

# CMOS Lock-in Pixel Image Sensors with Lateral Electric Field Control for Time-Resolved Imaging

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## I. Introduction

Time-resolved lock-in pixel image sensors have wide range of applications including biological, medical, scientific and industrial imaging systems. A time-of-flight (TOF) range imaging and a biological imaging with time-resolved fluorescence detection are typical examples. To implement the time-resolved image sensors with CMOS technology, several techniques have been reported. Most-widely used lock-in pixels use photogate-based structures [1][2][3]. It is useful for time-resolved imaging using an infrared light for the light source. However, it is not suitable for applications with visible lights because the gate materials are not always transparent to relatively short wave-length visible light. Another group of lock-in pixels uses pinned photodiodes in CMOS technology [4][5][6]. In these techniques, photo charge is transferred to a storage through a transfer gate. In this structure, a small potential barrier may be created in the photodiode edge during the charge transfer, which disturbs high-speed demodulation of the weak signal.

This paper presents a technique for high-speed demodulation using charge transfer controlled with lateral electric field, which is suitable for detecting very weak signal with very high time resolution.

## II. Lateral Electric Field Charge Modulator

Figure 1 and 2 show pixel structures of photo-charge modulator (demodulator) with lateral electric field control. The pixels use a pinned photo diode in a standard CMOS image sensor technology. Figure 1 is a single-tap modulator using draining gates only. This pixel has the pinned photo diode (PPD) and pinned storage diode (PSD), and draining gates (TD). The PSD region has higher potential well than that of the PPD. When the draining gates are closed, photo charges are automatically transferred to a storage within

a short time, e.g., less than nanosecond. While the draining gates are opened, the photo-charges are drained rapidly and are not transferred to the PSD, because the depleted potential is controlled by the lateral electric field created by draining gates. The single-tap modulator is called a draining only modulator (DOM).

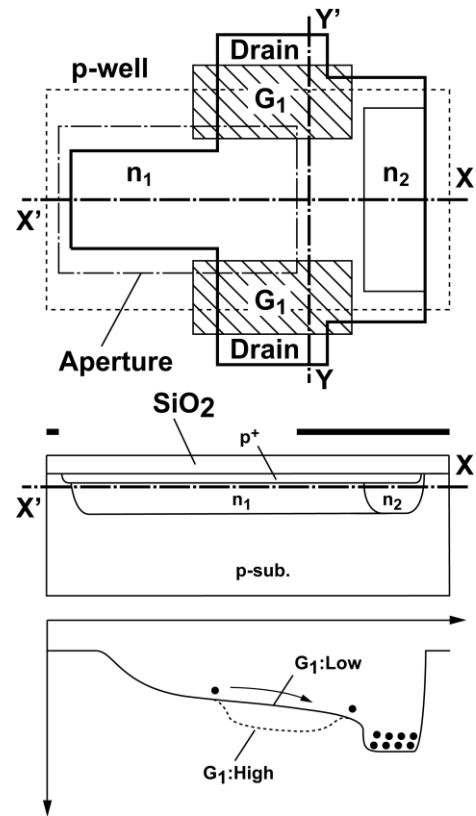
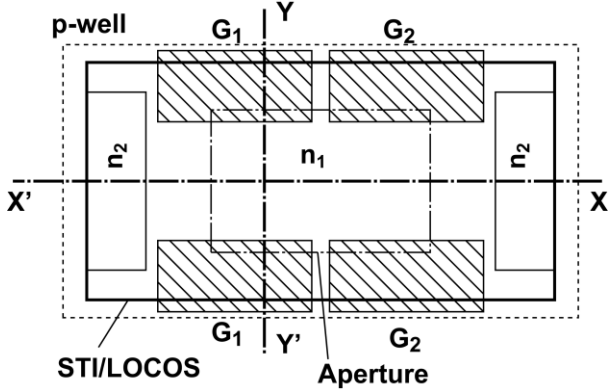


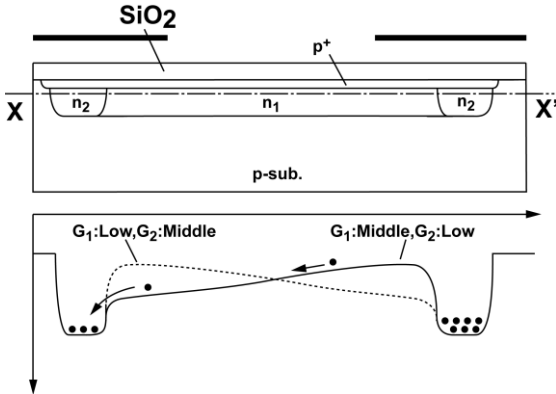
Figure1:Draining only modulation (DOM) pixel.

Fig. 2 shows another modulator with two taps using lateral electric field control. In this two-tap modulator called here a LEFM (lateral electric field charge modulator), two sets of gates ( $G_1$  and  $G_2$ ) for applying lateral electric field are used. The gates are not used for draining photo charge, but for controlling electric field of X-X' direction in Fig. 2(a). To do this, a relatively small positive voltage

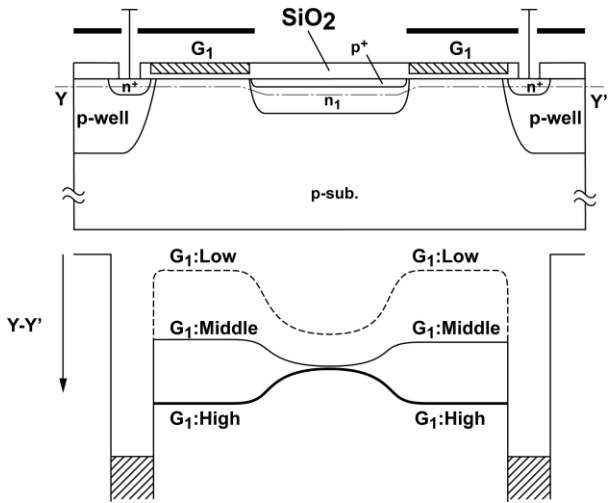
(middle = 1.3V) and negative voltage (low = -2V) are used for the operation. As shown in Fig. 2(c) (cross-section and potential profile in Y-Y' direction of Fig. 2(a)), by applying negative or small positive voltage to the gates, depleted potential can be modulated while maintaining the potential barrier to the drain. Fig. 3 shows the simulation results of the two-tap modulator using lateral electric field control.



(a) Top view

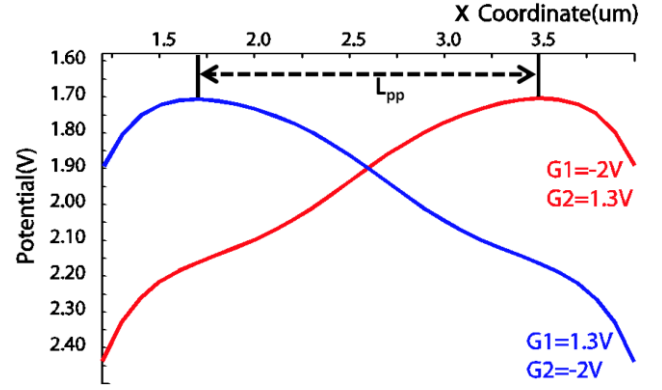


(b) Cross-section and potential profile in X-X'.

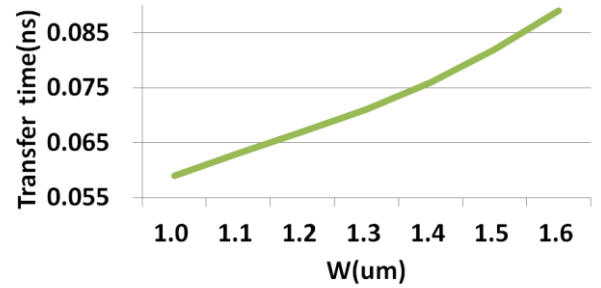


(c) Cross-section and potential profile in Y-Y'.

Figure 2: Lateral electric field charge modulator (LEFM).



(a) Potential profile



(b) Transfer time vs. width of photo diode

Figure 3: Simulation results of the two-tap modulator with lateral electric field.

By choosing carefully the device process parameters and device dimensions, a very high-speed two-tap modulator can be realized. In the results of Fig. 3(a), the electric field in X-X' direction is approximately  $0.5V/1.8\mu m = 2800V/cm$  for the photodiode width (W) of  $1.2\mu m$ . Fig. 3(b) is a simulation result of electron transfer time as a function of the width of the photodiode. In this simulation, an electron is initially located at  $(x=2\mu m, y=0\mu m, z=1\mu m)$  and measured at  $(x=4\mu m, y=0\mu m)$ . The transfer time can be less than 100ps. This two-tap modulator is useful for a TOF range imager and fluorescence lifetime imager with high range/time resolutions.

A problem of the DOM pixels for weak fluorescence detection is a phenomenon of charge scooping due to the interface trap of the draining gates. When a large gate voltage is applied to the draining gates, the Si-SiO<sub>2</sub> interface is once exposed to large amount of electrons in drain region, interface traps capture electrons and then release some of them into the PSD when the draining gates are closed[8]. In the LEFM, by using one of the two taps as the drain and the other as the signal detection, charge scooping effect can be

reduced in fluorescence lifetime measurements.

### III. Implementation and Applications

The DOM pixel with a single tap output is useful for a time-resolved image sensor for fluorescence lifetime measurements. A time-resolved CMOS image sensor with 256(V)x336 (H) 7.5 $\mu$ m-square DOM pixels has been implemented with 0.18 $\mu$ m CIS process. Fig. 4 shows the sensor chip photomicrograph. The fluorescence decaying process is measured by shifting a time window as shown in Fig. 5. The time window is set by the time when the TD gate voltage is set to LOW(-2V). Thanks to the elimination of the transfer gate between the PPD and PSD in the conventional structure [4], high-speed detection of very weak signal is realized. Fig. 6 shows the measurement results of fluorescence decaying of 4 fluorophores whose

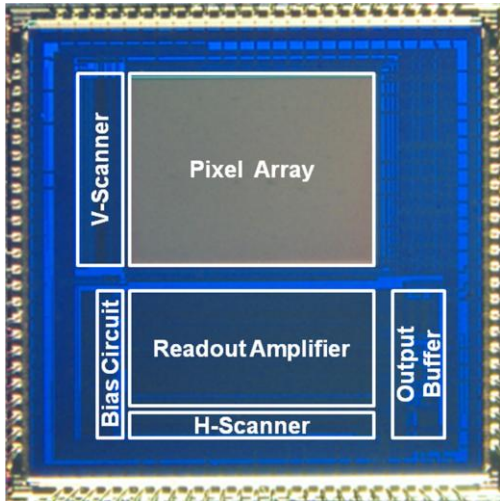


Figure 4: Time-resolved CMOS imager with DOM pixels.

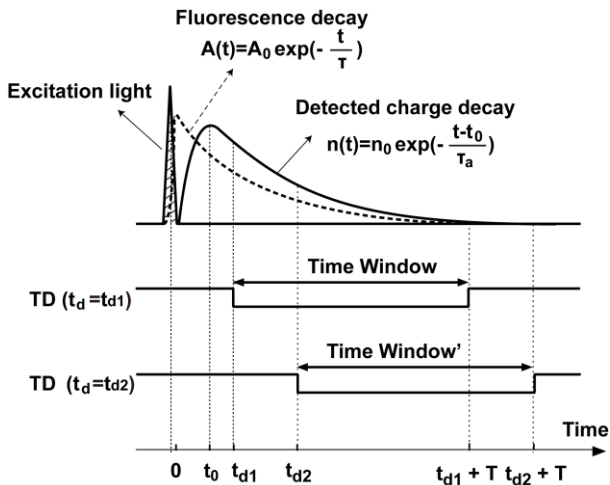


Figure 5: Time Windowing for Fluorescence Decaying Measurements.

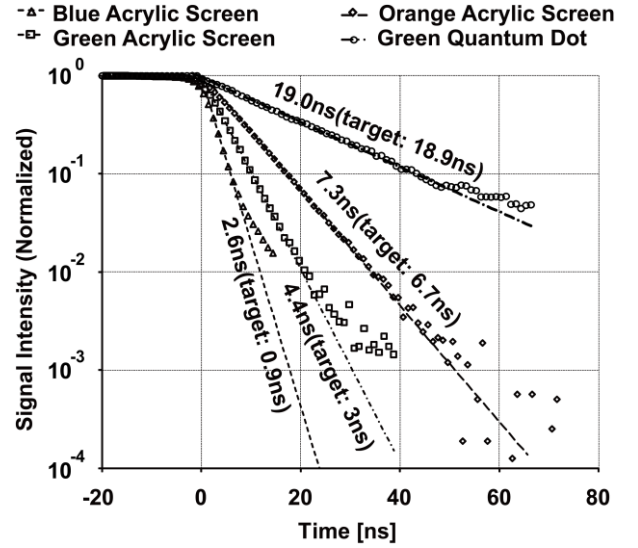


Figure 6: Measured fluorescence decaying.

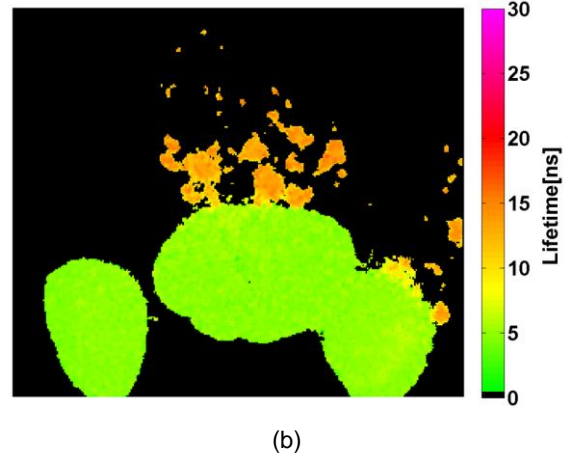
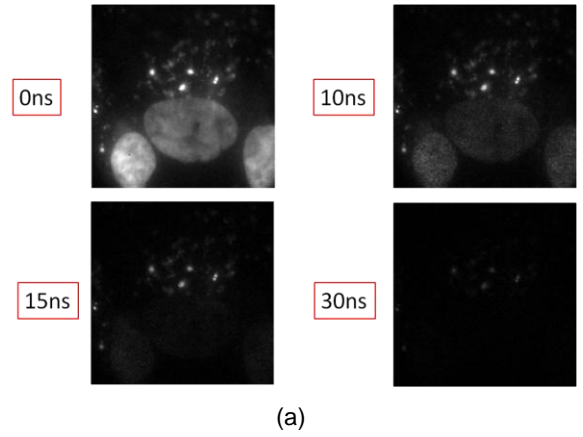


Figure7: Fluorescence Decaying Images of HeLa Cell.

lifetimes are 19ns, 7ns, 3ns and 1ns. An ultraviolet laser diode with a wavelength of 374 nm and a pulswidth of 80 ps is used for the measurements. Because of the intrinsic response of the DOM pixels (equivalent lifetime of 2ns), the measurement errors for small lifetime are relatively large. However, the influence of the

intrinsic lifetime of the device can be removed by a deconvolution technique and as a result the implemented time-resolved imager can be used for the lifetime measurement of 1ns or above with sufficient accuracy.

Figure 7 shows fluorescence decaying images(Fig. 7(a)) at 0, 10 and 15 and 30 ns and lifetime image (Fig. 7(b)) of HeLa Cells, where Hoechst(2.5ns) and Q-dot(10ns) are used for staining. These results demonstrate the implemented time-resolved image sensor is useful for the nano-second order lifetime imaging of very weak biological signals.

To improve the range resolution, the high-speed response of the LEFM pixel shown in Fig. 2 would be useful because of the small intrinsic lifetime.

The LEFM pixel with two or more taps can be applied to time-of-flight(TOF) range image sensors. A timing diagram for the operation of TOF range imaging using small duty light pulse is shown in Fig. 8. For photo-charge demodulation, LOW(-2V) and MIDDLE (1.3V) levels are applied for G1 and G2. Then the charge is modulated so as to transfer the charge to right and left charge accumulators when a light pulse with the pulse width of  $T_0$  and the delay (TOF) of  $T_d$  is received. The charges in the accumulators are given by  $Q_1 = I_{ph}(T_0 - T_d)$ , and  $Q_2 = I_{ph}T_d$ , respectively. The TOF is estimated by

$$T_d = T_0 \frac{Q_1}{Q_1 + Q_2} \quad (1)$$

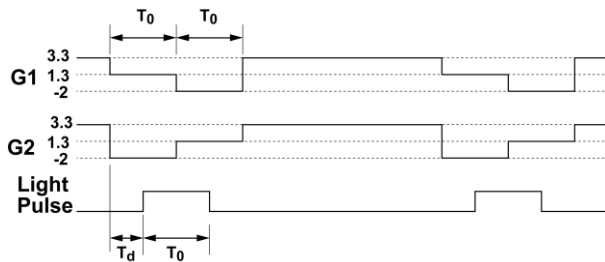


Figure 8: Timing diagram for TOF range imaging.

The rest in the cycle time and during the readout operation from pixels, HIGH(3.3V) level are applied to G1 and G2 in order to drain the photo-generated charge for reducing the influence of the background light. Because of the high-speed response of the LEFM pixel, high range resolution is expected if a very short laser light pulse is available.

## IV. Conclusions

This paper describes two types of lock-in pixels using lateral electric field control for highly time resolved imaging. Because of the charge transfer without potential barrier or potential steps, high-speed response is expected and this property improves the resolution in fluorescence lifetime imaging and TOF range imaging.

## Acknowledgements

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