Three-dimensional Image Sensor with MPPC for Flash LIDAR

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Three-dimensional (3D) image sensors have many applications, including enabling autonomous vehicles to avoid obstacles and providing guidance, navigation, and control for spacecraft immediately before landing on a celestial body. Flash LIDAR is a system that can acquire a 3D image by emitting a diffuse pulsed laser beam, and hence is suitable for both obstacle detection and terrain measurement. In the 3D image sensors used for Flash LIDAR, a photosensor array and time measurement integrated circuit are vertically bonded. Here, we report the results of a detailed evaluation of the principles, functions, sensitivity, and time measurement accuracy of a prototype 1-k pixel (32 \times 32 pixels) 3D image sensor based on a multi-pixel photon counting avalanche photodiode. By counting photons, a 3D image sensor is realized that has both high sensitivity and the ability to measure light intensity.

Key Words: LIDAR, 3D Image, MPPC, Planetary Explorer, Autonomous Vehicle

Nomenclature

- $D_r$: diameter of the receiver optics
- $h$: Planck’s constant
- $P$: probability
- $\lambda_i$: average number of photo-events
- $k$: number of occurrences of photo-events
- $n_i$: threshold
- $n_r$: received photons per pixel
- $N_{pix}$: number of pixels
- $R$: range
- $\rho_i$: target surface albedo
- $v$: frequency
- $\tau$: transmissivity of optics
- $\eta$: detection efficiency

1. Introduction

In recent years, many planetary explorers have been sent to the moon, planets, asteroids, and comets. The landing point selected for full-scale scientific observation and resource surveying does not necessarily coincide with a point where landing is easy. For this reason, a planetary explorer needs a sensor capable of acquiring a three-dimensional (3D) image to assess the topography of the landing site, avoid obstacles, and detect attitude. A Flash LIDAR sensor system can acquire 3D images from distances of hundreds of meters by emitting a diffuse laser beam over the field of view (FOV) of a 3D image sensor, which is a composite device in which pixels integrated with an avalanche photodiode (APD) and a distance-measuring circuit are arranged in an array. OSIRIS-Rex,† which was launched in 2016, is equipped with Flash LIDAR for guidance, navigation, and control (GN&C) just before landing in addition to the scanning LIDAR used for scientific observations, such as topography mapping of asteroids. NASA’s Autonomous Landing and Hazard Avoidance Technology (ALHAT) project is developing a system to quickly and autonomously identify safe landing sites for future planet landing gear GN&C. In ALHAT, Flash LIDAR‡ is positioned as an important sensor for obstacle detection.

This technology also has many other potential applications. A 3D image sensor is important for simultaneous localization and mapping (SLAM) when a rover is traversing a planetary surface. A spacecraft performing a rendezvous or docking in orbit, such as a cargo ship supplying the International Space Station, also requires a 3D image sensor to measure relative distance and relative attitude. The Japanese cargo ship HTV already has a mechanical scanning LIDAR for this purpose, and the SpaceX Dragon supply ship uses an ASC Dragon Eye Flash LIDAR system. Three-dimensional image sensor technology is also needed for autonomous vehicles or drones. Since 3D image sensors are a key technology for markets beyond the space industry, the competition in the LIDAR sector has become intense.

LIDAR systems that obtain a 3D image can be roughly divided into two types: scanning and flash. A scanning LIDAR system scans a narrow laser beam across the target, while flash LIDAR irradiates the FOV of a two-dimensional array sensor with a diffuse laser beam, as in digital imaging. Currently, scanning LIDARs are widely used for imaging on the ground. Since a narrow beam is used, long-range operation is possible, but the mechanical scanning mechanism is too complicated to increase the frame rate. In recent years,
a high-speed scanning LIDAR using an optical phased array has been proposed.\textsuperscript{41)} Against this background, the JAXA space exploration innovation hub is studying 3D image sensors for Flash LIDAR. The aim is to develop a general-purpose sensor for future space explorers and autonomous vehicles. The keys to this work are the development of an APD array, a read-out IC (ROIC) for time measurement, and a bonding technique to attach the APD array to the ROIC.

There are 3D image sensors for Flash LIDAR that use an APD in linear mode or a single-photon avalanche diode (SPAD) in Geiger mode. In the linear mode APD, the output current is proportional to the intensity of the light received; however, its multiplication factor $M$ is only about 100. On the other hand, $M$ for a Geiger mode SPAD is as high as 10\textsuperscript{5}, and it is possible to detect a single photon; however, the output current is not proportional to the light intensity received. MIT’s Lincoln Lab studied a 3D image sensor using a SPAD in 2002.\textsuperscript{5, 6)} The ASC Flash LIDAR mentioned earlier uses an APD in the linear mode.\textsuperscript{6)} Examples of SPAD arrays include the Si-SPAD Array from Photon Force, the InGaAs-SPAD Array\textsuperscript{7)} from Princeton Lightwave Inc., and the InGaAs-SPAD Array\textsuperscript{8)} from Hamamatsu Photonics. The SPAD type is an excellent sensor that has very high sensitivity and compensates for the insufficient light intensity of the diffuse laser beam in Flash LIDAR. However, it has a problem discriminating between laser photons and photons from interfering light sources, such as sunlight.

A multi-pixel photon counter (MPPC) silicon photomultiplier\textsuperscript{9)} is an APD that has both the linearity of linear mode and the sensitivity of Geiger mode. The technology of a MPPC sensor is based on having multiple SPADs as sub-pixels within one pixel. In principle, a MPPC can count as many photons as the number of sub-pixels. In this research, we have developed a prototype with a 1 k-pixel (32 $\times$ 32 pixels) MPPC 3D image sensor, which is the first in the world. In this paper, we report the results of developing the element technology with a small-scale circuit before fabricating a large-scale circuit.

The remainder of this paper is organized as follows. The budget for Flash LIDAR using this sensor is given in Section 2. An outline description of the sensor is provided in Section 3. An evaluation of the ranging circuit is described in Section 4. Our conclusions regarding the suitability of the system as a 3D imaging sensor are reported in Section 5.

## 2. LIDAR Budget

### 2.1. Obstacle detection sensor

Landers intended for scientific exploration and resource exploration on the moon need an obstacle detection sensor to avoid tumbling and damaging the structure of the body when landing. During the landing sequence of the SLIM,\textsuperscript{10)} small moon lander, the lander is capable of avoiding obstacles at altitudes of several hundred meters. The basic performance of an obstacle detection sensor required by such a lander is a range of 200 m or more, a viewing angle of 15\textdegree or more, a range-direction resolution of 10 cm or less, and a cross-range direction resolution of 50 cm or less. Therefore, a size of 128 $\times$ 128 pixels is required for the 3D image sensor. Furthermore, from the resolution in the range direction, the time resolution of the ROIC is required to be 666 ps or less.

Since Flash LIDAR laser pulses are diffuse, the laser energy that is allocated to each pixel is low. This makes the LIDAR budget design difficult. On the other hand, since the weight limitations for a planetary explorer are very strict, it is difficult to mount a large laser. The available laser output of the Hayabusa\textsuperscript{11)} and Hayabusa 2\textsuperscript{12)} is about 10 mJ/pulse.

#### 2.2. LIDAR budget

Flash LIDAR diffuses the laser energy into the FOV of the reception optics. Assuming that the laser energy is uniformly diffused, the number of photons received per pixel is given by

$$n_r = \frac{\tau D_r^2 P_t}{4 R^2 N_{pix} h \nu} P_t,$$

where, $\tau$, $D_r$, $P_t$, $N_{pix}$, and $\rho_t$ are the transmissivity of the optics, diameter of the receiver optics, range, transmission energy, number of pixels, and target surface albedo, respectively. According to Eq. (1) the number of photons received is 207 when the assumed LIDAR parameters are $N_{pix} = 128 \times 128$, $P_t = 10$ mJ, $\rho_t = 0.05$, $R = 200$m, $D_r = 20$ mm, and $\tau = 0.6$. The minimum receiving sensitivity of each pixel of the sensor should therefore be less than 207 photons in this case. For $R = 500$m with all other parameters remaining the same, the number of photons per pixel is 33. In this research, we assume that the longest distance for measurement is 500 m. Therefore, the minimum receiving sensitivity should be 30 photons or less.

### 2.3. Signal detection probability

In Geiger mode, the reverse bias voltage on the APD is higher than its breakdown voltage. Consequently, a large output current is generated by an electric discharge phenomenon even with the input of a single photon. (In this report this discharge phenomenon is called a “photo-event.”) Since this output current is a saturation current peculiar to the APD and is not dependent on the amount of incident light, it is impossible to read the light intensity from the current. The use of MPPC technology compensates for this drawback. A MPPC is composed of multiple Geiger mode APDs, and it can count photons by counting the number of photo-events generated by these APDs. Using the MPPC photon counting function, it is possible to discriminate between background light and the laser signal by utilizing a suitable threshold voltage.

When the number of photons received is $n_r$ and the detection efficiency is $\eta$, the number of photo-events on the MPPC can be approximated using Poisson’s distribution with the parameter $\lambda_r = n_r \eta$. Here, detection efficiency $\eta$ includes quantum efficiency, fill factor, and breakdown efficiency. When the photo-events do not overlap on the same sub-pixel, the probability of signal detection is expressed by

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The 3D image sensor is composed of two layers: a sensor layer having a 32 × 32 pixel (1,024 pixels) MPPC and an ROIC layer containing pixel circuits corresponding to each pixel. The MPPC in the sensor layer is vertically connected to the pad of the ROIC metal layer by flip-chip bonding for each pixel. Figure 1 shows a photograph of the prototype sensor chip, in which a MPPC chip is bonded to a 6.2 × 6.2 mm ROIC chip. The size of one pixel (MPPC) is 100 × 100 µm and each pixel is composed of 12 sub-pixels (SPADs) placed at a 25-µm pitch. Each sub-pixel has a metal quenching resistance with an excellent temperature coefficient. This resistor is connected in series with the ROIC input as a passive quench circuit. When Geiger discharge occurs in a sub-pixel, the discharge current causes a voltage drop by flowing through the quenching resistance of the passive quench circuit. This voltage drop causes the APD reverse bias voltage to drop and stop the Geiger discharge. The Geiger discharge current is input to the pixel’s circuit in the ROIC layer. The circuit in the ROIC measures the time of flight (ToF) of the laser pulse using a time-to-digital converter (TDC) and the pulse width by time over threshold (ToT). The peak current pulse depends on the number of photo-events. The peak current pulse is estimated using the correlation between pulse height and pulse width measured in the pixel circuit.

3.2. MPPC array

The MPPC array of the prototype sensor was based on a silicon MPPC S13720 commercially available from Hamamatsu Photonics K.K. This sensor does not require cooling and can operate at room temperature. The size of one MPPC pixel is 100 × 100 µm. This one pixel consists of 12 sub-pixels of size 25 × 25 µm and has 12 levels for photon counting. The main characteristics of the pixel are a multiplication factor of 1.1 × 10⁶, a sensitivity wavelength region of 350–1,000 nm, and a detection efficiency of 7% at a wavelength of 900 nm. The detection efficiency includes quantum efficiency, fill factor, and breakdown efficiency. Additional development was required to realize the MPPC 3D image sensor, including 100-µm narrow-pitch electrical connection and large-area uniformity. Through these developments, we have been able to improve the sensor mounting and wafer manufacturing processes.

The I-V curve of the sensor is shown in Fig. 2. This curve is obtained by applying a bias voltage to 1,024 MPPCs in a 32 × 32 pixel array after flip-chip bonding with the ROIC. The horizontal axis represents the reverse bias voltage applied to the MPPC, and the vertical axis represents the dark current. Initially, the dark current increases gradually as the reverse bias voltage increases. However, when the reverse bias voltage exceeds approximately 60 V, the current rapidly increases because of breakdown of the diode. The region exceeding the breakdown voltage is the Geiger mode, and the reverse bias voltage beyond the breakdown voltage V_{br} is described as the excess bias. The breakdown voltage of each pixel is described in detail in Section 4.

3.3. ROIC

The ROIC is manufactured using a 0.18-µm CMOS process. The ROIC consists of a serial peripheral interface, a phase lock loop (PLL), a clock repeater, and pixel circuits. The serial peripheral interface (SPI) reads data from each pixel. The PLL generates a high-speed clock. The clock repeater amplifies and distributes the clock. The pixel circuit functions as a TDC and measures pulse width using the ToT method. The circuit composition of the ROIC is shown in Fig. 3(a), and the pixel circuit is shown in Fig. 3(b). The power supply voltage is 1.95 V.

The PLL generates a signal at 16 times the frequency of the external reference clock to provide a high-speed clock. There are two kinds of high-speed clock: FAST00 and FAST90. FAST90 has the same frequency as the FAST00.
but its phase differs by 90°. In the sensor evaluation experiment described in Section 4, the PLL generates a 768 MHz clock using 48 MHz input externally. The clock signal is propagated by clock repeaters, first in the x direction and then in the y direction, to reach the pixel circuit. The repeaters are inserted every four pixels to prevent degradation of the clock signal during propagation in the y direction. In order to reduce power consumption, the high-speed clocks (i.e., FAST00 and FAST90) cease to oscillate while ARMIN is low, and hence, the pixel circuits are fully deactivated.

The data of the pixel circuit can be read out using the SPI by designating the coordinates of the X and Y decoders. All pixel circuits are divided into four blocks that consist of 16 x 16 pixels. The data can be read from each block in parallel. The readout clock frequency can be more than 30 MHz for a frame rate of 1 kHz or more.

The pixel circuit shown in Fig. 3(b) is composed of a bias adjustment circuit, a TDC circuit, and a pulse-width measurement circuit. The bias adjustment circuit receives the current from the APD at low input impedance and outputs it to the comparator with high impedance through impedance conversion (current voltage conversion). A reference voltage VREF2 can be set up for every pixel to compensate for the variation in the breakdown voltage caused by the manufacturing yield of the MPPCs. VREF2 can be adjusted by several hundred millivolts with a 4-bit DAC. However, since the MPPC yield was sufficient for the experiment reported here, a uniform voltage is applied to all pixels. Another reference voltage VREF optimally adjusts the input potential to the comparator.

The TDC is a 15-bit counter that is driven by the high-speed clocks, FAST00 and FAST90. By combining the phases of FAST00 and FAST90, a quarter-phase resolution of the clock is achieved. Two bits on the least significant bit (LSB)-side of the counter represents this combination of phases. The next four bits are toggle counters. The last nine bits (i.e., most significant bit side) are M series code generation sequences. The M series code circuit is utilized in order to suppress the circuit area. However, because all flip-flops operate simultaneously in the M series code circuit, the current consumption is large. By placing the M-sequence code sequence behind the 4-bit toggle counter, its operating frequency is reduced to 1/16th. The counter counts up when the ranging gate signal (ARMIN) is high. The count-up operation stops when ARMIN falls to low, or when the comparator detects Geiger discharge current from the MPPC. Therefore, this ROIC can measure a maximum distance of 1,600 m with a resolution of 49 nm using a high-speed clock at 768 MHz.

The pulse-width measured utilizing the ToT method is used for estimating the peak value. The capacitor of the comparator input part extends the pulse width for the pulse counter. The pulse width is measured using an 8-bit toggle counter.

4. Experimental Evaluation of the Sensor

4.1. Experimental apparatus

The experimental apparatus for evaluating the sensor is shown in Fig. 4. The package type of the sensor is chip-on-board. The evaluation board on which the sensor is mounted provides a power supply voltage and various bias voltages, enables writing and reading data, and outputs a laser firing trigger. The clock generator (CG 635) supplies the 48-MHz reference signal of the PLL to the evaluation board. The delay-pulse generator (DG 645) controls the laser emission timing and the distance-measurement gate timing of the sensor with reference to the laser trigger from the evaluation board. The wavelength, pulse width, and peak power of the pulse laser (PLP-10-850) are 850 nm, 70 ps, and 100 mW, respectively. The laser pulse propagates through a square-core fiber and forms a square top-hat beam (plateau flat rate <0.3) with dimensions of 363 x 363 µm on the sensor surface. Application software on a personal computer writes data to the sensor and displays the measurement data.

4.2. Evaluation of the ROIC

Important components of the ROIC are the PLL, pixel circuit TDC counter, and pulse-width counter. In this section,
the results of PLL evaluation and the counters are described. The PLL outputs the charge pump voltage and the monitor clocks for the input and output. Figure 5 shows the frequency characteristics of the charge pump voltage and the phase difference of the monitor clocks. The average and standard deviation of the phase difference are indicated in the figure. As the input frequency increases, the charge pump voltage increases and nearly reaches the power supply voltage at 86 MHz. The phase difference rapidly increases at 86 MHz and the PLL is locked off. It was confirmed that the PLL can be locked up to an input of 85 MHz. Therefore, the PLL has the capability of generating a 1.36-GHz (86 MHz/C_2) signal for use as the high-speed clock. The ROIC can input a counter stop trigger, called a test pulse (TP), from the outside. A TP stops 32 pixels in the y column simultaneously and can be used to electrically check the time measurement performance of the pixel circuit. In the experiment, the delay pulse generator inputs the ranging gate pulse and TP to the evaluation board. Figure 6 shows the relationship between the counter value of each pixel circuit and the delay of the TP from the ranging gate pulse. The counter driving clock of the pixel circuit is 768 MHz, and the time resolution is 326 ps. We can see that the (0, 0), (15, 15), and (31, 31) pixels count up correctly. A fluctuation with a period of 1.3 ns appears within the standard deviation, which corresponds to a cycle of 768 MHz. The reason for this fluctuation is that the duty ratio of the clock is not exactly 50%. Overall the standard deviation is less than 600 ps. Since the test using the TP includes the delay due to the length of the wiring and the delay in the repeater, the intrinsic delay of each pixel must be evaluated by light input.

4.3. Dark rate

Because the distribution of breakdown voltage and dark rate of each pixel represent the distribution of sensitivity and noise, these evaluations are important for a 3D image sensor. In the 1-k pixel sensor, it is not possible to determine the I-V characteristics of a single pixel. Therefore, when the reverse bias voltage that is applied to all pixels increases, the voltage at which breakdown starts in an individual pixel is defined as V_{br}. A contour diagram of the V_{br} distribution at room temperature is shown in Fig. 7. The horizontal direction of the screen is the x direction and the vertical direction is the y direction. We can see that V_{br} is tilted in the y direction. A difference in V_{br} of about 1 V occurs between y = 0 and y = 31. The cause of this voltage tilt is that the root of the wiring of the bias voltage input to each pixel has a combed-teeth shape from the y = 0 side to the y = 31 side. Therefore, the wiring root of the bias should be improved by replacing the combed-teeth with a mesh. Figure 8 shows the results of measuring the dark rate of each pixel. From the V_{br} distribution measured, the reverse bias voltage was set to −65 V so that the excess bias of all pixels was more than 1 V. The detection threshold is 104 mV. The dark signal is measured by opening the ranging gate without light input and detecting the signal. The dark rate is calculated as the ratio of the number of detections of the dark signal to the integration time of the ranging gate. The ranging gate time is 200 ns, and the number of repetitions of the measurement is more than 60,000. The dark rate shows the same tendency as the distribution of V_{br}, and there is a difference of about 70 kHz in the y direction. This indicates that sensitivity decreases as excess bias decreases from y = 0 to y = 31.
4.4. Capability of time measurement

The characteristics of a 3D image sensor are determined by the time measurement accuracy of each pixel included in the MPPC. Figure 9 shows the average values and standard deviations of time measurement using three pixel counters on the diagonal. The bias voltage, number of input photons, and detection threshold are $-65\,\text{V}$, 1,000, and 227 mV, respectively. As described in Section 3, the high-speed clock for the counter propagates in the $y$ direction after propagating through the clock repeater in the $x$ direction from the PLL. Therefore, $(0, 0)$ is the pixel closest to the PLL and $(31, 31)$ is the farthest. From the results shown in Fig. 9, we can see relative offsets of 4 ns on $(15, 15)$ and 6 ns on $(31, 31)$. The cause of the offset is the propagation delay of the clock repeater. The standard deviation for each pixel is less than 600 ps. This is same as the results obtained using the TP (Fig. 6), so the flip-chip bonding of the APD has no effect.

Figure 10 shows the results of investigating the delay offset of all the pixels. The number of photons incident on one pixel is 1,000. The delay offset increases from $(0, 0)$ to $(31, 31)$. The maximum delay distribution is about 6 ns, which is the same as the result shown in Fig. 6. Since the high-speed clock repeaters for the counter are placed at 4-pixel intervals, we can see the collective delay changes for every $4 \times 4$ pixel block. Figure 11 shows distribution histograms for the standard deviation of the time measurement of all the pixels for two numbers of incident photons. The horizontal axis represents the standard deviation of a counter, and the vertical axis represents the corresponding number of pixels. The LSB of the counter is 326 ps. When 1,000 photons are incident, the distribution is unimodal, centered on 1.5 LSB. When the number of incident photons is 60, the center of standard deviation distribution shifts to 2.5 LSB. The width of the distribution is also larger than in the case...
with 1,000 photons. Non-uniformity of the excess bias (Section 4.3) is one of the reasons for the change in the width of the standard deviation distribution. In the case of a small number of incident photons, the jitter of the Geiger discharge with low excess bias is large. This is considered to be the cause of the shift in distribution center.

In the pulse detection circuit, because of the threshold, the detection timing varies depending on the pulse intensity. Due to the characteristics of the amplifier, the detection timing also depends on the number of incident photons. On the other hand, the number of photo-events in the MPPC is reflected in wave height. Figure 12 shows the average and standard deviation of measurement time, when the number of incident photons on (0, 0) is changed. We can see that the measurement time and standard deviation rapidly increase in the region where the number of photons is 100 or less. When designing the Flash LIDAR system, this point should be considered.

4.5. Intensity measurement

This is one of the features of this sensor that results from utilizing the MPPC as its detector. As already explained in Section 3, the pulse width in the pixel circuit is measured using the ToT method in order to estimate the peak. Figure 13 shows the output average value of the intensity counter as a function of the number of photons incident on (0, 0). The pulse width count increases as the number of photons increases. When the detection threshold is low, the pulse width increases. However, the overall shape of the curve does not change. So, we can see that the signal strength can be estimated utilizing pulse width. The curve has an inflection point near 200 photons; however, it has not reached saturation. The reason for this inflection point is not clear. The detection efficiency of the MPPC used in this sensor is 0.07 at a wavelength of 850 nm and the number of sub-pixels is 12. To generate a photo-event on every sub-pixel of this MPPC (12 photo-events), 171 photons are necessary. Since the inflection point is close to the number of photons and the position of the inflection point, there appears to be a relation. The reason why the counter does not saturate is thought to be due to multiple photo-events overlapping on one sub-pixel. The photo-events generated are distributed to the 12 sub-pixels utilizing a natural number partition; therefore, an excessive number of photons are needed to induce a photo-event at every sub-pixel simultaneously.

4.6. Threshold and detection probability

As described in Section 2.3, the probability of signal detection from the MPPC depends on the threshold \( n_{th} \). From Eq. (2), it is estimated that the signal detection probability changes stepwise with respect to the threshold level. Figure 14 shows the relationship between threshold and signal detection probability when 60 photons are incident on (0, 0). The horizontal axis represents the threshold voltage for signal detection in the pixel circuit. More than 2,000 laser shots are used to acquire one point. Here, signals detected after a delay of 4 ns or more from the laser incidence timing are not counted and are considered to be after-dark phenomena. The theoretical value for each photo-event estimated from Eq. (2) is shown on the right side of the figure. The curve of the detection probability shows a staircase shape re-
reflecting the number of photo-events. The steps of detection probability are almost the same as the theoretical values.

Using this characteristic of the MPPC, it is possible to distinguish real signals from dark events. Most of the photo-events due to dark events are at the 1-Pe level. Therefore, most dark events can be excluded using a 2-Pe level threshold. Dark events caused by sunlight can also be eliminated with an appropriate threshold.

5. Conclusion

We produced and evaluated a prototype $32 \times 32$ pixel 3D image sensor for Flash LIDAR using a MPPC capable of photon counting. The pixel circuit achieves a time resolution of 326 ps. The sensitivity and time resolution of the prototype sensor are sufficient for it to serve as an obstacle detection sensor on a lunar or planetary lander. In future work, we will evaluate the radiation tolerance of the sensor as a mounted item and increase the number of pixels.

Flash LIDAR sensors that can obtain 3D images with excellent time simultaneity can be useful in many applications, including the control of autonomous vehicles. We hope that this sensor will be utilized in many fields and contribute to their development.

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