# Hybrid Back-Side Illuminated Distance Measuring Sensor Array with Ring Gate Structure

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***Abstract*—A new type of back side illuminated distance measuring sensor, which consists of ring gate structure, is presented. It is found that the ring gate structure is advantageous for its high-speed transfer rate and its high sensitivity. 100% of fill factor is realized by combining with back-side illuminated technique. The number of incident photons has been increased by six times in comparison with the front side illumination, and 2.6mm distance resolution at 1m distance could be achieved. The maximum measurement range could be extended up to 7m.**

***Index Terms*—Distance Measuring Sensor, Ring Gate Structure, Back Side Illumination, Time-of-Flight**

## I. INTRODUCTION

THE demand for real-time distance imaging is growing for the application of factory automation, security, vehicle, virtual reality and gaming. In order to improve the accuracies, the distance must be detected with higher resolution for various reflections from the object. For better accuracy, it is significant to increase the number of incident photons with suppressing the noise factors (shot, readout, and quantization noise) effectively. Though the enhancement of light source may help the improvement for better accuracy, another problem such as excess of power consumption, cost, or system size must occur. Therefore, it is necessary to improve an aperture ratio for individual pixel of the sensor. Sophisticated sensors for distance measuring, which utilize CCD technology [1], hybrid CMOS-CCD technology [2] and fully CMOS technology [3], have been already developed. But however, front illuminated types were adopted for all the prior cases. For instance, even if the length of PG (Photo Gate) is extended, the charge cannot be transferred at high speed for its weak electric field, though the aperture ratio may be improved. It seems extremely difficult for a conventional front illuminated structure to improve the aperture ratio. The back illuminated structure is efficient to improve the aperture ratio [4], [5], [6]. The distance measuring sensor with the back illuminated structure seemed not proposed yet. Even if it simply adopts the same structure as a conventional front illuminated structure, sensitivity of the back illuminated one cannot be improved, because it is unable to convey charges effectively at high speed from the incident region to collection node. In order to solve such problem, we propose back side illuminated sensor with ring gate structure for ideal distance measuring. The proposed structure can guarantee high fill factor (100%) with increased quantum efficiency and transferring the charge at high speed. In this paper, the principle of the ring gate structure and experimental results of implemented chip are presented.

## II. THE PRINCIPLE OF THE RING GATE STRUCTURE

Fig. 1 shows a cross sectional view of a conventional photo modulation device. The photo gate (PG) is the photosensitive region of the pixel. Both side of PG, additional gates(G1 and G2) are used to control the direction of photoelectron flow in order to realize time-of-flight (TOF) detection. FD1 and FD2 are floating diffusion used to collect signal charges from PG through transfer gates G1 and G2, respectively. In this structure, photons can be transferred toward only single direction at a time. To improve the aperture ratio, longer PG seems suitable, but it makes the transfer speed slower.

Fig. 2 shows an idea for the modification to the device. FD1 and FD2 are enclosed at the G1 and G2, respectively, so that photons generated by surrounding PG are collected completely without any loss. Photons enter the detector from the backside, and the resultant photo-electrons are collected at the front-side around PG.

Fig. 3 shows the pixel's bottom view and how lateral surface potential is applied to perform charge transfer and distribution of the generated photoelectrons among dual gates of G1 and G2 according to delay- time ($T_d$). In Fig. 3 and Fig. 4, the resulting potential profile during Phase=0°(G1=on and G2=off) and Phase=180°(G1=off and G2=on) are shown along with the cross section of the pixel at line A-A', B-B' and C-C', respectively. In Fig. 3, the potential profile at

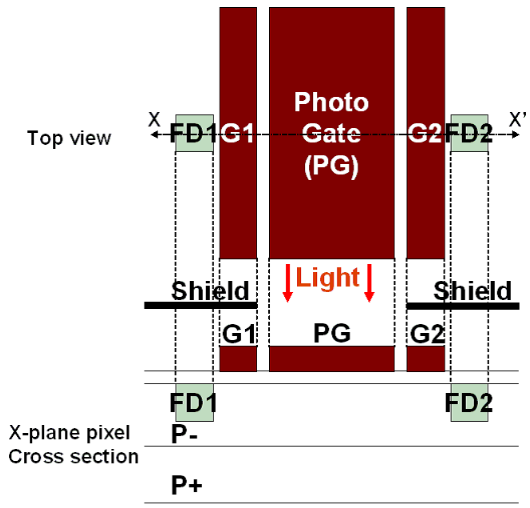


Fig. 1. Conventional pixel structure.

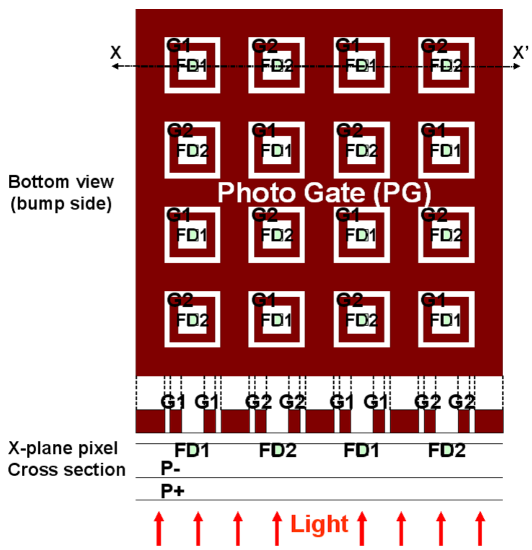


Fig. 2. Proposed pixel structure.

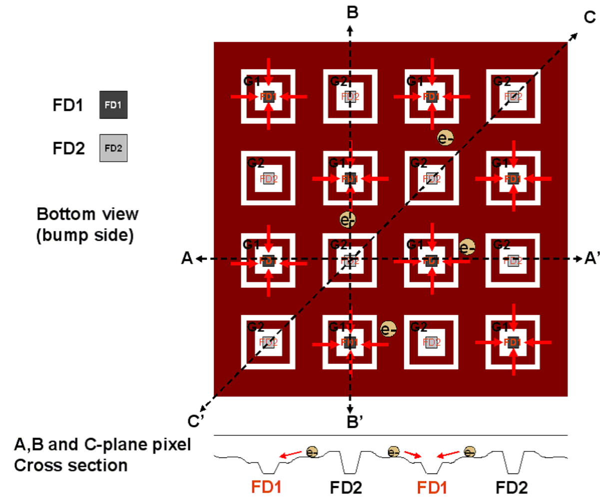


Fig. 3. Charge distribution during Phase=0 °.

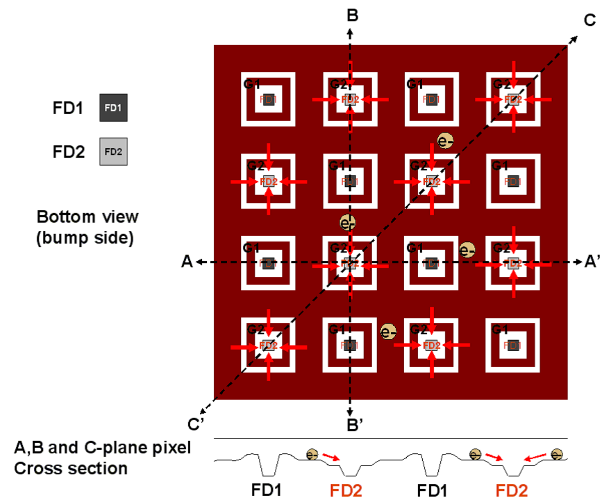


Fig. 4. Charge distribution during Phase=180 °.

Phase=0° is shown how the trapped photon is transferred to FD1 through G1. The potential profile is valid for all the cross-sectional directions (A-A', B-B', C-C'). At Phase=180° in Fig. 4, photoelectron is transferred with same manner as the explanation above.

Fig. 5 shows a pixel schematic. Each pixel of the 16 $\times$ 16 array includes a PG, two transfer gate (G1 and G2), a reset transistor (M1 and M2), a source follower transistor(M3 and M4), and a select transistor(M5 and M6). The gates structure symbolized by the transistors labeled G1 and G2 are controlled by pulses $\phi$VG1 and $\phi$VG2, respectively. PG is connected to VPG (a fixed voltage). The reset transistors are labeled M1 and M2, and those are connected individually to a reset voltage Vr. PMOS transistor is used for the reset transistor to maximize the signal swing and electric field strength. The pixel operation is detailed as follows. The image acquisition starts by resetting the FD1 and FD2 through M1 and M2, respectively. After that, the two gates (G1 and G2) are modulated so that the photo-generated charge is distributed towards collection node FD1 and FD2 during the whole accumulation time. The pixel array is then read out by selecting row, and pixel Fixed-Pattern-Noise (FPN) can be suppressed by means of Correlated Double Sampling (CDS) circuits. Finally, the signal is read through the buffer.

## III. EXPERIMENTAL RESULTS

### A. Prototype

Photo detector part was fabricated independently from CMOS read-out IC(ROIC). Both are connected with stack bump, shown schematically in Fig. 6. Fig. 7 shows the die micrograph. It consists of distance measuring sensor array,

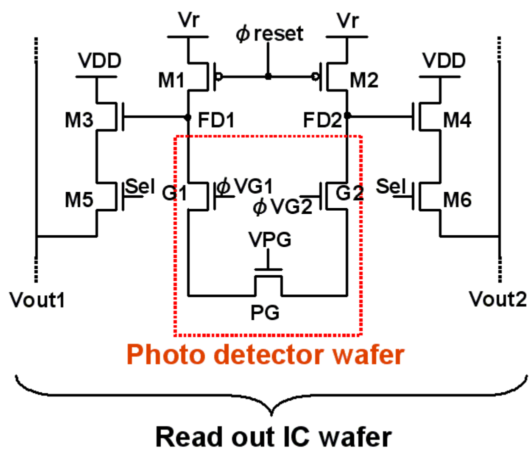


Fig. 5. Equivalent circuit diagram.

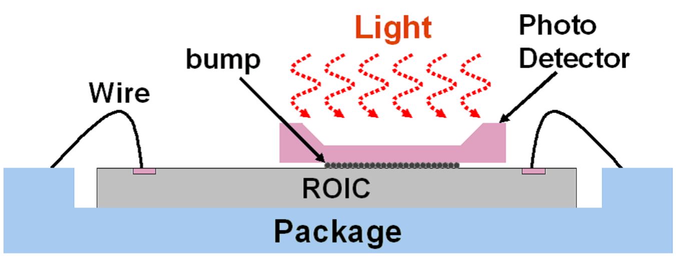


Fig. 6. Schematic cross section of a hybrid distance measuring sensor.

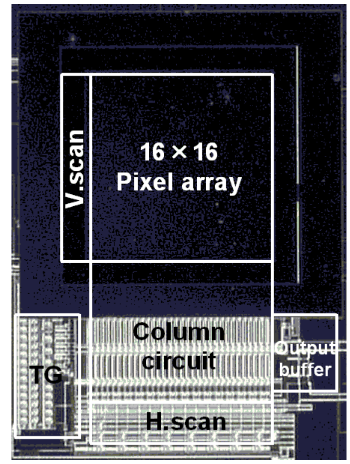


Fig. 7. Die micrograph.

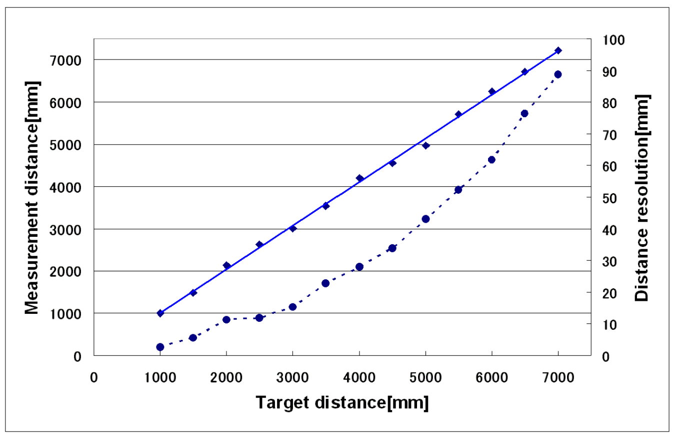


Fig. 8. Distance measurement performance, target distance versus measured distance and distance resolution.

column(CDS) circuits, vertical and horizontal scanners and timing generator. 100$\mu m$ square pixel with 16 $\times$ 16 pixels has been fabricated. The fill factor of each pixel is 100%. Monolithic device of back side illumination [4], [5] contains the photo detector as well as the circuit area in pixel. But in conventional case of such monolithic one, the photon generated at the circuit area out of photosensitive region cannot be collected as the effective signal. By adopting the fully hybrid type such like [6], the photon loss can be avoided and it can be regarded as 100% of fill factor.

### *B. Range Measuring Capabilities*

The capability as the distance sensor is tested by using a system for measuring distance consisting of 20M$Hz$ LED sources ($\lambda$=870$nm$), FPGA and proposed sensor. Fig. 8 is a plot of measured distance for a white reflecting board as the target. The accumulation time (Tacc) is 10$ms$ and the measurement condition is 8$mm$ lens (F1.2) and room light (200$lux$). Thirteen points were measured from 1.0$m$ to 7.0$m$ in steps of 500$mm$. The distance resolution was calculated based on 200 data recorded at each 500$mm$ step. The distance resolution is less than 2.6$mm$ below 1$m$ distance and it does not exceed 100$mm$ up to 7$m$.

TABLE. I summarizes the specifications for the sensor chip. The pixel characteristics between front illuminated type and back illuminated type was compared at same measurement condition. For this experiment, our own front illuminated test sample was utilized. Therefore, the result of measuring in terms of the unit area, the incident photons of back illuminated type was measured as six times better compared with the one of front illuminated type. The measurement range of the back illuminated type measured up to 7$m$ could be improved compared with the front illuminated type measured up to 5$m$. Moreover, the distance resolution is greatly improved as the result of comparison between the front illuminated type and the back illuminated. For instance, for the back illuminated type the result was 2.6$mm$ at 1$m$ distance whereas for the front illuminated the result was 11.3$mm$. The ring gate structure with combining the back side illumination transfers the photon at high speed and without any loss. The characteristic of sensitivity can be improved greatly.

TABLE I
SENSOR SPECIFICATION.

| Parameter | | Description |
|---|---|---|
| Number of pixels | | 16 × 16 |
| Pixel size[μm□] | | 100 × 100 |
| Fill Factor[%] | | 100 |
| Modulation Frequency[MHz] | | 20 |
| Maximum measument Range[m] | | 7 |
| Distance resolution [mm] | @ 1m | 2.6 |
| | @ 5m | 43.0 |
| | @ 7m | 88.9 |

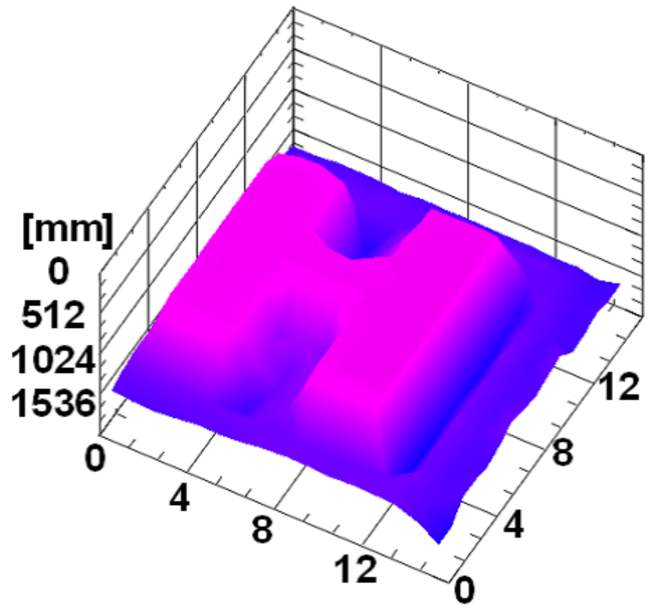


Fig. 10. 3D-plots recorded with the 16 x 16 distance measuring sensor array.

### C. Sample image

To verify the distance imaging capabilities of the sensor, sample images were taken. Fig. 9 shows the depth map with an image of the scene taken with a commercial digital still camera. The scene shown in Fig. 10 is the 3D-plots under the condition in Fig. 8. The target object was the cube character ”H” located at 800$mm$ from the sensor. The image of high distance resolution was measured.

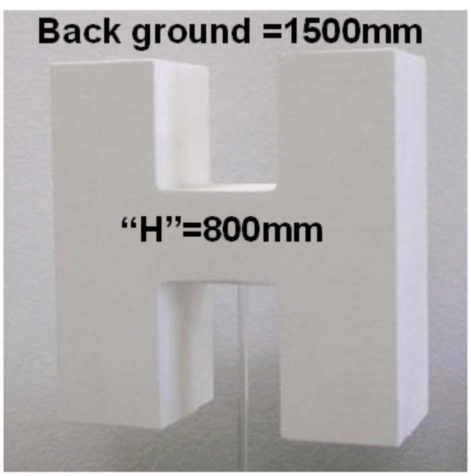


Fig. 9. Sample image recorded with digital still camera.

## IV. CONCLUSION

Distance measuring sensor array with ring gate structure illuminated from bask side has been presented. It is found that the ring gate structure is advantageous for its high-speed transfer rate and its high sensitivity. The number of incident photons has been increased by six times compared with a front illuminated type. And, the measurement result of distance resolution achieves 2.6$mm$ at 1$m$ distance. The maximum measurement range has been expanded up to 7$m$. The improvement of the sensitivity for the sensor can contribute to minimize the system size and reduce the total cost.

## REFERENCES


[1] T. Spirig, P. Seitz, O.Vietze, and F. Heitger,” The lock-in CCD-Two dimensional synchronous detection of light,”*IEEE J. Quantum Electron*, **31**, pp. 1705–1708, Sep.1995.

[2] R. Lange and P. Seitz, ”Solid-State Time-of-Flight Range Camera, ” *IEEE J. Quantum Electronics.*, **37**, no. 3, pp. 390–397, Mar. 2001.

[3] S. Kawahito, I. A.Halin, T. Ushinaga, T. Sawada, M. Homma, Y. Maeda, ”A CMOS Time-of-Flight Range Image Sensor With Gates-on-Field-Oxide Structure, ” *IEEE Sensors Journal.*, **7**, no. 12, pp. 1578–1586, Dec. 2007.

[4] B. Pain et al, ”A Back-Illuminated Megapixel CMOS Image Sensor, ” *Proc. 2005 IEEE Workshop on CCD and Advanced Image Sensors.*, pp. 35–38, June. 2005.

[5] S. Iwabuchi et al, ”A Back-Illuminated High-Sensitivity Small-Pixel Color CMOS Image Sensor with Flexible Layout of Metal Wiring, ” *ISSCC Dig. Tech. Paper.*, pp. 302–303, Feb. 2006.

[6] V. Suntharalingam et al, ”Megapixel CMOS Image Sensor Fabricated in Three-Dimensional Integrated Circuit Technology, ” *ISSCC Dig. Tech. Paper.*, pp. 356–357, Feb. 2005.