A Time-Of-Flight Image Sensor with Sub-mm Resolution Using Draining Only Modulation Pixels

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***Abstract*— This paper describes new TOF measurement technique for high range resolution of the order of sub-mm or several tens of um. For the distance caliculation, impulse response of photocurrent by means of very short light pulse is used. A draining-only modulation pixel provides high response and loss-free electron integration. The test chip fabricated in 0.11 um CIS technology demonstrates modulation contrast is measured to be 85%. The average range resolution is measured to be 210 um at measurable range of 50 mm.**

I. Introduction

Recently, various indirect Time-of-flight(TOF) range imagers are presented [1]–[4]. However, their range resolutions are limited to several millimeters. To apply the TOF sensors in microscopic region, such as 3D microscope or nondestructive inspection for miniature devices, sub-millimeter or more accurate range resolution is desired.

Indirect TOF measurements imagers can be classfied by driving manners of a light source: continuous wave [1], [2] and pulsed illumination [3], [4]. Their range resolution is determined by signal intensity and a modulation frequency or pulse width. To attain the resolution of $<$ 100 um, for example, the required modulation frequency is more than 350 MHz, even if accumulated charge is 10^6 e- in the former case. For latter case, the pulse width of $<$ 1 ns is necessary. Realization of light sources such a high modulation frequency or short pulse without any distortion is difficult. The distortion causes a large error in TOF measurement results.

This paper introduces a new TOF measurement technique using very short light pulse and photocurrent response. If the light pulse is assumed to be an impulse, distortion of a light source is negligible and the photocurrent response can be used for the range measurement. The photocurrent response and modulation characteristic become high speed by using draining only modulation(DOM) pixels [5], [6].

II. Proposed TOF measurement principle

Fig. 1 shows the timing diagram of proposed TOF measurement principle. A short pulse with about a hundred picoseconds is emitted to a target object, the reflected light generates photocurrent, I_{ph}, at a photodiode. When the response of photocurrent is assumed to be a linear equation as

$$I_{ph} = \begin{cases} 0 & (t < t_d) \\ \frac{I_M}{T_0}(t-t_d) & (t_d \le t < T_0 + t_d) \\ I_M - \frac{I_M}{T_0}(t-t_d) & (T_0 + t_d \le t < 2T_0 + t_d) \end{cases} \quad (1)$$

where, I_M, t_d are a peak photocurrent, and a delay time(=time of flight), respectively.

For $T_1 - T_0 < t_d \le T_1$, accumulated charges, N_1, N_2 and N_3, which are modulated by the time window(TW) (1), TW(2) and TW(3), are given by

$$\begin{aligned} N_1 &= \int_{t_d}^{t_d+2T_0} \frac{I_M}{qT_0}(t-t_d)dt \\ &= \frac{I_M \cdot T_0}{q} \end{aligned} \quad (2)$$

$$\begin{aligned} N_2 &= \int_{t_d}^{T_1} \frac{I_M}{qT_0}(t-t_d)dt \\ &= \frac{I_M}{2qT_0}(T_1 - t_d)^2 \quad (3) \\ N_3 &= 0 \quad (4) \end{aligned}$$

where q is elementary charge. The N_3, which is modulated by TW(3) is used in order to cancel an offset of common undesired signal. If the generated charge is perfectly drained outside the time window, the N_3 equals zero.

By solving the Eqs. (2)-(4), the time of flight, td, is given by

$$t_d = T_1 - T_0\sqrt{2r} \quad (5)$$

where, the signal charge ratio, r, is defined by

$$r = \frac{N_2 - N_3}{N_1 - N_3} \quad (6)$$

Ideally, the r takes a value between 0 and 0.5. The distance to a object, L, is given by

$$L = \frac{c}{2}\left(T_1 - T_0\sqrt{2r}\right) \quad (7)$$

where, c is the velocity of light. When the T_1 is set to T_0, measureable distance range is given by

$$0 < L \le \frac{c}{2}T_0 \quad (8)$$

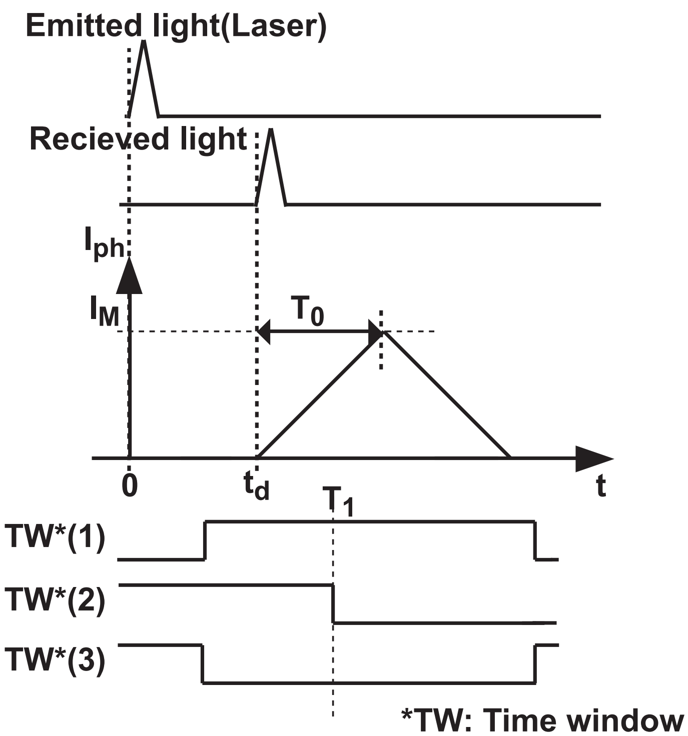

Fig. 1. Timing diagram of the proposed TOF measurement.

If shot noise is dominated and background light is zero, the measurement accuracy, σ_L, is given by

$$\sigma_L = \frac{cT_0}{2}\sqrt{\frac{1+r}{2N_1}} \tag{9}$$

Since the T_0 shown in Fig.1 is determined by the photodiode response T0, higher range resolution needs high-speed charge transferring and high handling capacity. For example, when T_0 and N_1 are 100 ps and 10^6, respectively, the resolution is calculated to be below 13 um at the measurable range of 15 mm.

Here, the photocurrent response is assumed to be a linear equation. However, the actual response is more complicated, and modeled by a hign order equation. If we use a high order equation, the target distance is derived in the same manner as Eq.(1-7). The more accurate equation may provide a wider measurable range, which is under study.

III. Proposed Pixel

Figs. 2 and 3 show the proposed pixel configuration and structure of the DOM detector [5], [6]. In the DOM detector, when a draining gate(TD) is opened, all of generated electrons at photodiode are drained out. While the TD is closed, generated electrons are transferred into a floating diffusion(FD). The charge transfer and draining are controlled by lateral electric field. From the operation, it is equivalent that PD and FD are separated by a virtual switch. Since the DOM detector

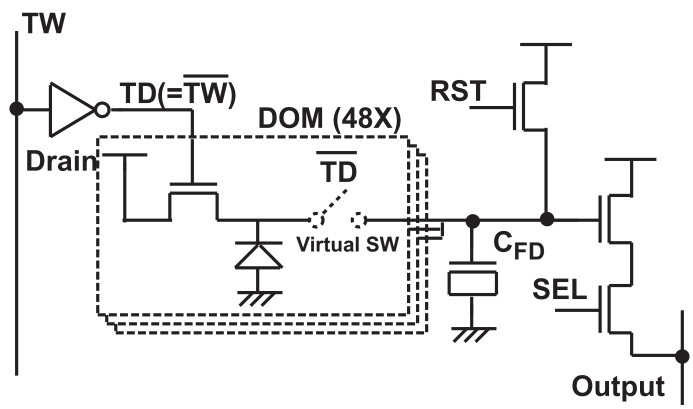

Fig. 2. Pixel schematic.

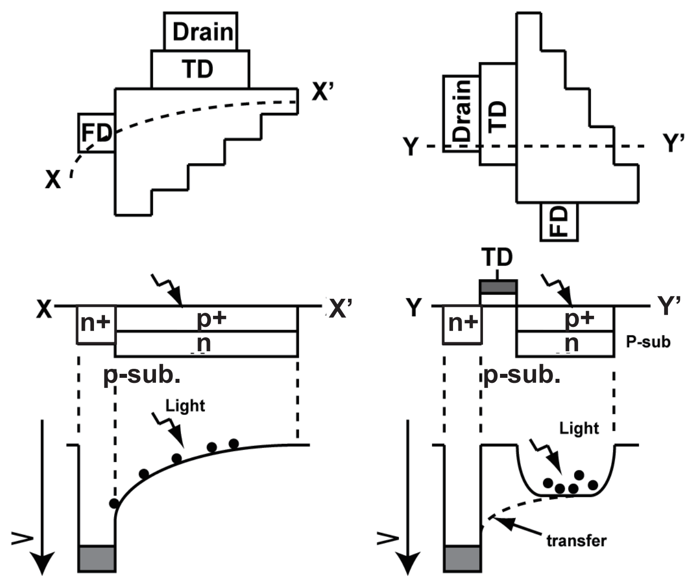

Fig. 3. DOM structure.

does not have any transfer gate in signal path, high-speed charge modulation and loss-free repetitive accumulation can be achieved. Signal charge is directly transferred to a FD, which has large capacitance($>$100fF) by adding a MOS capacitor, in order to enhance handling capacity. To satisfy both high-speed charge transfer and high sensitivity, unit size of the DOM detector is diminished to 2.8 um $\times$ 2.8 um. Therefore, 38 detectors are arrayed in the pixel size of 22.4 um $\times$ 22.4 um and the rest of pixel area is filled by MOS capacitors and in-pixel circuits.

The operation of the test chip is shown in Fig.4. In the proposed TOF measurement, three signals acquired with different phases of TD are necessary. Since the DOM pixel obtains one-phase signal by a single measurement, N_1, N_2, and N_3 are accumulated and read out in series.

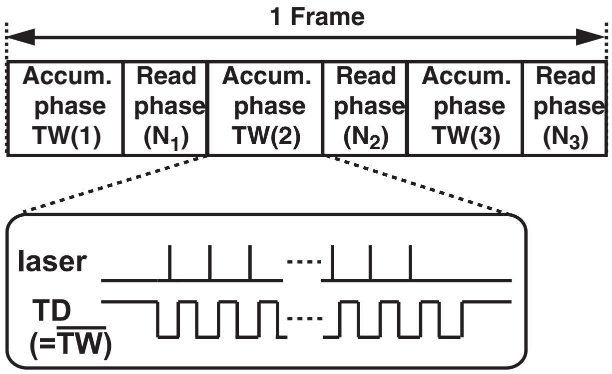

Fig. 4. Timing sequence.

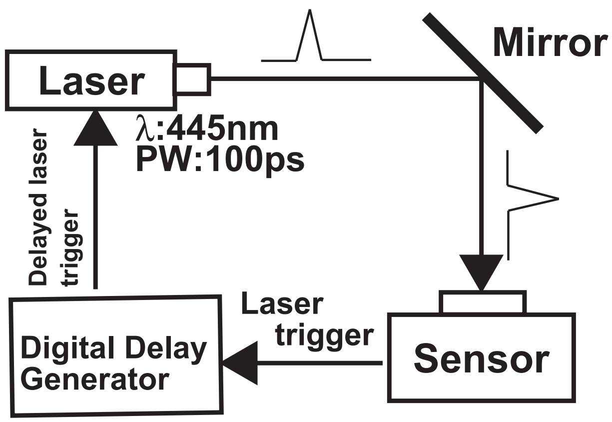

Fig. 5. Measurement setup.

IV. Experimental Results

To demonstrate the performance of proposed techniques, we developed a test chip with the proposed pixel fabricated in a 0.11um CIS technology.

Fig.5 shows the setup for the measurements of Figs.6-7. The sensor board provides a laser emission trigger to a 445nm laser via a digital delay generator. The DDG can accurately control the delay time of laser trigger. In the measurements, the number of repetitive accumulation is set to 4×10^4, and repetition frequency is 7.5 MHz. Unlike Fig.1, the rising edge of TW pulse is used.

Fig.6 shows normalized pixel outputs: N_1, N_2, N_3, and the differential value of the N_2 as a function of delay time, where the differential value corresponds to the photocurrent. The modulation contrast is measured to be 85%. Fig. 7 shows measurement results of the measured equivalent distance and range resolution. Since the change of delay time is equivalent to change of target distance, horizontal axis is expressed as equivalent target distance. The non-linearity is below 5 %FS at 50mm range. The average range resolution is measured to be less than 210 um.

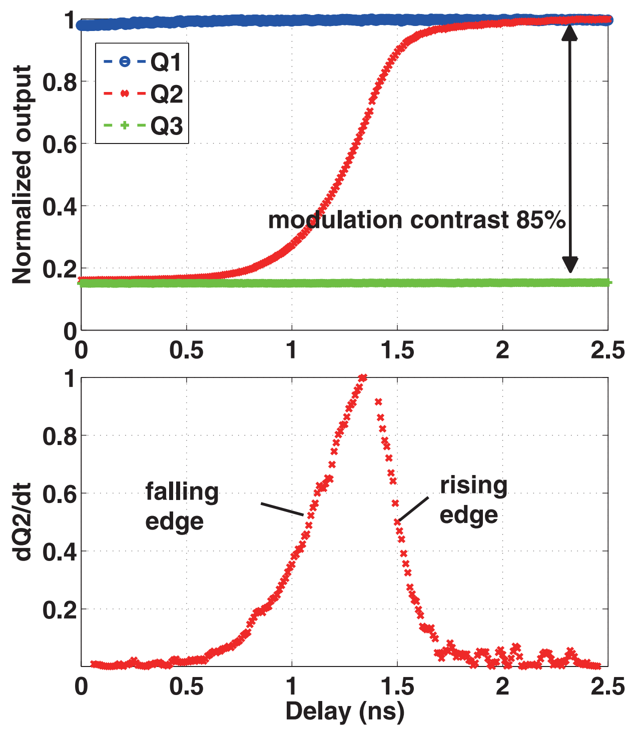

Fig. 6. Measured modulation characteristic.

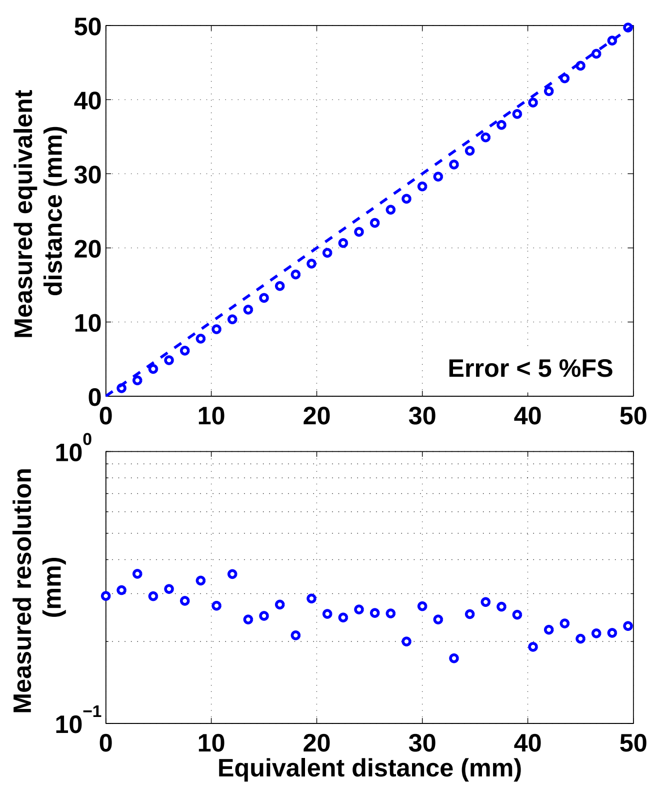

Fig. 7. Measured modulation characteristic.

V. Conclusions

In this paper, new TOF measurement technique for sub-mm or um range resolution by means of very short light pulse is presented. In the proposed techniques, the characteristic is determined by a photocurrent response without any distortion of light sources. The use of DOM pixels provides high-speed charge modulation and loss-free accumulation. The test chip fabricated in 0.11 um CIS technology demonstrates modulation contrast of 85%. The average range resolution is measured to be 210 um at measurable range of 50 mm.

Acknowledgment

This work was partly supported by the Ministry of Education, Culture, Sports, Science and Technology under the Knowledge Cluster Initiative and Grant-in-Aid for Scientific Research (A), No. 22246049 and No. 25249045.

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