Spatiotemporally Varying Exposure Imaging for High Quality Image Reconstruction

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ABSTRACT

In this paper, spatiotemporally varying exposure imaging for high quality image reconstruction is introduced and a CMOS image sensor with a spatiotemporal exposure control function is presented. Moreover, we show the effectiveness of the spatiotemporally varying exposure imaging by reconstructing high quality image by simulation.

I. INTRODUCTION

In the real-world scene, capturing high quality images is required to satisfy various image properties, such as spatial resolution, temporal resolution, sensitivity, and dynamic range. Most of the conventional image sensors have fixed imaging parameters over all pixels. In that case, satisfying all of image properties is challenging because of the trade-off between them.

Some conventional approaches spatially vary imaging parameters of pixels on the single-chip image sensor [1, 2]. The concept of these approaches is to exploit spatially varying imaging parameters, and compute a high quality image from the obtained images [1, 2]. In [1], Nayar and Mitsunaga proposed a high dynamic range (HDR) imaging method using a single image with spatially varying pixel exposures. In this method, an optical mask with spatially varying optical transmittance is placed on the pixel array to vary the amount of light that reaches each pixel. This realizes spatially varying exposures for each pixel, allowing a single shot to capture the HDR image. In [2], Ugawa et al. proposed an imaging method using different spatiotemporal resolutions for each color for high sensitivity imaging. This method uses a long exposure time for green pixels and short exposure time for red/blue pixels on a single chip image sensor with a Bayer pattern color filter array. Moreover, color images having high sensitivity as well as high spatiotemporal resolution are reconstructed by utilizing motion information and color correlation.

These approaches focus on the improvement of specific image properties. However, image properties required for each imaging scene is different.

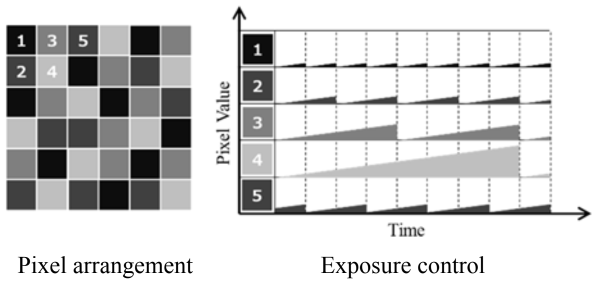
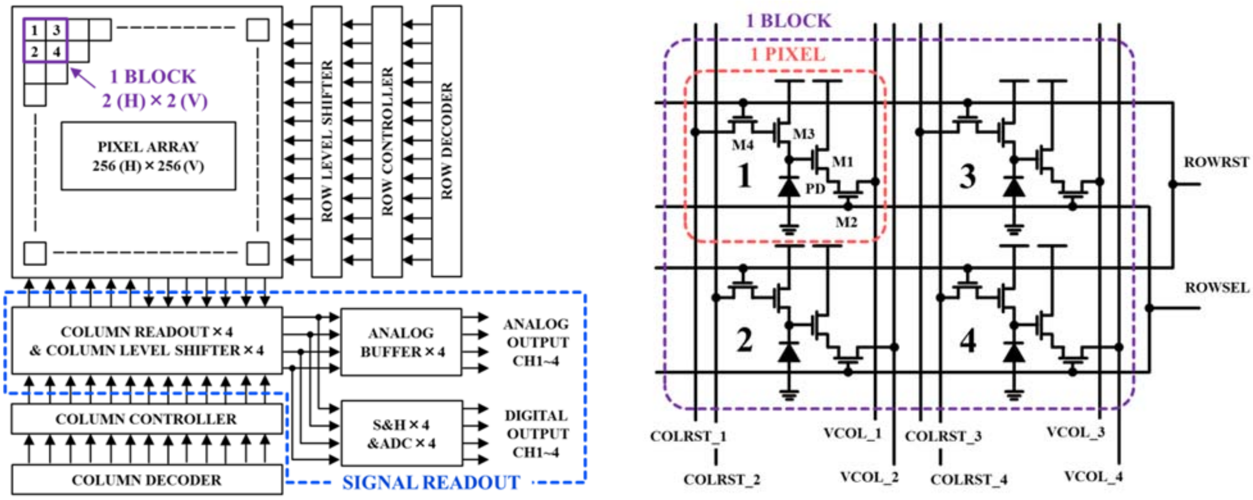


Fig.1 Spatiotemporally varying exposure

We introduce spatiotemporally varying exposure imaging and propose an image sensor with a spatiotemporal exposure control function to adaptively optimize imaging parameters in various imaging scenes. In addition, we show the effectiveness of spatiotemporally varying exposure imaging of the proposed image sensor by reconstructing high quality image in simulation.

II. SPATIOTEMPORALLY VARYING EXPOSURE IMAGING

In this paper, we introduce spatiotemporally varying exposure imaging for high quality image reconstruction. In this imaging, plurality of images having different image properties are captured at the same time by spatially and temporally varying the exposure over all pixels. By utilizing various image properties of the captured images, a high quality image can be reconstructed. To realize the spatiotemporally varying exposure imaging, the proposed image sensor controls exposure time, signal readout speed, and phase for each pixel, as shown in Fig. 1. In Fig. 1, pixels 1 to 4 have no phase shift and different exposure time, while pixels 2 and 5 have different phase and same exposure time. As a result, the proposed image sensor can obtain images that simultaneously have different temporal resolution and exposure. Moreover, the proposed image sensor is capable of setting imaging parameters for each pixel in order to flexibly change the image properties according to the imaging scenes. To realize the above exposure control, the proposed image sensor is equipped with a reset function and a readout selection function for each pixel.



(a) Block diagram (b) Pixel block circuit

Fig. 2 Architecture of the proposed image sensor

III. DEVICE ARCHITECTURE

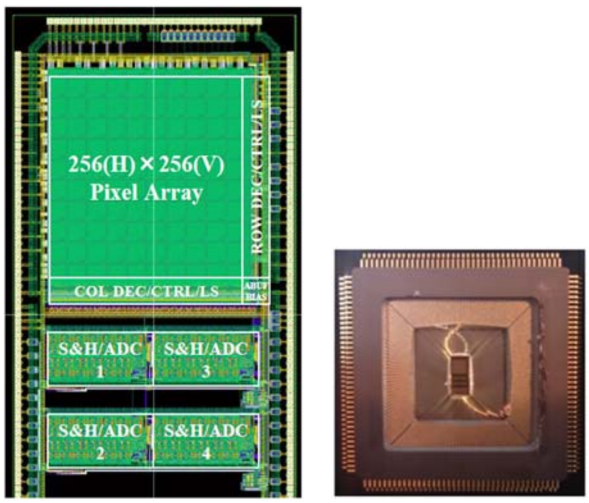
The architecture of the proposed image sensor is illustrated in Fig. 2. This image sensor can control exposure time, signal readout speed, and phase for each pixel in the pixel block. The pixel block circuit is composed of 2(H) × 2(V) pixels as shown in Fig. 2(b). In order to realize the individual reset operation at each pixel, the pixel circuit is composed of conventional three-transistor pixel circuit and a reset transistor as shown in Fig. 2(b). Row and column decoders generate a select signal to select the pixel block. The row and column scanning control circuits generate a control signal for each pixel. The control signal individually controls exposure operation and readout operation for each pixel in the selected pixel block. The row and column level shifters boost the voltage applied to reset transistor for hard reset operation. The hard reset operation prevents image lag. The signal readout circuit is composed of column readout circuit, column level shifter, analog buffer, sample and hold(S&H), and A/D converter (ADC); it realizes analog signal readout as well as digital signal readout for chip verification. In the proposed image sensor, four signal readout circuits are implemented to enable simultaneous readout of pixel signal values of the selected pixel block.

IV. PROTOTYPE CHIP

We developed a prototype image sensor using a ROHM 0.18 µm 1P5M standard CMOS process. Table 1 shows the main specifications of the image sensor. This image sensor has 256 (H) × 256 (V) pixels and an individual reset function for each pixel. The pixel pitch is 7 µm and the pixel aperture ratio is 25 %. In addition, 2.5 MS/s pipeline ADCs are integrated and they achieve 10 bit A/D conversion.

Table 1 Chip specifications

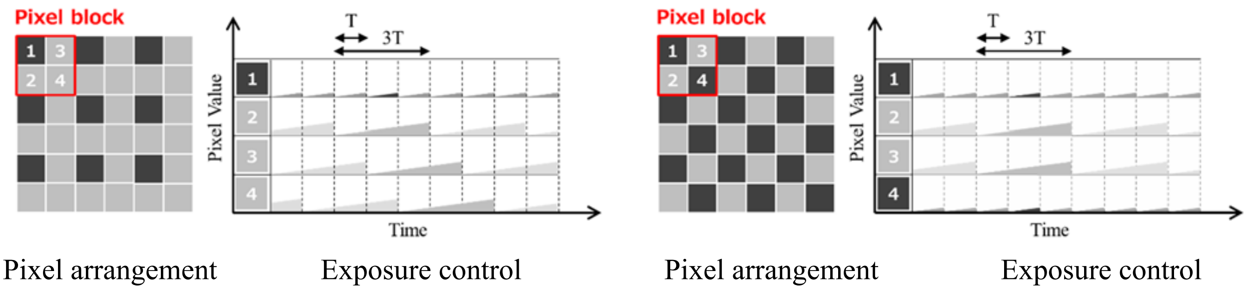
Technology	ROHM 0.18-µm 1P5M CMOS
Die Size	2,520 µm (H) × 5,180 µm (V)
Number of Pixels	256 (H) × 256 (V)
Pixel Size	7 µm × 7 µm
Pixel Structure	Individual Reset Pixel, 4 Tr
Aperture Ratio	25%
Power Supply Voltage	1.8 V, 2.7 V, 3.3 V, 3.5V, 4.2V
Maximum Frame rate	600 fps (Analog)
ADC Resolution	10 bit (pipeline ADC)



(a) Chip layout pattern (b) Photograph of the chip

Fig. 3 Prototype image sensor

The maximum frame rate is 600 fps. Fig. 3 shows chip layout pattern and a photograph of the chip developed in this work.

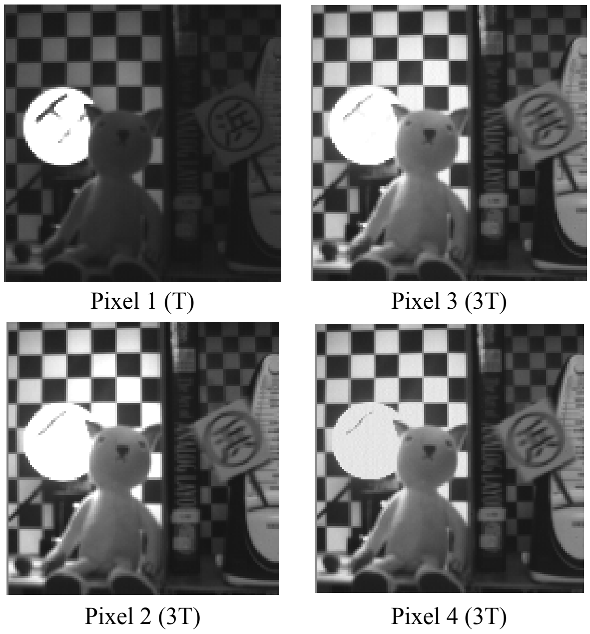


(a) Method 1 (b) Method 2

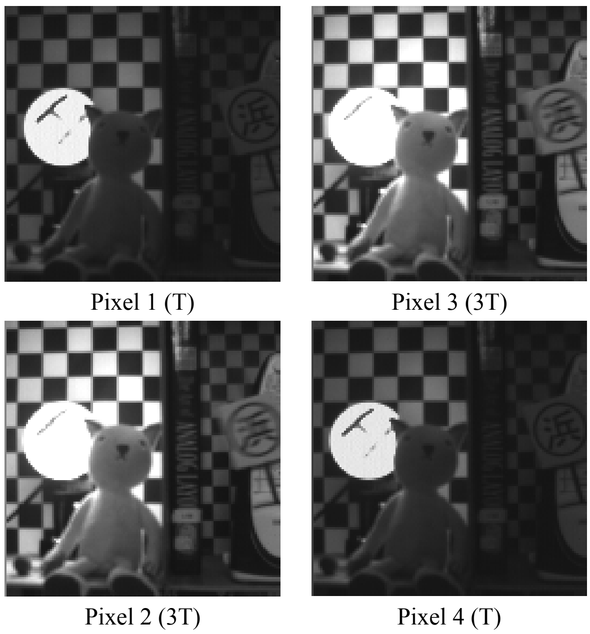
Fig. 4 Implemented imaging method

V. IMAGING RESULT

We implemented two imaging methods (Method 1 and Method 2) using the prototype image sensor to verify the spatiotemporal exposure control function. The implemented imaging methods are shown in Fig. 4. In Method 1, short exposure time imaging (pixel 1) and long exposure time imaging (pixels 2 - 4) with multiple phases at the same time, as shown in Fig. 4(a), are performed. In Method 2, short exposure time imaging (pixels 1 and 4) and long exposure time imaging (pixels 2 and 3) with no phase shift at the same time, as shown in Fig. 4(b), are performed. In the implemented methods, short exposure time imaging is set to short exposure time T = 1/60 s, and long exposure time imaging is set to long exposure time 3T = 1/20 s. The imaging results of the implemented imaging methods are shown in Fig. 5. From the imaging results, it can be confirmed that the prototype image sensor is capable of spatially and temporally controlling the exposure over all pixels.



(a) Method1



(b) Method2

Fig. 5 Results for implemented imaging methods

VI. IMAGE RECONSTRUCTION

In this section, we show the effectiveness of spatiotemporally varying exposure imaging of the proposed image sensor by reconstructing a high quality image by simulation. The proposed image sensor can satisfy the required image properties by using a suitable reconstruction method as well as adapting imaging parameters in various imaging scenes. We are investigating various reconstruction methods. In this paper, we focus on the restoration of spatiotemporal resolution that is lost by spatiotemporally varying exposure imaging. Let us provide just a brief overview of the reconstruction method because this method is not the focus of our work in this paper.

Let us consider the case where Method 2 is used as illustrated in the previous section. Short exposure time images have high noise level, high temporal resolution, and low spatial resolution. Long exposure time images have low noise level, low temporal resolution, and low spatial resolution. In addition, s-hort exposure time images and long exposure time images have irradiance information of different spatial positions obtained from each other.

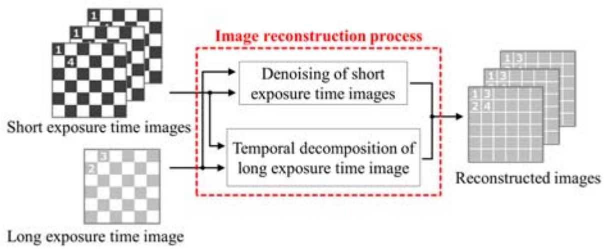
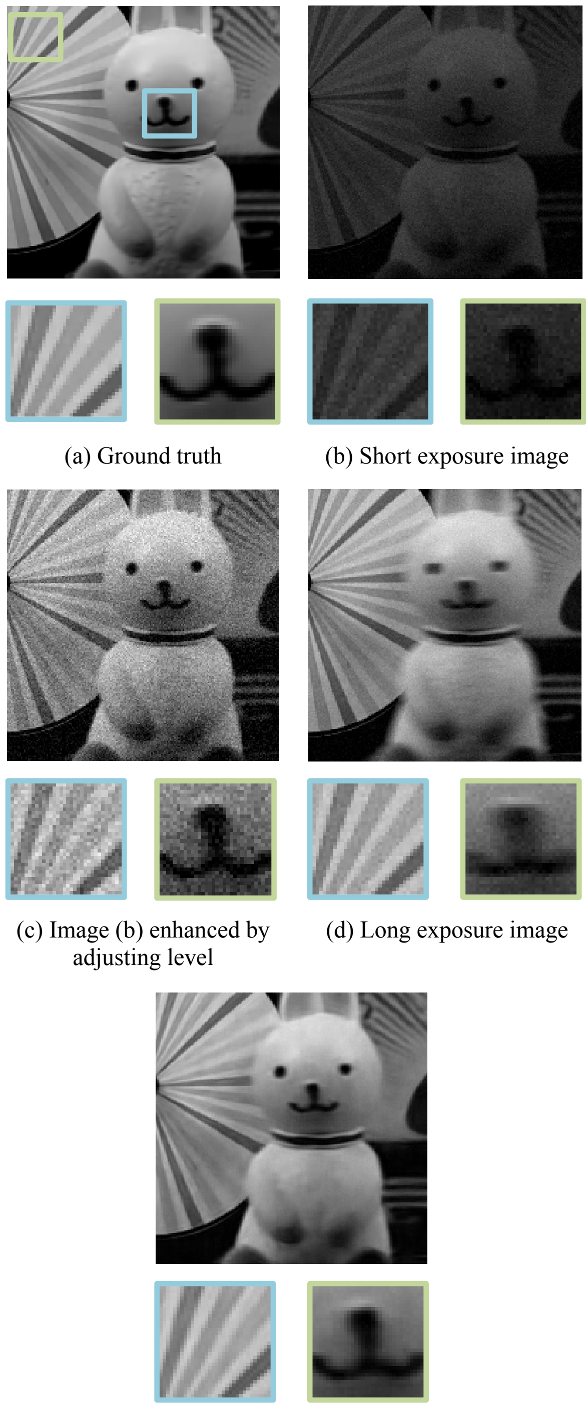


Fig. 6 Image reconstruction process

High quality images having low noise level and high spatiotemporal resolution can be reconstructed from short exposure time images and long exposure time images. The image reconstruction process is shown in Fig. 6. As shown in Fig. 6, the denoising of short exposure time images and the temporal decomposition of long exposure time images are performed simultaneously in the reconstruction process. By using the irradiance information obtained from each other, short exposure time images are denoised and long exposure time images are temporally decomposed.

In the simulation, we reconstruct high quality images from three short exposure time images with high noise level and a long exposure time image with low temporal resolution. The reconstructed results are shown in Fig. 7. The reconstructed image has lower noise level and higher spatiotemporal resolution than those of short/long exposure time images as shown in Fig. 7. From this reconstructed image, the effectiveness of spatiotemporally varying exposure imaging can be confirmed.



(a) Ground truth (b) Short exposure image

(c) Image (b) enhanced by adjusting level (d) Long exposure image

(e) Reconstructed image

Fig. 7 Reconstructed image and examples of images

VII. SUMMARY

In this study, a CMOS image sensor with a spatiotemporal exposure control function was designed and it was verified that this image sensor is capable of spatially and temporally controlling the exposure over all pixels by implementing two imaging methods. Furthermore, we also confirmed the effectiveness of the spatiotemporally varying exposure imaging with simulation.

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