Implantable CMOS image sensor with incident-angle-selective pixels

K. Sugie, K. Sasagawa, M.C. Guinto, M. Haruta, T. Tokuda and J. Ohta

Angle-selective pixels fabricated by using metal layers of the image sensor chip are proposed. Four incident-angle-selective pixels share one aperture. The selective pixel has a peak at 40° and full width at half maximum of ∼23°. An image sensor composed of normal and angle-selective pixels was designed and fabricated. The reconstruction of a high-resolution image from the blurred image using five different views is demonstrated.

Introduction: We have developed implantable devices which, because of their small size and light weight, are suitable for observation of deep brain and brain functional changes corresponding to behaviour [1–4]. The sensor has no lens and contacts the observation target to obtain high-resolution images. However, the spatial resolution decreases with the distance from the sensor surface. In case the device is inserted into biological tissue, the cells on the boundary of the device are damaged. Thus, it is desirable to be able to obtain high-resolution images of an area several tens of microns away from the device surface.

One way to mitigate this problem is to increase the depth of field by limiting the sensitive angle of incidence [5, 6]. This can be realised by fabricating a high-aspect-ratio aperture on a pixel. However, the detection efficiency of the pixels decreases as the depth of field increases.

A lens is regarded as a device that converts the incident-angle information into position information on the focal plane. This means that the focal plane image can be reconstructed from angular distribution information through the use of computational techniques instead of a lens. Following this principle, a compound-eye camera, which is composed of a micro-lens array and an image sensor, has realised high spatial resolution, distance estimation, and refocusing by image processing [7]. Light field microscopy uses a similar technique and realises 3D imaging [8, 9]. These studies used a lens to obtain separated images. However, using lenses leads to an increment of invasiveness due to its size. By applying such technologies to lensless implantable image sensors, it is expected that tissues could be observed several tens of microns away with a resolution as high as the pixel pitch.

One of the solutions is to use angle-sensitive pixels based on diffraction gratings fabricated by metal wiring layers [10–12]. This technique realises relatively high angle resolutions. However, it is also affected by polarization, phase, and wavelength. The response also shows a periodic response to incident angles. It is required to prepare pixel sets composed of many pixels with different phase relations to the gratings.

In this Letter, we propose a simple angle-selective pixel structure that enables observation with a high spatial resolution near the pixel array, which is composed of normal and angle-selective pixels. This simple structure is expected to detect larger inclination incident light than diffraction gratings can. Multi-view observation with pixels enables high spatial resolution near the pixel array. We demonstrate its effect by observing fluorescent beads through 50 µm-thick glass. The proposed image sensor enables observation with a spatial resolution close to the pixel pitch.

Image sensor with angle-selective pixels: Fig. 1a shows the micrograph of the proposed sensor. This sensor is based on our previous implantable image sensor [1–4]. There are two types of apertures in the pixel array: rectangular, which corresponds to a normal pixel, and octagonal, which is shared by four angle-selective pixels. The pitch of each aperture type is ∼16.8 µm. The grid is tilted by 26.6°. Thus, a single pixel set is composed of five types of pixels: one normal and four angle-sensitive pixels. Since the target area of the present image sensor is up to several tens of microns from the chip surface, the number of types of pixels is reduced.

Fig. 1b shows the schematic representation of the angle-selective pixel structure unit. This structure is manufactured from metal layers based on the standard CMOS process. Thus, no post-processing fabrication is required. The top metal layer formed an aperture which includes four angle-selective pixels. These pixels detect incident light, especially from different angles. The normal incident component through the aperture is reflected by the second and first metal layers. By this structure, high rejection performance against normal incidence can be realised. In comparison to grating-based angle-sensitive pixels, the angle resolution of the proposed pixels is low. However, this structure does not use diffraction or interference effects, so it is not as affected by wavelength. Furthermore, in case the observation is close to the sensor surface, a large observation angle is required to obtain sufficient parallactic difference. The proposed angle-selective pixels can detect only highly tilted incident light by sharing one aperture with 4 px.

Table 1 shows the specifications of the proposed sensor, which is based on a 3-transistor active pixel sensor. This sensor is manufactured in a standard 0.35 µm CMOS process metal layer. The total number of pixels is 40 × 120. The pitches of horizontal and vertical scanners are both 7.5 µm. Thus, the imaging area is 300 µm × 900 µm. Since each set of pixels has one normal and four angle-selective pixels, 920 sets are included in the pixel array.

Table 1: Specifications of fabricated CMOS image sensor chip

| Specification            | Value                        |
|--------------------------|------------------------------|
| Process technology       | 0.35 µm standard CMOS process |
| Supply voltage (V)       | 3.3                          |
| Chip size (µm²)          | 450 × 1560                   |
| Pixel type               | 3-transistor active pixel sensor |
| Pixel size (µm²)         | 7.5 × 7.5                    |
| Pixel array size         | 40 × 120                     |
| Photodiode type          | Nwell–Pwell                  |

Fig. 2 shows the relationship between the pixel output and the incident angle. The recorded outputs are normal pixels and two angle-selective pixels located across the aperture. The plane of incidence...
was set to 45° to both vertical and horizontal axes of the pixel array. The normal pixel shows peak sensitivity at 0°, with a full width at half maximum (FWHM) of 66°. By contrast, the angle-selective pixels have very low sensitivity for normal incidence. The angle-selective pixels have peak sensitivity at around 40°, with FWHM of about 23°. The extinction ratio of the peak to normal incident light was ∼25. The normal pixel has lower angular resolution and higher sensitivity than the angle-selective pixels because the normal pixel has a larger aperture and FWHM for capturing light. However, the angle-selective pixels show similar sensitivity at around 40° from optimising the photodiode position. As shown in Fig. 2, it is concluded that this sensor can obtain images including different angle information through the use of these different pixels.

The excited fluorescent bead emits fluorescence omnidirectionally. Thus, the normal and angle-selective pixels observe the fluorescent image in different views. The obtained images are shown in Fig. 4. As mentioned above, the pixel grid is tilted by 26.6° against the horizontal direction of the chip. The cross lines are drawn additionally as guides for eyes. Here, the image under each type of pixel was separated as a single shot from the raw image by image processing (MATLAB R2018b, Mathworks). The image contrast was normalised according to the peak intensity of each image. Also, the background caused by leaked excitation light and auto-fluorescence of the yellow filter was subtracted.

The result shows that the actual fluorescence images were blurred. The diameter of the fluorescent bead is lower than the pitch of each pixel because of the spreading of the emission light through the spacer between the image sensor and fluorescent bead. The fluorescent spot observed by the normal pixel is at the centre. By contrast, the images observed by the angle-selective pixels are off-centred and in different areas. This result shows that the proposed image sensor can observe the fluorescent target apparently from five different views. Since the offset of the image corresponds to the distance and the incident angle, it is also possible to estimate the distance between the sensor and target by the triangulation method.

The image of the sufficiently small fluorescent bead shows blurring pattern from a point light source. In this Letter, we used the measured pattern as point spread functions for image reconstruction. The observation targets are three fluorescent beads.

The image processing procedure is as follows. First, an obtained raw image was separated into each pixel type. The separated images are shown in Fig. 5. In these images, the beads are not separated. Next, the image resolution was doubled by bicubic interpolation implemented in MATLAB. The obtained image was deblurred by using a deconvolution method based on the Richardson–Lucy algorithm. In this method, the obtained image asymptotically approaches the true image by iterating. However, though increasing the iterations number results in a high-resolution image, artefacts such as noise amplification and ringing occur. In this Letter, we obtained the geometric mean of the five deconvoluted images in order to reduce the artefacts.

The reference image obtained by using a fluorescent microscope is shown in Fig. 6a. The distance among the beads was ∼20 μm. Fig. 6b shows the reconstructed image from the blurred image obtained by the proposed sensor. It should be noted that the resolution of this image was doubled from each raw image. The result shows that the spatial resolution of the reconstructed image is comparable with the

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**Fig. 2** Pixel output of normal and angle-selective pixels as functions of incident angle.

**Fig. 3** Experimental setup of fluorescent beads imaging: 50 μm-thick cover glass was used as spacer.

**Fig. 4** Fluorescent bead images separated into five viewpoints, i.e. images obtained by normal and four angle-selective pixels.

**Fig. 5** Images of three fluorescent beads obtained by proposed image sensor. Raw image was separated into five different views.
processing, we have con...pixel array pitch. The ringing around the fluorescent beads is reduced by the algorithm using the five views.

**Fig. 6** Comparison of three fluorescent beads observation results by fluorescence microscope and combination of proposed image sensor and image processing

- **a** Reference image with fluorescent microscope
- **b** Reconstructed image from five different images obtained by proposed image sensor

**Conclusion:** We proposed a lensless CMOS image sensor with incident-angle-selective pixels that can be manufactured by standard CMOS process. By using the proposed image sensor and image processing, we have confirmed that fluorescent beads separated by 50 μm from the sensor were reconstructed with a spatial resolution close to the pixel pitch.

The proposed sensor is not suitable for high angle resolution, but it is suitable for separated detection of incident light with large inclination. It is useful for 3D or high-resolution imaging at the specific distance by lensless imaging setup. In addition, it is expected that spatial resolution and sensitivity can be increased by using a fine process and a thick high-performance filter.

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One or more of the Figures in this Letter are available in colour online.

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