Geiger-mode three-dimensional image sensor for eye-safe flash LIDAR

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Abstract Explorers attempting to land on a lunar or planetary surface must use three-dimensional image sensors to measure landing site topography for obstacle avoidance. Requirements for such sensors are similar to those mounted on vehicles and include the need for time synchronization within one frame. We introduce a 1K (32 × 32)-pixel three-dimensional image sensor using an array of InGaAs Geiger-mode avalanche photodiodes capable of photon counting in eye-safe bands and present evaluation results for sensitivity and resolution.

Keywords: image sensor, LIDAR, Geiger, InGaAs, SPAD

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

1. Introduction

In recent years, many probes have been sent to the moon, planets, asteroids, and comets for science observations. Many of these probes carry light detection and ranging (LIDAR) systems that can measure ranges from tens to hundreds of kilometers [1, 2, 3, 4, 5]. We have already developed the customized IC “LIDARX” for a receiver of long-range LIDAR and it will be installed on the Martian Moons Explorer (MMX) [6]. On the other hand, in the case of a spacecraft landing on the moon or planet for scientific observation or resource exploration, spacecraft landing sites are generally unexplored sites, which may not always be ideal for landing. Pinpoint landings on such unexplored sites require three-dimensional (3D) images for terrain measurements, obstacle avoidance, and detection of attitude with respect to the ground immediately before landing. 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 G&KC [7, 8, 9]. In ALHAT, Flash LIDAR [10, 11, 12, 13] is positioned as an important sensor for obstacle detection. As a typical example, OSIRIS-REx, launched in 2016, uses Flash LIDAR for guidance, navigation and control [14, 15, 16, 17].

Flash LIDAR is a sensor that captures 3D images in a manner similar to flash photography, by diffusing and irradiating laser pulses onto the field-of-view of a camera that has a 3D image sensor [18, 19, 20, 21]. The pixel array on this sensor integrates an avalanche photodiode (APD) and a time-to-digital converter (TDC) [22, 23].

The JAXA Space Exploration Innovation Hub is engaged in joint research on 3D image sensors with the aim of developing obstacle detection sensors for planetary explorers [24, 25] and general-purpose sensors that can be applied to autonomous vehicles. For high general versatility, APD adopts InGaAs, which is sensitive to eye-safe wavelengths [26]. Because flash LIDAR irradiates a diffused laser light, the amount of received light is relatively low compared with a scanning LIDAR. Thus, Geiger-mode [26], which is capable of photon counting, is adopted as the APD operational mode. There are few 3D image sensors using InGaAs Geiger-mode APDs, other than a device by MIT Lincoln Laboratory [27], Princeton Lightwave [28, 29] and one by our research group, Hamamatsu Photonics [30]. To increase the number of pixels in the future, in this study we reduced the pixel spacing from 100 μm as in Ref. [30] to 55 μm by means of changing the pixel circuit. As a result of this improvement, the time resolution and the standard deviation of timing were improved.

Section 2 describes the basic structure, circuit configuration, and functions of a prototype 3D image sensor with 55-μm pixel spacing and 1K (32 × 32) pixels. Section 3 presents the results of evaluations for sensitivity and time measurement accuracy.

2. Sensor outline

2.1 APD array

The 3D image sensor (Fig. 1) comprises two layers, an upper layer with 1024 InGaAs Geiger-mode APDs (GmAPDs) arranged in a 32 × 32 pixel array, and a lower read-out integrated circuit (ROIC) layer having a TDC circuit for each pixel. The sensor-layer GmAPD is back-illuminated and connected to a metal pad on the ROIC layer by an indium bump. The chip size is 4.6 × 4.6 mm and it is mounted directly on a printed circuit board by the chip-on-board method. The wavelength sensitivity range, effective area diameter, and sensor-layer InGaAs–GmAPD pixel spacing are respectively 900–1690 nm, 9 μm, and 55 μm. Each effective area has a surrounding isolation trench to prevent optical crosstalk between adjacent pixels and to block surface leakage currents.

Geiger discharge current from the APD enters the pixel circuit. The GmAPD requires a quench circuit to halt Geiger discharge. However, the pixel circuit in this prototype does not have a quench circuit, then bias voltage is applied as

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pulses. In addition, the layout is designed to allow a quench resistor of several hundred kΩ to be inserted for a passive quench circuit. Specifically, a DC bias (VKDC) below the breakdown voltage is continuously applied to the APD, and a pulsed bias (VKpulse) synchronized with the ranging gate (<8 µs) is superimposed using a bias tee.

2.2 ROIC

The ROIC, which is fabricated by a 0.18-µm CMOS process, consists of a phase lock loop and a distribution circuit for a 1-GHz high-speed clock, a TDC circuit for each pixel, and a serial peripheral interface (SPI) for reading data from each pixel. In Reference [30], a 200 MHz clock was delivered to the pixels and the time resolution was fine-tuned by a delay chain within each pixel. In contrast, the circuit shown in Fig. 1 improved the detection timing variation and reduced the size of the circuit by directly distributing the high-speed clock. The ROIC power supply voltage is 2.0 V. The 1-GHz high-speed clock (FAST00) used as the drive clock for the TDC circuit is generated by multiplying the external 62.5-MHz reference clock by 16 in a phase-locked loop (PLL). FAST00 is distributed to each pixel together with FAST90, which has the same frequency and a 90° phase difference. The clock is distributed in the X-direction by a FANOUT circuit with equal-length wiring, then propagated in the Y-direction to reach each pixel. In Y-direction propagation, a repeater inserted every four pixels prevents waveform deterioration. To lower power consumption, FAST00 and FAST90 are delivered to pixels only when the ranging gate signal (ARMING) is set to high.

Pixels are divided into four 16 × 16 blocks (A–D), and the pixel data of each block is read out in parallel via the SPI. The read clock is up to 40 MHz and the frame rate is up to 1 kHz.

Pixel TDC circuits operate when ARMING is set to high, and the TDC stops when the ARMING is set to low or the comparator detects a signal from the GmAPD (a photo event). The TDC is a 15-bit counter, with the two least-significant bits used in combination with FAST00 and FAST90 phases to provide a time resolution of one-quarter the clock cycle. The next 4 bits are a toggle counter, and the 9 most-significant bits are an M-sequence code generation circuit, which has a small circuit area but consumes large current because all flip-flops operate simultaneously. Therefore, the operating frequency of the M-sequence code generation circuit is reduced to 1/16 by using the lower 4 bits as the toggle counter.

3. Experimental evaluation

3.1 Experimental equipment

The prototype 3D image sensor is sealed in a vacuum vessel and cooled to −20°C by a Peltier cooler. The original 62.5-MHz PLL signal is supplied from a clock generator (CG635), and the emission timing of laser pulse, the ranging gate (ARMING), and the pulsed bias (VKpulse) are supplied by a delay-pulse generator (DG645). The pulsed bias (VKpulse) is superimposed 200 ns before the ranging gate. The wavelength and the pulse width of the laser (PLP-10-1550) used in these experiments were 1540 nm and 70 ps, respectively. Laser light is incident on the sensor surface by a single-mode fiber and a microscope objective lens. The footprint of the laser light on the sensor surface is 20 µm in diameter. Assuming that the photons in the footprint have a Gaussian distribution, 40% are incident on the effective APD area, because its diameter is 9 µm.

3.2 Breakdown voltage

In a 3D image sensor that applies a common bias voltage to all pixels, the breakdown voltage distribution in the image plane represents the sensitivity distribution there [31]. In this report, the minimum bias voltage VK (= VKDC + VKpulse) at which the Geiger discharge current is detected in the pixel circuit is defined as the breakdown voltage Vbr of the pixel. Figure 2 shows the mosaic map of the Vbr distribution measured at −20°C in the image plane. The DC bias VKDC and the pulse bias VKpulse are 38.0 V and 0–5 V, respectively. The Vbr of image plane pixels is distributed between 62.1 and 62.8 V, but there is an area near the upper right corner of the image plane where Vbr is low. In this device, GND pads for supplying the ground level of the bias voltage VK from the outside are concentrated near X = 15 to 31 at the top.
The gradient of the GND potential is thus formed from the upper right (31,0) to the lower left (0,31) of the image plane, so that the bias voltage of the image plane is inclined. Figure 2 shows that the area near the lower left of the screen is less affected by this incline. For example, the standard deviation of $V_{br}$ in the rectangle region from (2,22) to (11,31) is less than 0.1 V. This value is likely due to fabrication yield of InGaAs–GmAPD pixels. Improved arrangements of power and ground pads should be investigated in the future.

### 3.3 Sensitivity of GmAPD

The I–V (current–voltage) curve measurement is a typical evaluation method for APDs. However, in this 3D image sensor, individual I–V characteristics of the pixel GmAPD cannot be measured. Therefore, we measured dependence of the photo event detection rate on the number of incident photons using the ROIC pixel circuit. Here, the median value of all data of the individual pixel counter $\pm$16 counts (4 ns) is defined as a photo event caused by laser light. However, data with a minimal value for the pixel counter (an event due to dark current before the ranging gate) or a maximal value (undetected) are excluded from data processing. Figure 3 shows the detection rate of photo events detected at (0,0), (0,1), and (1,0) by laser incidence on the (0,0) pixel. The number of data at each point is processed from 1200 shots. The bias voltage $V_K$ is 64 V. Because Fig. 2 shows the $V_{br}$ of (0,0) as 62.6 V, Fig. 3 shows the sensitivity at an excess bias of 1.4 V. The photo-event rate reaches nearly 100% with about 60 photons. When an event due to dark current is sufficiently small, the photo event detection rate with the number of incident photons $n$ is expressed as $1 - (1 - p)^n$, where $p$ is the photon detection probability (PDP). We estimated the PDP of (0,0) in the region $3 < n < 60$, because the number of photons is relatively large, and the photo event detection rate is not saturated. The white circle shows the PDP. From this result, we can estimate that the PDP at (0,0) with excess bias 1.4 V is 8%–9%.

In contrast, the detection rates at (0,1) and (1,0) do not correlate with the number of incident photons at (0,0) and are around 2% or less. There is thus no interference with adjacent pixels. It can be seen that we succeeded in reducing the pixel spacing from 100 [30] to 55 without increasing the interference between adjacent pixels.

### 3.4 TDC Accuracy

Figure 4 shows the time-offset distribution for photo event detection in the image plane by laser light incidence on each pixel. The number of photons incident on one pixel is 1000 or more, and there are about 50 laser shots on each pixel. The bias voltage $V_K$ is +62.5 V. As described in section 2.2, the high-speed clock for driving the TDC is distributed in the X-direction by a FANOUT circuit with equal-length wiring, then propagated in the Y-direction to reach each pixel. Propagation delay is nearly uniform in the X-direction and about 10 counts in the Y-direction. Since the high-speed clock repeater is placed every four pixels, a change in delay is seen every four pixels. We can find pixels where TDC behavior malfunctions in columns $X = 22$, 26, and 27.

Figure 5 shows the pixel TDC response. The incident photon counts and bias $V_K$ are the same as in Fig. 4, the plotted data are average values, and the standard deviation is about 600 laser shots. Because the TDC count linearly increases at each pixel, it can be verified that the TDC counter and phase circuit operate very well. The standard deviation of those pixels is about 300 ps (1.2 count). The standard deviation of the detection timing was improved from about

![Fig. 3](image3.png) InGaAs-GmAPD detection rate, measured using a pixel circuit. The breakdown voltage at (0,0) is 62.6 V, and the bias voltage is 64 V.

![Fig. 4](image4.png) Delay offset distribution at each pixel. The high-speed clock generated by the PLL is distributed in the X-direction by the FANOUT circuit in the same phase, then propagated in the Y-direction (top to bottom). The bias voltage is 62.5 V.

![Fig. 5](image5.png) Pixel TDC response to the 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 62.5 V. Data are averages of over 600 shots.
450 ps [30] to about 300 ps by means of changing from the delay chain of individual pixel to distribute a fast clock from the PLL. Therefore, this pixel circuit achieves a reduction in the dispersion of the detection timing and a reduction of the circuit area to about one quarter. Because the clock propagates in the Y-direction, pixels (15,15) and (15,31) have relative time offsets from (0,0) of 1 ns and 2 ns, respectively.

4. Conclusion

We prototyped a 32 × 32 pixel 3D image sensor for flash LiDAR using an InGaAs-GmAPD with sensitivity in eye-safe wavelengths. The prototype sensor has a 250-ps time resolution and sensitivity capable of detecting a single photon. There was no increase in interference with adjacent pixels due to the narrowing of the pixel spacing to 55 μm. Its sensitivity and time resolution are sufficient for use in lunar or planetary lander obstacle detection sensors. In the future, we plan to improve the sensor filling factor and to increase the number of pixels in the image plane.

Flash LiDAR that can obtain 3D images with excellent time simultaneity can be useful in many applications. We hope that this sensor will be utilized in many fields and contribute to their development.

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