LETTER

1K Pixel Silicon-MPPC Three-Dimensional Image Sensor for Flash LIDAR

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Abstract Flash LIDAR is needed in order to take 3D images for obstacle avoidance and to measure relative distances and attitudes during lunar and planetary landings, surface exploration, and orbital rendezvous docking with spacecraft. Meanwhile, commercial Flash LIDAR is being developed for capturing 3D images required by autonomous cars and drones. We have developed a prototype 1K pixel 3D image sensor using Silicon-MPPC, which is capable of photon counting, as the light-receiving sensor [1]. In this paper, we describe the basic structure, circuit configuration, functions, and evaluation results of the basic performance of the sensor.

key words: Si-PM, Si-MPPC, LIDAR, Geiger mode, Image sensor

Classification: Integrated circuits (memory, logic, analog, RF, sensor)

1. Introduction

In order for a spacecraft to land and explore a survey point in scientific or resource exploration missions, Flash LIDAR capable of taking 3D images is strongly desired due to the need to measure the terrain before landing, avoid obstacles during landing, and detect the attitude of the spacecraft [2,3,4,5,6,7,8]. Flash LIDAR is also useful for on-orbit rendezvous and docking, such as docking of transfer vehicles to the International Space Station, due to the need to determine relative distance and attitude [9,10,11, 12, 13]. As a typical example, the ASC "Dragon Eye" Flash LIDAR has been installed on the SpaceX Dragon supply ship. The OSIRIS-REx asteroid probe [14, 15, 16, 17] is also equipped with Flash LIDAR for guidance, navigation and control [12, 13].

Flash LIDAR is a sensor that takes 3D images in the manner of flash photography by diffusing laser pulses into the field of view of a 3D image sensor containing pixels that integrate avalanche photo diodes (APD) and ranging circuits [18,19,20,21].

JAXA Space Exploration Innovation Hub has been

conducting joint research on 3D image sensors using Geiger mode APDs [1,22,23,24] to develop versatile sensors that can be applied to landing sensors for lunar and planetary probes, on-orbit rendezvous, and autonomous cars. In this paper, we report a 3D image sensor using Si multi pixel photon counting (MPPC) as the photodetector. MPPC is a kind of Geiger mode APD, which has the function of counting the number of photons by bundling multiple Geiger mode APDs [25,26]. Therefore, MPPCs are excellent sensors that have high sensitivity necessary for Flash LIDAR, which irradiates a diffuse laser, and a photon counting function to distinguish it from background light from the sun and other sources. In addition, in an appropriately defocused image, the light intensity data for each pixel can be used for centroid processing to obtain an angular resolution higher than the pixel resolution. Centroid processing is a commonly used data processing technique for improving the angular resolution of satellite onboard star trackers. Hamamatsu Photonics is the only company that manufactures 3D image sensors using Si-MPPC [1,23].

In this report, we have modified the integrated circuit of the 1K (32×32) pixel 3D image sensor reported in Reference [1] to achieve a time resolution of 250 ps. The basic structure, circuit configuration, and functions are described in Section 2, and the evaluation results of time and light intensity measurements are described in Section 3.

2. Outline of 3D image sensor

2.1 Si-MPPC array

The 3D image sensor consists of two layers: a sensor layer with 1024 Si-MPPCs arranged in an array of 32×32 pixels, and a readout IC (ROIC) layer with a time-to-digital converter (TDC) circuit [27,28] for each pixel. The Si-MPPC in the sensor layer is back-illuminated and is connected to the pad of the ROIC metal layer by flip chip bonding (FCB). The photo in Fig. 1 shows the prototype 3D image sensor, which is a 6.2×6.2 mm chip mounted directly on the substrate. This sensor can operate at room temperature. Each pixel has one MPPC with dimensions of 100×100 μm .

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Fig. 1 Outline of the 3D image sensor. The sensor is a composite device in which an Si-MPPC array and CMOS integrated circuit are bonded by FCB. The high-speed clock FAST00/FAST90 from the PLL is 1 GHz. Pixel data can be read from four serial lines in parallel and the frame rate is up to 1 kHz.

This MPPC consists of 12 sub-pixels of $25 \times 25 \mu\text{m}$ and has a 12-level photon counting function. One pixel has the area of 16 sub-pixels, but the four corners need to be wired, so the number of sub-pixels is 12. Each sub-pixel has a metal quenching resistor with an excellent temperature coefficient, which is connected in series with the input pad to the ROIC to form a passive quench circuit. The passive quench circuit stops the Geiger discharge when it occurs (photo event) due to photon incidence by dropping the bias voltage below the APD breakdown voltage as the discharge current flows through the quenching resistor. The Si-MPPC of this prototype sensor has a sensitivity range of 600-1000 nm and a detection efficiency of about 10% at a wavelength of 900 nm. While the prototype in reference [1] employed a front side illuminated APD, the prototype in this report employs a back-illuminated APD to suppress the surface reflectivity and improve the efficiency. However, the detection efficiency depends on the bias voltage.

2.2 ROIC

The ROIC is fabricated using a $0.18 \mu\text{m}$ CMOS process and consists of a circuit for generating and distributing a high-speed clock, a pixel circuit for 1024 pixels, and a serial peripheral interface for reading the pixel counter. The overall configuration and pixel circuits are shown in Figure 1. The supply voltage of the ROIC is 2.0 V. The 1 GHz high-speed clock that is delivered to each pixel circuit is generated by multiplying an external reference clock of 62.5 MHz by 16 in the phase locked loop (PLL) section. The PLL generates two types of high-speed clocks (FAST00 and FAST90) with a phase difference of 90° . In the ROIC reported in Reference [1], the high-speed clock propagates from the PLL through the transmission line wired in the X direction ($X=0$ to 32) and then is delivered in the Y direction ($Y=0$ to 32), resulting in propagation delays in the X and Y directions. In addition, because of deficiencies in the transmission line repeaters, the clock frequency that can be delivered to all pixels is limited to 768 MHz due to the clock

waveform losing shape along the transmission line. In the ROIC of this report, the transmission path for distributing the high-speed clock from the PLL in the X direction is improved to a FUNOUT circuit with an equal length of wiring and repeaters placed at intervals of $800 \mu\text{m}$ or less to prevent degradation of the clock waveform. In the Y direction, repeaters are inserted every 4 pixels to prevent clock degradation. With these improvements, the ROIC in this report is able to provide a 1GHz clock for all pixels, and has successfully improved the time resolution from 318ps in Reference [1] to 250ps. The improvement in time resolution corresponds to an improvement in distance resolution from about 5 cm to about 4 cm. The high-speed clocks FAST00 and FAST90 are delivered to the pixel circuit only during the period when the ranging gate signal (ARMING) is set to High in order to reduce power consumption.

The pixel circuit has a TDC circuit for time-of-flight (TOF) measurement and a time over threshold (TOT) circuit for pulse width measurement [29, 30]. The TDC circuit counts up when the ranging gate signal (ARMING) is high, and stops counter operation when the ARMING goes low or the comparator detects a photo event signal from the MPPC. The threshold VTH and the input bias VREF of the comparator can be adjusted by the internal DAC. The TDC is a 15-bit counter, and the two least significant bits (LSBs) are a combination of the FAST00 and FAST90 phases, achieving a time resolution four times that of the clock. The next 4 bits are a toggle counter, and the 9 bits on the MSB side are an M-sequence code generator. The M-sequence code generator reduces the circuit area but consumes a large amount of current because all FFs operate simultaneously. Therefore, the lower four bits are used as a toggle counter to reduce the operating frequency of the M-sequence code generation circuit to $1/16$. In the TOT circuit used for pulse width measurement, the TOT has a capacitance in the comparator input section to extend the pulse width of the photo event, and then FAST00 drives the 8-bit toggle counter to measure the pulse width. [1]

The distance measurement data is read out in parallel via SPI in four blocks of 16×16 pixels (A to D) as shown in Figure 1. The readout clock can be up to 40 MHz, which supports frame rates of 1 kHz or higher.

3. Evaluation experiment

3.1 Experimental apparatus

In the experiment on the prototype 3D image sensor in this study, the optical system for beam scanning and all the evaluation boards are placed in a thermostatic oven. The temperature of the device is controlled by a Peltier device placed on the back side of the substrate on which the device is mounted. All the experimental results reported in this paper were measured at $+20^\circ\text{C}$, which was maintained by the thermostatic oven and Peltier element. The bias voltage (VK) of the APD is a DC voltage.

The light source for testing the optical performance is a pulsed laser (PLP-10-850) with a wavelength of 843 nm and a pulse width of 70 ps. The timing between the ranging gate ARMING and the laser pulse is controlled by the delay pulse generator DG645. The laser pulse is directed onto the sensor surface by a multimode fiber, collimator and microscope objective with a square top-hat profile of $160 \times 170 \mu\text{m}$. The uniformity within the footprint is about 20%. The maximum incident light intensity is 100 fJ/pix/shot, which is adjusted by a manual attenuator.

3.2 Breakdown voltage

The breakdown voltage V_{br} is important to evaluate for 3D image sensors because the distribution of V_{br} for each pixel represents the distribution of sensitivity within the screen. However, after the sensor layer and integrated circuit layer are joined by FCB, the I-V characteristics of each pixel cannot be measured. Therefore, the minimum voltage that is broken down by the bias voltage V_K applied to the entire chip is measured for each pixel, and this is defined as the breakdown voltage V_{br} for the pixel. Therefore, it should be noted that in addition to the I-V characteristics of Si-MPPC, the characteristics also include the operating characteristics of the pixel circuit. Figure 2 shows a contour plot of the distribution of V_{br} measured at $+20^\circ\text{C}$ in the screen, showing that V_{br} slopes from the top of the screen ($Y=0$) to the bottom ($Y=32$) by about 1 V. The V_{br} of about 90% of all pixels is distributed between 0.8 V. This result indicates that the effective excess bias of each pixel is tilted by about 1 V between the pixel on the $Y=0$ side (upper side) and the pixel on the $Y=32$ side (lower side). Therefore, the sensitivity on the $Y=0$ side tends to be relatively better than that on the $Y=32$ side in the screen. In this device, the pads that supply the GND potential, which serves as the reference for the bias voltage V_K , from the outside are concentrated in the upper part of the screen near $X=15$ to 31. As a result,

Fig. 2 Distribution of the breakdown voltage at each pixel. The breakdown voltage is defined as the voltage at which the Geiger discharge starts.

a gradient in the GND potential is created from the upper right to the lower left of the screen, which is thought to cause a gradient in the bias voltage applied to the APD of each pixel. This is the same trend as in Reference [1]. The placement of the power and ground pads was unavoidable in this prototype for layout reasons, and is a point that needs improvement in the future.

3.3 Time measurement function

The time measurement accuracy and the distribution of the delay offset between pixels that have an integrated MPPC are important characteristics of 3D image sensors. Figure 3 shows the measurement results for the offset distribution of photo event detection in each pixel by directing a laser into each pixel. The bias voltage $V_K = -47.0 \text{ V}$, the number of photons incident on each pixel is about 1000, and the number of times the laser is irradiated onto each pixel is about 30 per pixel. To discriminate events due to dark current and photo events due to optical input, the median of the data $\pm 4 \text{ ns}$ was processed as a signal.

From the trend of the breakdown voltage V_{br} shown in Fig. 2, it was expected that the sensitivity of the upper side of the screen would be higher than lower side. However, as explained in Section 2.2, the high-speed clock for TDC drive is distributed from the PLL to the FANOUT circuit in the X direction by an equal-length line, and then propagated in the Y direction. For this reason, it is expected that the propagation delay is almost uniform in the X direction but varies in the Y direction.

Figure 3 shows that the count value of the TDC circuit of the pixels is about 4 ns higher on the upper side of the screen than on the lower side. This difference depends on the distribution of delay and sensitivity due to the direction of clock delivery. In addition, since the repeaters for the high-speed clock are placed every 4×4 pixels, a change in delay

Fig. 3 Delay offset distribution at each pixel. The high-speed clock propagates in the Y-direction (top to bottom). The bias voltage V_K is 47.0 V, the compactor threshold $V_{TH} = 855 \text{ mV}$, and the bias adjuster $V_{REF} = 750 \text{ mV}$.

Fig. 4 Delay offset distribution at each pixel. The high-speed clock propagates in the Y-direction (top to bottom). The bias voltage VK is 47.0 V.

Fig. 5 Pixel TDC response to laser pulse delay. LSB of the pixel TDC is 250 ps. The relative offset between pixels depends only on the clock propagation delay. The bias voltage is 47.0 V. Data are averages over 300 shots.

can be seen every 4 pixels in the Y direction.

The standard deviation of the count value of each pixel shown in Figure 3 was almost uniform with no bias in the screen. The histogram of the standard deviation of all pixels is shown in Figure 4. The horizontal axis shows the standard deviation of the count values, and the vertical axis shows the number of pixels. The LSB of the TDC is 250 ps. These results show that the counters are almost normally distributed around 150 ps below 250 ps, indicating that the counters are operating well overall. In this TDC circuit, a time resolution of a quarter of the clock period is achieved by combining the phases of FAST00 and FAST90. Therefore, the results in Fig. 4 are due to the improvement of the high-speed clock delivery circuit described in 2.2, which improved the degradation of the clock waveform and its duty ratio during propagation. The number of defective pixels with a standard deviation of 500 ps or more is 12 pixels.

Figure 5 shows the results of measuring the detailed behavior of the pixel counter under the same conditions as in Figure 3. The horizontal axis shows the pulse delay value by the delay pulse generator, the left vertical axis shows the

measured value by the TDC circuit of the pixel, and the right vertical axis shows the standard deviation. The average values and standard deviations over about 300 laser irradiations are shown. The results in Fig. 5 show that the five pixels arrayed in the screen in the X and Y directions increase linearly while maintaining a constant delay offset, and the counter is operating normally with a resolution of 250 ps. It can also be read from Fig. 5 that the standard deviation, which was 500 ps in Reference [1], has been improved to less than 250 ps. The delay offsets of (0,0), (15,0), and (31,0) located at Y=0 are the same, indicating that the delay time is equalized by the equal length distribution of the fanout circuit. A 3 ns offset difference is visible for (15,0), (15,15), and (15,31) located at Y=15. This is consistent with the results in Figure 3.

3.4 Light intensity measurement function

One of the features of this sensor is that it uses MPPC, which is capable of photon counting as a detector. As explained in Section 2.2, the pixel circuit measures the pulse width by TOT circuit instead of measuring the wave height. Figure 6 shows the averaged output of the intensity counter (TOT circuit) and the averaged count of the TDC circuit when the number of photons incident on (0,0) is increased by about 50 dB from a single photon. In Fig. 6, as the number of photons increases, the pulse width count increases. Therefore, the signal strength can be estimated from the pulse width. In the literature [1], the intensity could not be measured when the number of incident photons was less than 10, but in this report, by improving the sensor, the intensity can be measured from a single photon. As the incident intensity increases, the count value of the TDC circuit becomes faster by about 1 ns. This is attributed to the increase in the operating speed of the comparator with the increase in the amount of photocurrent. The curve also has an inflection point around 200 photons as in Reference [1], and the trend of the curve remains the same. The reason for this inflection point is not clear, but it is assumed to be due to the distribution of the generated photo events into 12 sub-pixels by an integer partition.

Fig. 6 Response of intensity counter. Data are the averages of more than 300 laser shots on (0, 0). The bias voltage VK is 47.0 V.

4. Conclusion

We have fabricated and evaluated a 1K pixels 3D image sensor for Flash LIDAR using an Si-MPPC array capable of photon counting. The prototype sensor was able to achieve a distance resolution of 250 ps by improving the high-speed clock distribution circuit, and the standard deviation of the TDC circuit was also improved. In addition, improvements in sensors have made it possible to measure the incident intensity of light from a single photon. In the future, we need to increase the pixel size for commercial use.

We hope that Flash LIDAR will be used in many fields including future lunar and planetary exploration, and that it will contribute to expanding the frontiers of human knowledge and activities.

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