A CMOS Image Sensor with Draining Only Modulation Pixels for Sub-Nanosecond Time-Resolved Imaging

Shoji Kawahito*, Zhuo Li**, and Keita Yasutomi*

*Research Institute of Electronics, Shizuoka University,
3-5-1 Johoku, Hamamatsu, 432-8011, Japan
**Graduate School of Science and Technology, Shizuoka University,
3-5-1 Johoku, Hamamatsu, 432-8011, Japan
EMAIL: kawahito@idl.rie.shizuoka.ac.jp, Phone: +81-53-478-1313 FAX: +81-53-412-5481

I. Introduction

Pinned photodiode technology in CMOS image sensors improves their imaging characteristics like noise and sensitivity. This technology is also useful for time-resolved imaging of phenomena which occurs repetitively in a very short period of time. This is because the carrier transfer time with a dimension of a few micrometer and small electric field in a depleted pinned diode is a few nanosecond or less than one nanosecond. This response time is sufficient for observing repetitive instantaneous phenomena with sub-nanosecond resolution. Typical applications include time-of-flight range imaging[1][2][3][4] and fluorescence lifetime imaging[5].

Fluorescence lifetime imaging microscopy (FLIM) requires an imager with very low noise, high sensitivity and very fast response (nanosecond order) in-pixel charge detector. The authors developed a two stage charge transfer pixel using a storage diode in a pixel to intensify the fluorescence signal [5]. In the previous structure, it requires a transfer gate between photo diode and storage diode. Surface traps under the transfer gate cause charge transfer noise and transfer delay. This paper presents a new sensor structure with draining only modulation (DOM) pixels, which controls the direction of carrier flow without transfer gates but with draining gate only.

II. Draining Only Charge Modulation

The pixel layout, structure and potential profile during operation of the DOM pixel is shown in Figure 1. The pixel uses standard CMOS image sensor pinned photo diode technology. The pinned photodiode (PPD) is connected to a pinned channel along with which a charge draining gate (TD) is connected. The other end of the channel is connected to a pinned storage diode (PSD). Reading out a photo-induced signal stored in the PSD is the same as that in the conventional 4-transistor active pixel sensor. To store sufficient amount of charge, the PSD region has higher potential well than that of the PPD or the pinned channel. To do this the area other than the PSD has another p-type doping layer. In Figure 1, the left part shows the charge transfer from the PPD to PSD, the right part shows the charge draining from the PPD to a drain through the TD. In the design of this structure for the FLIM, potential-barrier-less charge transfer from the PPD to PSD and the PPD to drain is

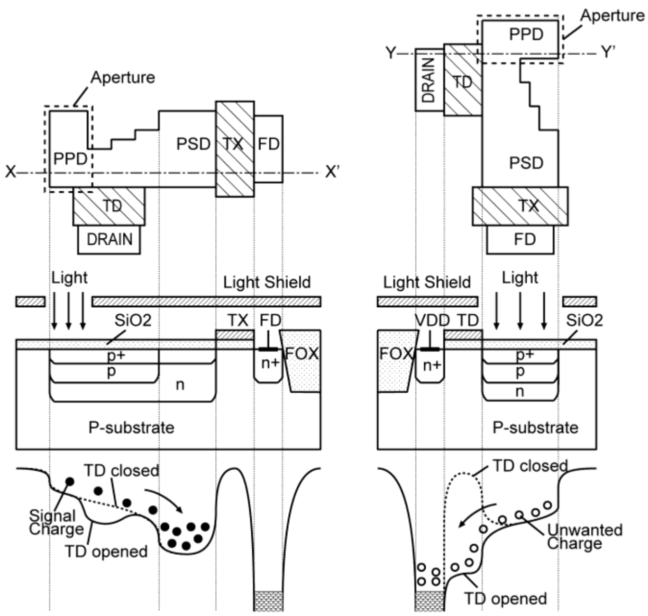

Figure 1: Pixel layout, structure and transfer mechanism.

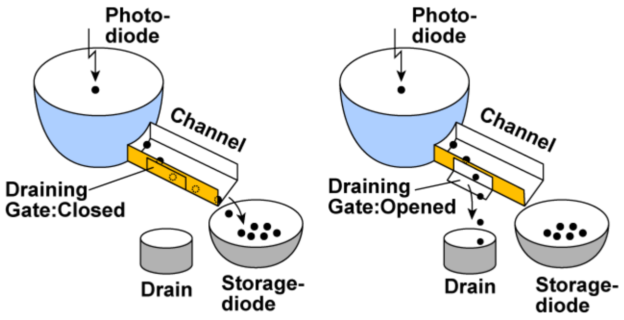

Figure 2: Operation of DOM pixel.

necessary. To meet this, the size and shape are optimized with a device simulator. Figure 2 shows a conceptual figure to explain the operation of the DOM pixel.

The simulated potential profile is shown in Figure 3, which is coincident with the predicted profile in Figure 1. The full depletion potential difference between the channel and PSD is more than 1V, which is sufficient for signal charge accumulation in the PSD. When the TD is opened, accumulated signal charges in PSD in previous time windows may be drained as a leakage current if the barrier height between the channel and the PSD is not large enough. When the TD is closed, no potential barrier is created in the channel to the PSD.

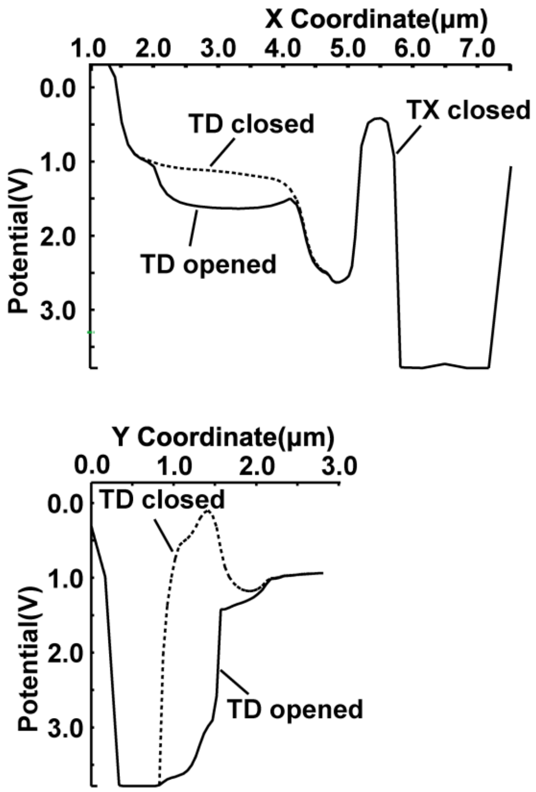

Figure 3: Simulated potential along X-X' and Y-Y'.

III. Applications to FLIM and TOF Imager

The DOM pixel can be applied to various time-resolved imaging applications. A typical and useful application is a detector for the fluorescence lifetime imaging microscopy (FLIM). Figure 4 shows a windowing to measure the fluorescence lifetime using the DOM pixel. Windowed fluorescence signal can be detected in the following process: During the light pulse excitation, TD is opened to drain unwanted charges generated by the excitation light. Then fluorescence light with exponential decaying is emitted and it generates signal charges. TD is still opened until the beginning of the time window. During the time window, TD is closed. Therefore, a part of the decayed signal charges generated in the PPD are transferred to the PSD. This process is repeated many times to intensify the weak fluorescence signal. The delay time of the time window is set to two ways, T_1 and T_2, and the lifetime is calculated with the intensified charges, $Q(T_1)$ and $Q(T_2)$ as

$$\tau = \frac{T_2 - T_1}{\ln \dfrac{Q(T_1)}{Q(T_2)}} \qquad (1)$$

To perform a time-windowed signal detection, the sensitivity when the TD gate is opened is an important characteristic and should be as low as possible. Figure 5 shows sensitivity curves to light intensity when the TD is opened and closed. The sensitivity ratio when the TD closed to opened is 450 for the accumulated electrons in the PSD of less than 10,000.

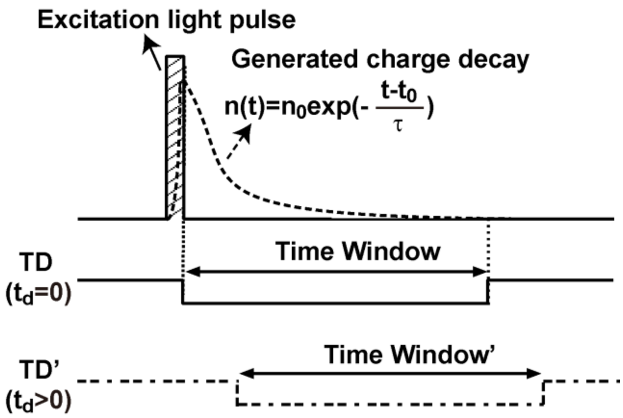

Figure 4: Windowing for fluorescence lifetime measurements.

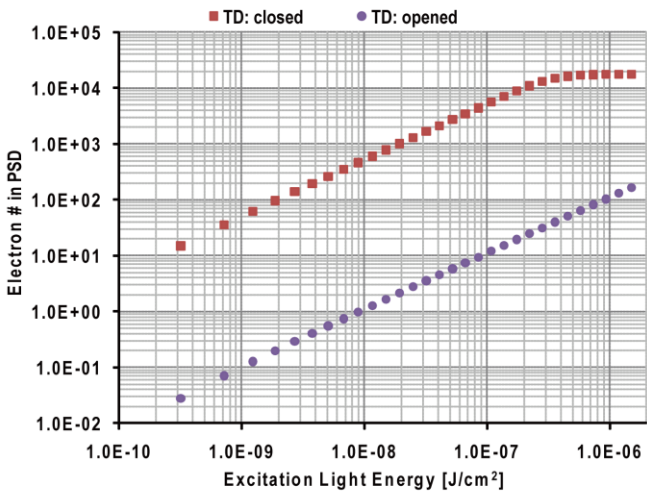

Figure 5: Sensitivity when TD closed and TD opened.

In the application to the TOF range imaging, time-windowed images for three cases are captured with the timing shown in Figure 6. In the three cases(a), (b) and (c), charges, Q_1, Q_2 and Q_3 stored in the PSD are expressed as

$$Q_1 = N_c I_p (T_0 - T_d) + Q_A + Q_{SR} \qquad (2)$$

$$Q_2 = N_c I_p T_0 + Q_A + Q_{SR} \qquad (3)$$

$$Q_3 = Q_A + Q_{SR} \qquad (4)$$

where I_p is the photo current induced by the received pulse light, Q_A is a charge generated by the ambient light, and Q_{SR} is a charge due to slow response carriers, and N_c is the number of repeats of charge transfer. Using Eqs. (2),(3) and (4), the range is given by

$$L = \frac{c}{2} T_d = \frac{c}{2} T_0 \frac{Q_2 - Q_1}{Q_2 - Q_3} \qquad (5)$$

The range can be calculated without the influence of the ambient light unless the signal does not saturate.

IV. Implementation and Experimental

For testing the new pixel structure for the time-resolved imagers, a image sensor chip has been fabricated using 0.18µm standard CMOS pinned diode process. The pixel array includes many test element groups. The pitch of all the pixel types is 7.5µm. Figure 7 shows the signal output when the TD gate bias changes. In this measurement, the TD gate voltage is set to a fixed value (d.c.). The wavelength of the illuminated light is 440nm. In the small TD gate bias (<2.6V) region, a potential barrier to prevent the photo charge to be drained is created in the channel, and the photo charges are transferred to the PSD, resulting a large signal voltage. In the large TD gate bias, most of photo charges are drained, and the resulting signal level is very low. The signal level in the PSD when the TD gate is opened is approximately 1/30 of that when the TD gate is closed.

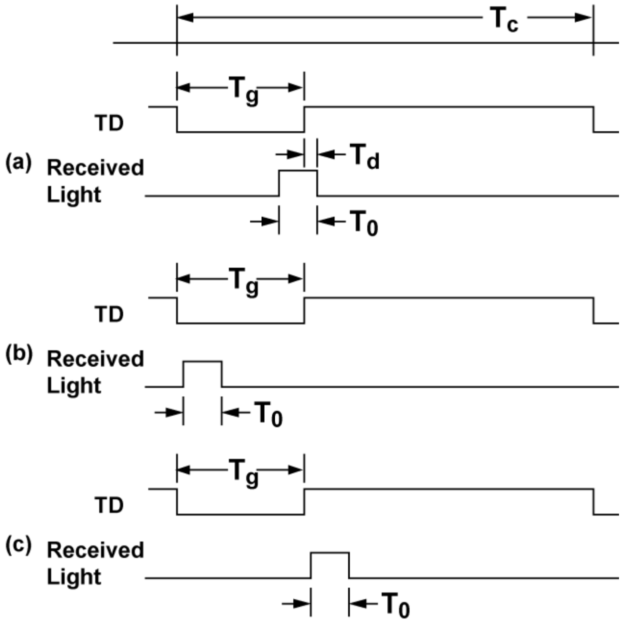

Figure 6: Operation for TOF range imaging.

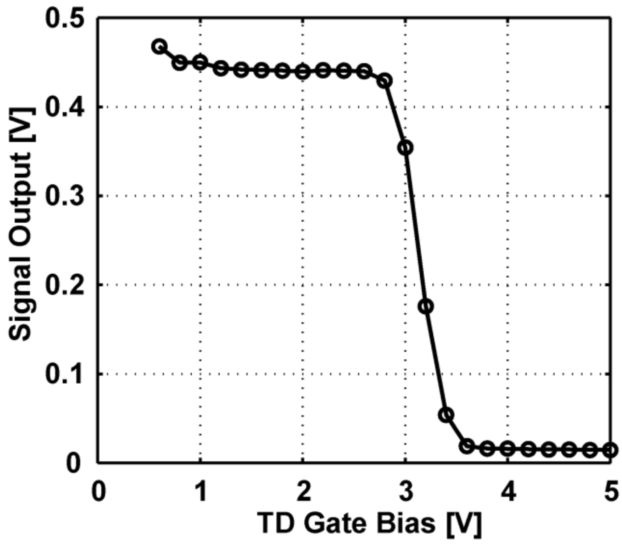

Figure 7: Signal output as a function of TD gate bias.

Figure 8 shows the signal output as a function of the delay time of the time window. In this measurement, the response to a laser light with very short pulse width (70ps) and wavelength of 440nm is measured while changing the delay time of the time window. In the readout channel, a gain of 30 is applied. The gradient of the exponentially decaying region gives the time constant of the response of the DOM pixel implemented and it is measured to be 1.73ns. This is sufficiently small for the application to fluorescence lifetime imaging with reasonable resolution.

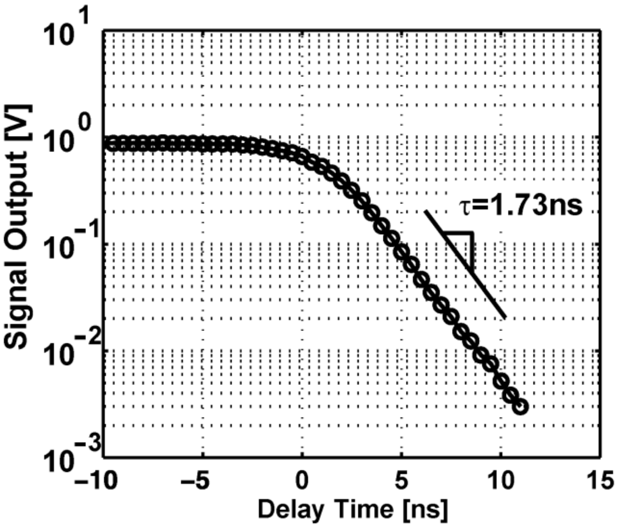

Figure 8: Signal output as a function of the delay time of the window.

Conclusions

In this paper, a time-resolved image sensor with sub-nanosecond resolution using draining only charge modulation pixels has been presented. The measured time constant of 1.73ns is good enough for the measurement of fluorescence lifetime of nano-second order. Experiments with biological samples are left as a near future subject.

Acknowledgements

This work is supported in part by the Ministry of Education, Culture, Sports, Science and Technology under a Grant-in-Aid for Scientific Research(A), No. 22246049.

References

[1] V. Berezin, A. Krymski, E. Fossum, "Lock in pinned photodiode photodetector," USP6239456, 2001.

[2] C. Tubert et al. "High-speed dual port pinned photodiode for time-of-flight imaging, " Proc. IISW, pp. 249-251, Bergen, 2009.

[3] H. Takeshita, T. Sawada, T. Iida, K. Yasutomi, S. Kawahito, "High-speed charge transfer pinned-photodiode for a CMOS time-of-flight range image sensor," IS&T/SPIE Electronic Imaging, vol.7536, No.407536, OR1-7536OR9, San Jose, Jan. 2010.

[4] D. Stoppa et al.,"A range image sensor based on 10um lock-in pixles in 0.18um CMOS imaging technologies, IEEE J. Solid-State Circuits, vol. 46, no. 1, pp. 248-258, Jan. 2011.

[5] H. J. Yoon, S. Itoh, S. Kawahito, "A CMOS image sensor with in-pixel two-stage charge transfer for fluorescence lifetime imaging," IEEE Transactions on Electron Devices, Vol 56, pp 214–221 , Feb. 2009.