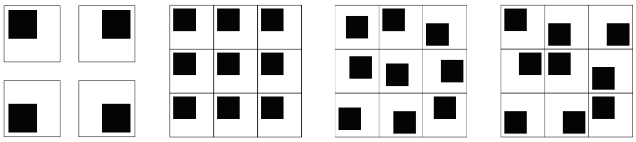
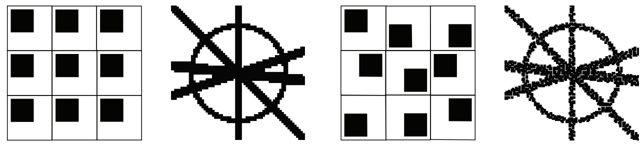


(a) (b) (c) (d)

Fig. 2. Models of pixel placement, (a) Four types of unit pixel, (b) Consistent lattice placement, (c) Lattice placement with random displacement, (d) Pseudorandom placement.



(a) (b)

Fig. 3. Examples of the effect of directional dependency in two types of pixel placements. (Left: example of pixel placement. Right: represented image.) (a) Image obtained with conventional lattice pixel placement, (b) image obtained with pseudorandom pixel placement. Pseudorandom placement reduces the effect below the level of perception.

Fig. 4. Jaggies that appears in the horizontal lines when pseudorandom pixel placement is applied.

jaggies becomes low. Our eye and brain perceive such jaggies with emphasis, and thus they are often serious factors that decrease images clarity. Here, we call this effect that the clarity of the images depends on the direction of the objects in the image, 'directional dependency' on the clarity of image representation. The effect of directional dependency on the clarity of image representation that is described above cannot be completely eliminated by increasing the resolution, because each jaggy is made up of a pair of pixels; however jaggy is one of the important factors in the clarity of image representation. In addition, the size of jaggies may changes dynamically in the movies. Our eye and brain perceive such temporal changes of jaggies with emphasis.

B. Pseudorandom pixel placement and image representation

The effect of directional dependency on the clarity of image representation is caused by the mismatch between pixel placements in imaging systems, including image sensors and displays, and the placement of the photoreceptor cells on the retina. Implementing the pixel placement of the imaging systems in a pattern identical to that of photo receptors on the retina would be ideal, however, placing pixels in completely random configuration is impossible. The signal of the pixels arranged in the lattice placement of conventional image sensors can be read out in a sequential scan, vertical access followed by the horizontal access. Presently, no methods are available to read signals from pixels placed in a random pattern like that of the retina when using the usual manner, and thus random placement is not suitable for use of current image sensors.

Here, we describe a realistic idea for implementing pixel placement that prevents the negative effect of directional dependency on the clarity of image representation. An active area, the photo diode, in pixels performs as intrinsic interface in the image sensors. The active area cannot occupy the entire pixel because it must have peripheral circuits, such as the source follower and reset transistor. Figure 2(a) illustrates four types of pixels; the white box represents the pixel boundary and the inner black box represents the active area. Conventional image sensor with lattice pixel placement can be represented as shown in Fig.2(b) by placing one of the four types of unit pixels in a lattice layout.

The random placement of points in the plane is well approximated by the random displacement of the points from conventional lattice positions[5], [6] as shown in Fig.2(c). Using this idea for implementing pseudorandom pixel placement in image sensors is difficult because designing an architecture in which all the types of the pixel have random displacement of their active area is not practical.

Here, we assume randomly choosing one of the four types of unit pixel shown in Fig.2(a), and putting it in the lattice positions, as shown in Fig.2(d), which we call 'pseudorandom placement.' The placement of the active area in Fig.2(d) is expected to be a good approximation of random placement, which is shown in Fig.2(c), for example. The pseudorandom pixel placement is expected to be similar to the photoreceptor placement on the retina, and thus to eliminate the effect of directional dependency on image clarity that is caused by the lattice pixel placement applied in the conventional image sensors. Figure 3 shows the examples of effect of eliminating directional dependency.

Jaggies appear in the displayed images even in horizontal lines when pseudorandom pixel placement is applied, as shown in Fig.4, even though no jaggies appear in them when the lattice pixel placement is used. However, the size of the jaggies in the displays is always equal to that of the pixels themselves, and we cannot perceive objects the size of one pixel in the current high resolution displays. For example, the typical pixel pitch of LCD displays is 0.3 mm, and the viewing angle for one pixel becomes about 0.03 degrees when we view a display from the distance of 60cm. This viewing angle of one pixel is close to the lower limit of the viewing angles that humans can perceive[7], and we cannot perceive an individual pixel. Moreover, the size of one jaggy is close to the same pixel size when pseudorandom pixel placement is applied.

On the other hand, we can perceive an object at the viewing angles down to approximately 0.1 degrees[7]. As described above, the size of the jaggies that appear in the slanted lines, especially those with small slope, captured by the image sensor with lattice pixel placement becomes large enough for us to perceive it, and this becomes a fatal factor that affects image clarity. Some technical methodologies are already available to improve image clarity, such as smoothing, but the effect of directional dependency in lattice pixel placement on image clarity can not be completely eliminated by applying them. The technique of pseudorandom pixel placement can be ap-

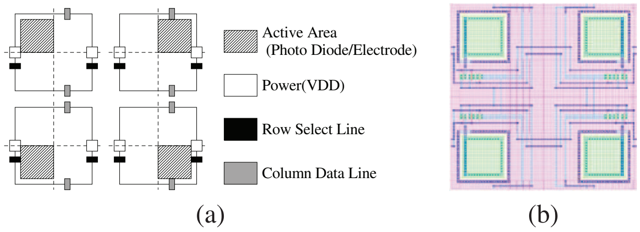


Fig. 5. (a)Floor plan of unit pixel layout, and (b)the designed layout of four types of unit pixels.

plied for multi-valued pixels in conjunction with these other technical methodologies that improve image clarity to achieve even better image clarity.

The advantages of using pseudorandom pixel placement described above in image sensor for better image clarity can be summarized as follows.

- The image clarity or jaggy size in the displayed images does not depend on the direction of lines (no effect of directional dependency on image clarity)
- The existing jaggies in the displayed images are so small that we do not perceive them in well-developed imaging systems

C. Pixel placement in display system

It is ideal to apply the identical pseudorandom pixel placement with identical sequences of unit pixels for display system to achieve the most effective performance in the clarity of image representation. However, great efforts have been made on developments of display systems for achieving higher ratio of active area, the area which emits the light in the display pixel. Higher ratio of active area in pixel decrease the merits of pseudorandom pixel placement. The combination of the display system using conventional lattice pixel placement with the image sensor using pseudorandom pixel placement is one of the practical solutions. In this type of image system, image acquisition is carried out by the pseudorandom pixel image sensor, and the value of each pixel is represented by the lattice pixel in the display. The merit of pseudorandom pixel placement, no directional dependency on the image clarity of image representation, can be achieved by image sensor with pseudorandom pixel placement. This combination of different types of pixel placements is expected to be an approximation of the system for no directional dependency on the clarity of image representation for practical implementation.

III. Design of CMOS Image Sensor with Pseudorandom Pixel Placement

A. Design of unit pixel

Image sensor with pseudorandom pixel placement can be achieved with pairs of the four types of pixels as shown in Fig.2(a). These four types of pixels must have electrical connections that are correctly implemented independently on the sequence of pixel placement. The positions of the required electrical connections, such as powering lines, reset signal, and column data line, must be adjusted to have the same positions, as shown in Fig.5(a). Figure 5(b) shows the designed four types of unit pixels, whose active areas (photo diodes) are located at upper left, upper right, lower left, and lower right corner, respectively using CMOS 0.18μm technology with five layers of metal. The pixel size is $10 \times 10[\mu\text{m}]$, and the photo diode size is $5 \times 5[\mu\text{m}]$, with fill factor of 25%.

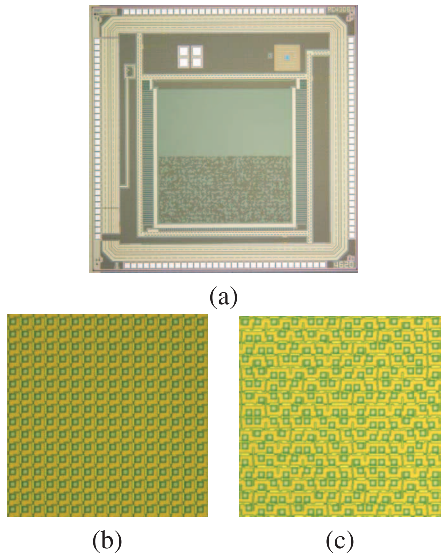


Fig. 6. Fabricated CMOS image sensor with pseudorandom pixel placement.(a)whole circuit, (b)part of lattice pixel plain, and (c)part of pseudorandom pixel plain.

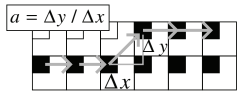


Fig. 7. Local slope of line edge, a.

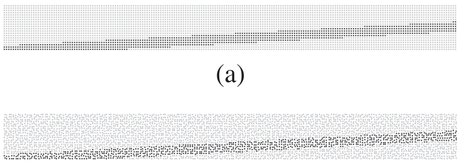
B. Design of CMOS image sensor with pseudorandom pixel placement

The CMOS image sensor with pseudorandom pixel placement is designed using the designed unit pixels in Fig.5(b). The photograph of the fabricated CMOS image sensor with both lattice and pseudorandom pixel placement is shown in Fig.6(a)[1], and the parts of both lattice and pseudorandom pixel plains are shown in Fig.6(b) and (c), respectively. The number of pixels is 128×64 for both types of pixel plains, and the pixel size is $10\times10[\mu\text{m}]$.

IV. Evaluation of Designed CMOS Image Sensor in Terms if Line Representation

We have been carrying out the experimental evaluations of the fabricated CMOS image sensor in Fig.6, and their results will be reported in out future works. In this section, we describe our evaluation of the characteristics of the designed CMOS image sensor, especially in terms of line representation.

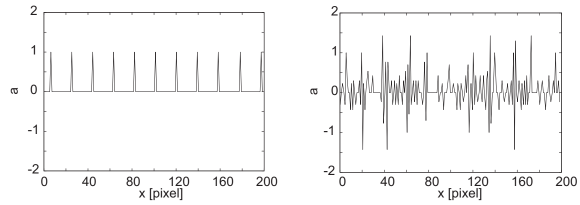
[1]The VLSI chip in this study has been fabricated in the chip fabrication program of VLSI Design and Education Center(VDEC), the University of Tokyo in collaboration with Rohm Corporation and Toppan Printing Corporation.



(a)

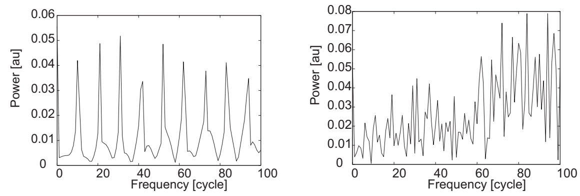
(b)

Fig. 8. Representation of line with slope of 3 degrees. (a) Lattice, (b) Pseudorandom.



(a) (b)

Fig. 9. Trend of local slope of line edge, a, (a) Lattice, (b) Pseudorandom.



(a) (b)

Fig. 10. Spectrum of a trend, (a) Lattice, (b) Pseudorandom.

Here, we consider the local slope of active areas composing the line, $a = \Delta y/\Delta x$, as shown in Fig.7. The line in the lattice placement has a of 0 for most pixels, and a of 1 for some pixels with an interval according to the angle of the slope. This drastic change of a for the particular interval becomes a jaggy with lower spatial frequency that can be perceived by our eyes. In other words, the spatial frequency component of a in the image according to this change of a 'stands out' compared with other spatial frequency components in the spatial spectrum of a.

We generated two base images representing the slant line with slope of 3 degrees and the width of 5; one with lattice and the other with pseudorandom placement of the active areas, both of which are composed of 200×200 'virtual pixels,' as shown in Fig.8(a) and (b). Here, 'virtual pixel' is the technique of representing the pseudorandom pixel placement using the conventional lattice pixel placement. One virtual pixel is a pair of 2×2 pixels including one active pixel, which is black for 'virtual pixel' included in the line, while white in other cases. The other pixels in the virtual pixel are also white, and virtual pixel represents the 'pixel' with fill factor of 25%. The location of the active pixel in one virtual pixel is randomly determined for the virtual pixels with pseudorandom placement, while is fixed for the virtual pixels with lattice placement.

The viewing angle of one virtual pixel is approximately 0.04 degrees when you see Fig.8 viewed at the distance of 40cm from the paper. The viewing angle that our eyes can perceives is down to approximately 0.1 degrees[7], and thus, the jaggies with larger than 2 or 3 pairs of virtual pixels, whose view angle is within that range we can perceived.

The trends of local slope a for lines represented in both Fig.8(a) and (b) are shown in Fig.9, and the spatial power spectrums of both trends of a are shown in Fig.10. In Fig.10(a), lattice placement, the spatial frequency component of 10 cycles, or the interval of 20 virtual pixels present a sharp spectrum, as well as its higher harmonic components. Because the first spatial frequency component of 10 cycles exists within the range that our eyes perceive, we recognize it as a serious jaggy.

On the other hand, a similar component exists for pseudorandom placement as shown in Fig.10(b); however, the other spatial frequency components with large amplitude appear near this component. In other words, the spatial spectrum component of 10 cycle does not stand apart from the whole spatial spectrum compared with nearby components, and thus, our eyes do not perceive the jaggy.

The ratio of the spatial power spectrum components amplitude of 6 cycles against the nearby components is estimated as 1:10 for lattice placement in Fig.10(a), but is 1:1 for pseudorandom in Fig.10(b).

V. Conclusions

Directional dependency negatively affects image representation clarity. In this paper, we proposed the pseudorandom pixel placement for image sensors that eliminates the effect of directional dependency on image clarity. We designed the practical CMOS image sensors with two types of active area placements, conventional lattice and pseudorandom proposed. We also evaluated the characteristics of pseudorandom placement in terms of representation of line, and our results show that pseudorandom placement significantly improves image representation clarity, especially that for slant lines.

We will report the subjective evaluation of the image clarity using pseudorandom pixel placement, as well as its relation with the image characterstics in our future work.

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