

Design of Pixel for High Speed CMOS Image Sensors

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Abstract — Large size photodiode used in high speed CMOS image sensor pixel suffers from slow signal charges transfer speed and large image lag. To solve these problems, in this paper, we present a new device structure for high speed CMOS image sensor pixel with lateral graded-doping profile pinned photodiode and non-uniform doped channel transfer gate. Theory analysis and TCAD simulation results indicate that the proposed pixel can increase the signal charges transfer speed and reduce the image lag effectively. The measurement results show that, the proposed pixel is able to achieve 40ns readout time and 0.44% image lag. Compare to conventional pixels, 64 times higher readout speed enhancement and five times lower image lag were achieved.

Index Terms—High speed CMOS image sensors, graded Doping Photodiode, non-uniform doped channel, signal charge transfer speed, Image Lag

I. Introduction

High speed CMOS image sensors (CIS) are widely used in broadcast, sports, machine vision and scientific research applications. There are two important design issues in high speed CIS pixel design. Firstly, since the exposure time is very short, large-area photodiode (PD) e.g. $160\mu\text{m}^2$ in [1] and $232\mu\text{m}^2$ in [2], is required to enhance the sensitivity. The large-area PD results in that the lateral electric field in PD area is weak and that the signal charges can be transported only by carrier diffusion, as shown in Fig. 1. Therefore, the lateral velocity of the signal charges is slow. To speed up signal charge transfer, either trapezoidal PD [3] or lateral drift-field photodiode (LDPD) [4] can be used to enhance the lateral electric field. However, the former suffers from small fill factor, and the latter suffers from inaccurate LDPD fabrication, which is harmful to the lateral electric field.

Secondly, image lag problem is one of the challenges in design of the high speed CIS pixel. To reduce image lag, the past work focused on suppressing potential barrier or potential pocket around the transfer gate edge [5]. Although the signal charges transfer from PD to floating diffusion (FD) is complete when TG is

on, there is another source that can induce image lag. As shown in Fig. 2, when the transfer gate (TG) is switched off from its ON-state, the charges in the TG channel region will move to either the PD side or the FD side. Such charges backward to PD will result in image lag.

II. Working principle

This paper proposes a new pixel for high speed CIS. It can enhance the lateral electric field and reduce the image lag by optimizing the pixel layout and adjusting the ion implantation process. Fig. 3 shows the cross-section view of the proposed pixel device. Compared with conventional pixel device shown in Fig. 1, the pixel inserts additional ion implantation layers N and P in PD and TG channel, respectively. N- and N ion implantation layers in PD region are formed by first and second n-type ion implantation processes, respectively. Thus, a lateral graded-doping profile pinned photodiode (GD-PPD) is produced, which enhances the lateral electric field and speeds up the signal charge transfer from PD to TG. Furthermore, the additional N ion implantation layer can also increase the full well capacity of PD and thus increase the dynamic range of the pixel.

In TG channel shown in Fig. 3, P- and P ion implantation layers form a non-uniform doped channel (NUDC). As a result, the electron potential at PD side is always higher than that at FD side. When TG is turning off from its ON-state, channel electrons can only move toward FD node. Therefore, image lag due to the electrons backward from TG channel is reduced effectively.

III. Device Simulation

To prove the effectiveness of the proposed techniques, we design two kinds of typical pixels: square pixel and L-shaped pixel. Fig. 4 and Fig. 5 show two-dimensional (2D) and three-dimensional (3D) simulated device structures of the pixels, respectively. We used TCAD simulator to perform 2D and 3D simulation of the six kinds of the pixel devices with different layout and ion implantation layers, as listed in

Table. I.

Fig. 6 shows the 3D simulation results of signal charge transfer characteristics in PPD. Fig. 6(a) gives the simulated dependence of PD electron number on time when TG switches from OFF to ON-State. In conventional pixels (Pixel 1 and 4), first the number of the electrons decreases rapidly, then the drop rate of the number becomes slow dramatically after 2ns. The results indicate that the lateral electric field at PD region away from TG is weak and results in the speed decrease of the charge transfer. However, in proposed pixels with GD-PPD structure (Pixel 2, Pixel 3, Pixel 5 and Pixel 6), the number of electrons decreases continually and quickly. After 7ns, the number of the residual electrons is smaller than 1% of the full well capacity. Fig. 6(b) shows the dependence of PD electron number on time when TG switches from ON-state to OFF-State. The proposed pixels with GD-PPD and NUDC structure (Pixel 3 and Pixel 6) can reduce the backward electrons of PD.

IV. Measurement Results

Fig. 7 shows the die photograph of the implemented sensor chip in $0.18\mu\text{m}$ which includes the six kinds of the designed pixels. Fig 8(a) shows the measured charge transfer characteristics: dependence of output signal voltages of six pixels on ON-state time of TG. V_{SEL} is the 4T pixel select gate control voltage, V_{RX} is reset gate control voltage and V_{TG} is TG control voltage. T_{TG} stands for ON-state time of TG. T_{TG} can be tuned and the minimum tunable step is 40ns. As shown in Fig. 8(a), the pixels with GD-PPD structure (Pixel 2, Pixel 3, Pixel 5 and Pixel 6) can finish the signal charges transfer within 40ns. However, the pixels without GD-PPD structure (Pixel 1 and 4) cannot finish the signal charge transfer within 40ns.

Fig. 9 shows the measured results of the image lag. LED represents a control signal of LED light source. The pixels with GD-PPD and NUDC structures (Pixel 3 and 6) show a better image lag characteristic. Their image lag is at least five times lower than that of pixels without the GD-PPD and NUDC structures.

Fig. 10 shows the captured images of moving objects by the high speed image sensor. The capture frame rate is 500fps. The T_{TG} is set to 40 ns in experiment. Table II summarizes the performance of Pixel 1 ~ Pixel 6. The performance of the pixels with GD-PPD and NUDC structure (Pixel 3 and 6) is better than that of pixels without the GD-PPD and NUDC structures.

V. Conclusions

This paper proposed a novel pixel device with graded-doping pinned photodiode (GD-PPD) and non-uniform doped channel transfer gate (NUDC) structures. The simulated and measured results

demonstrate that the pixel can enhance the lateral electric field and reduce the image lag. Compared to conventional pixel, 64 times higher readout speed enhancement and five times lower image lag were achieved.

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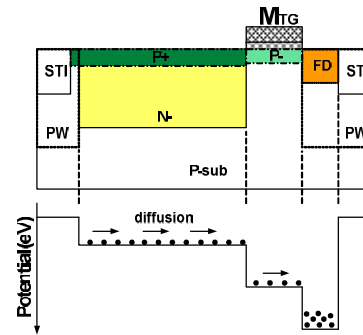


Fig. 1 Cross-sectional view and the signal electron transfer of the conventional photodiode, M_{TG} is transfer gate, FD is floating diffusion.

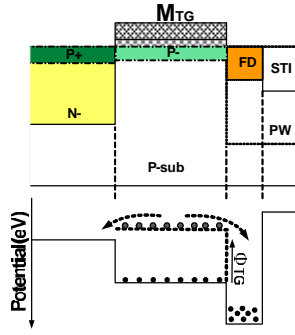


Fig. 2 Cross-sectional view and channel charge injection effect of conventional TG, ϕ_{TG} is the potential of transfer gate channel.

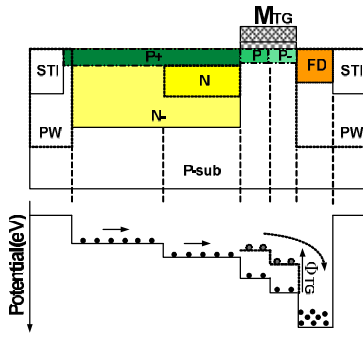


Fig. 3 Cross-sectional view and the signal electron transfer of the proposed pixel

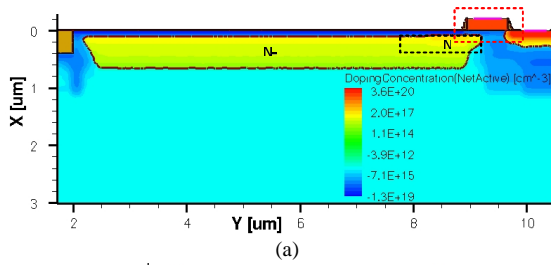


Fig. 4 2D simulated doping concentration profiles of (a) Graded-doping photodiode and (b) non-uniform doped channel

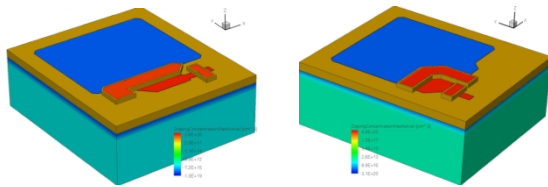


Fig. 5 3D Simulated Square pixel and L-shaped Pixel

Table I six kinds of pixels

Pixel 1	Conventional Square pixel
Pixel 2	Square GD-PPD pixel
Pixel 3	Square GD-PPD and NUDC TG pixel
Pixel 4	Conventional L-shaped Pixel
Pixel 5	L-shaped GD-PPD pixel
Pixel 6	L-shaped GD-PPD and NUDC TG pixel

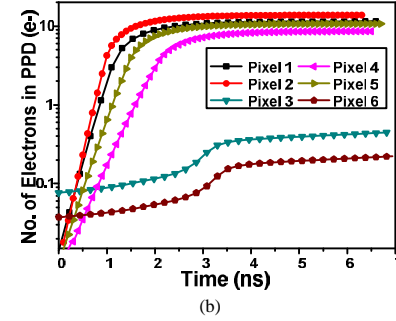
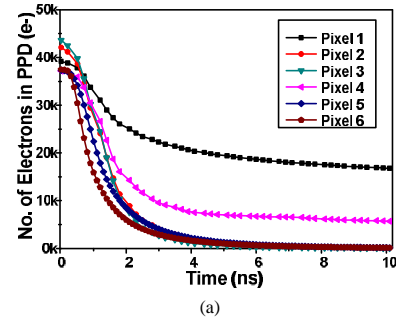


Fig. 6 3D simulation results of charge transfer characteristics: (a) dependence of PD electron number on time when TG switches from OFF to ON-State (b) dependence of PD electron number on time when TG switches from ON-state to OFF-State

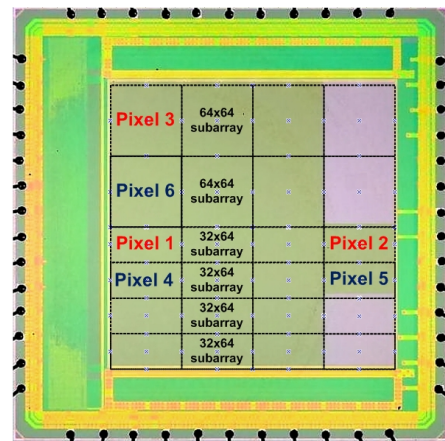


Fig. 7 Micrograph of sensor which includes the six kinds of designed pixels

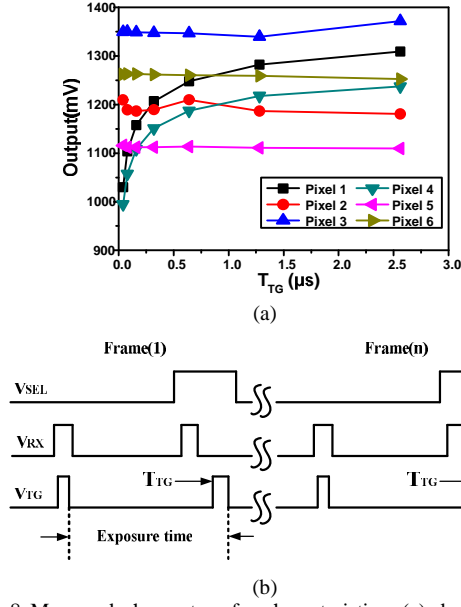


Fig. 8 Measured charge transfer characteristics: (a) dependence of output signal voltages of six pixels on ON-state time of TG; and (b) timing diagram

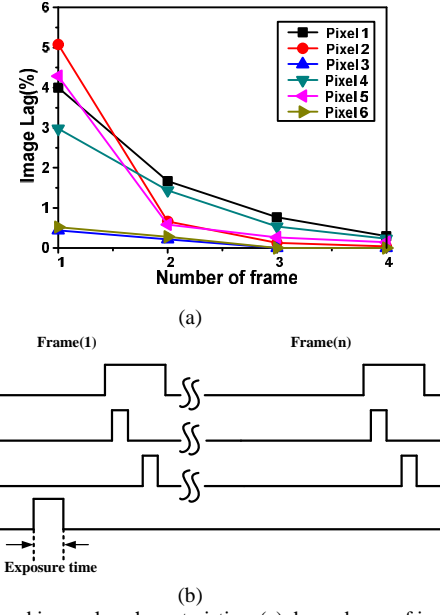


Fig. 9 Measured image lag characteristics: (a) dependence of image lag of six pixels on frame after one time LED lighting; and (b) timing diagram

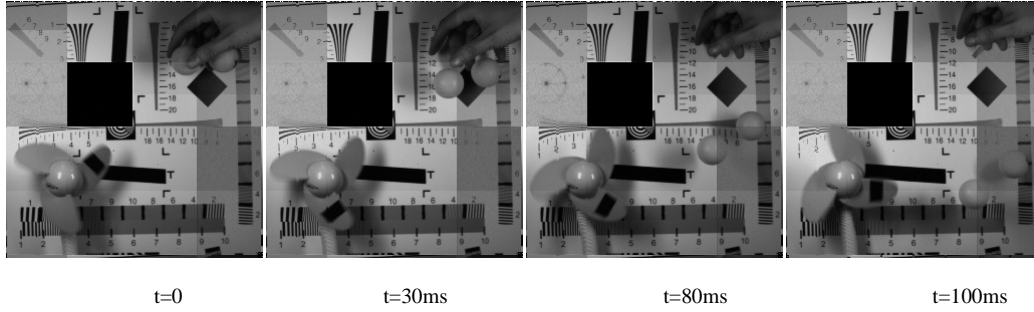


Fig. 10 Images captured at 500fps. Exposure time is 960 μs , illumination level is 1100 Lux, T_{TG} is 0.04 μs .

Table II Performance summary of Pixel 1~ Pixel 6

Parameter	Pixel 1	Pixel 2	Pixel 3	Pixel 4	Pixel 5	Pixel 6
Pixel Size (μm)	10.0	10.0	10.0	10.0	10.0	10.0
Fill factor	60.0%	60.0%	60.0%	60.0%	60.0%	60.0%
Sensitivity(V/Lux.S)	8.9	8.4	9.3	8.4	9.4	8.6
Conversion gain($\mu\text{V}/\text{e}$)	26.8	31.1	23.0	25.1	25.5	21.7
Random noise(e)	26.3	20.2	24.2	23.6	18.5	22.1
Signal to noise ratio(dB)	51.8	54.5	56.0	49.7	51.5	55.6
Dynamic Range(dB)	61.40	60.32	64.78	61.04	60.65	63.87
Full Well capacity(e)	49.65	41.63	61.89	44.64	38.74	60.22
Image Lag (%)	4.00	5.08	0.44	2.98	4.29	0.52