A Modified a 3-Tr CMOS X-ray Image Sensor for Low-Distortion Pixel Output in Source Follower

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***Abstract*–This paper presents a low distortion source follower (LDSF) method in 3-Tr (Transistor) CMOS X-ray sensor. Most of the important parameters in source follower is a gate to source voltage (V_{gs}) difference. This additional circuit reduces fill factor of the photodiode from 86% to 78% in the 50 μm x 50 μm size. This circuit requires only a 1 P-mos and 1 N-mos. Simulation test represented that the LDSF method makes V_{gs} more constant. It means that V_{gs} is not easily affected by V_{ds}.**

I. Introduction

CMOS X-ray imaging systems, which are an alternative to film-based system, has been dramatically developed as a common in a number of field [1]. A 3-Tr X-ray pixel structure is a widely used circuit to implement the CMOS X-ray sensor. There are a reset, a source follower, and a select transistor in the 3-Tr pixel structure. These components has a noise to decrease a dynamic range of the sensor. A source follower buffers photodiode and an output node. The output of the photodiode is determined by V_{photo}-$V_{gs(source\ follower)}$. The V_{gs} is determined by bias current which is passing through source follower. And the bias current is affected by source-to-drain voltage of the source follower. To see influence of the source-to-drain voltage to the source follower, circuit to keep a source-to-drain voltage constant is added parallel with a source follower so that it can make a source-to-drain voltage difference constant and reduce distortion from the source follower in the 3-Tr structure.

II. Introduction

The 3-Tr CMOS X-ray is composed of 3 components; reset Tr, selection Tr, and source follower. First of all, select Tr makes that each pixel can be read out by sharing one column line. When a control signal of the select Tr is high, the output column line is connected with the pixel. The select Tr is operated in the triode region Second, the reset Tr makes the photodiode reset for photon coming. Photons are generated in the scintillator on the CMOS X-ray sensor. Those photons are absorbed in the photodiode. Those generates information which has how much X-ray incidents. The reset Tr is also operated in the triode region. Finally, the source follower transfers gate signal which is connected photodiode to source of the source follower and buffers output node (source of the source follower). This Tr is operated in the saturation region. Fig. 1. shows a 3-Tr CMOS X-ray pixel structure.. The reset, source follower, and select Trs are also depicted in the Fig. 1. And bias Tr is shown in the Fig. 1. , additionally.

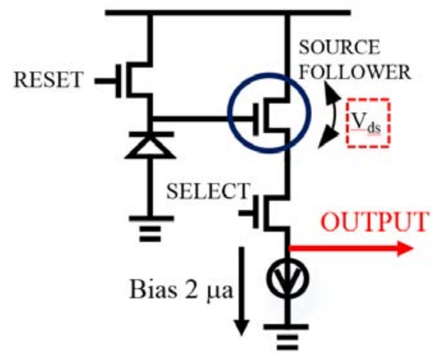

Fig. 1. A 3-Tr CMOS X-ray pixel structure

The source follower is the first stage in the read-out process stages. So, the source follower needs to have good linearity without a distortion. However, the distortion is mainly comes from variation of the gate-to-source voltage (V_{gs}) [2]. As in (1), the V_{gs} is determined by not only saturation current (I_{sat}) of the bias Tr but also the drain-to-source voltage (V_{ds}) of the source follower.

$$I_{sat} = \frac{1}{2}\mu_{n,p}C_{ox}\frac{W}{L}(V_{gs}-V_{th})^2 \times (1+\lambda(V_{ds})) \quad (1)$$

Where, $\mu_{n,p}$ indicates mobility of the charge and C_{ox} represents gate oxide capacitance of the Tr. The λ shows output impedance constant of the Tr. The W is width of the Tr and the L is length of the Tr. As in (1), the current, $I_{sat,}$ is a design parameter. It`s value is determinded by the bias current. Other parameters are W and L. Thoes are changable to design the source follower in the 3-Tr CMOS X-ray. If these are fiexed, the V_{gs} is maintained constantly as shown in Fig. 2. Then, the voltage of the photodiode is detected at the output node as shown in Fig. 1. The output voltage plus the V_{gs} equal photodiode voltage, exactly.

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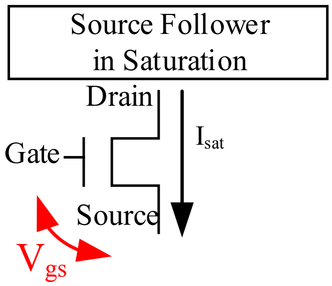


Fig. 2. The source follower in the 3-Tr CMOS X-ray pixel

However, the V_{ds} is distiortion term in the (1). As the photodiode voltage decreases, the source tracks the photodiode voltage well. This situation with time is shown in Fig. 3. The V_{ds} difference is changing after the start ot the photon integration. The V_{ds} change affects parameter value change in the (1). Even though the I_{sat} is design vlaue, the I_{sat} is not changed. The I_{sat} is affected by the Tr bias voltage which is generated in the out of pixel. The only changable parameter term is the V_{gs} in the (1).

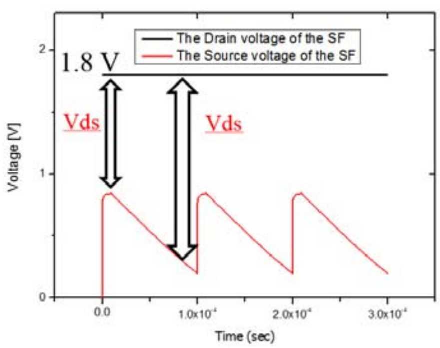


Fig. 3. A simulation of voltage at source and drain of the source follower

III. PROPOSED METHOD

We proposed the Low-Distortion Source Follower (LDSF) method which keeps the V_{ds} constant. The constant V_{ds} maintain the V_{gs} constant so that the photodiode voltage is transferred to the source node of the source follower without distortion.

The proposed LDSF method applied in the 3-Tr CMOS X-ray sensor is shown in Fig. 4. As shown in Fig. 4. the LDSF needs P type mosfet (P-mos) and additional bias mosfet to support the P-mos in the saturation mode. Physically, P-mos requires N well to be made. It affects the pixel fill factor which the ratio of the photodiode area to whole pixel area.

The main benefit of the LDSF method is in the P-mos source follower. The source follower always try to keep V_{gs} constant. To maintain V_{ds} constant of the source follower in the 3-Tr CMOS X-ray pixel, the complementary type, the P-mos source follower, is used. The V_{gs} of the P-mos is produced by the LDSF method. That generated voltage, V_{gs}, is applied to the source follower of the 3-Tr CMOS X-ray. The source follower is sharing the source node of a M1-Tr. As a result, V_{gs} is always kept constant as shown in Fig. 5.

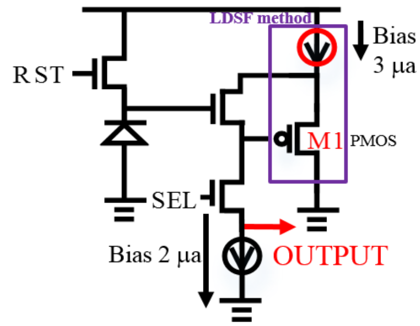
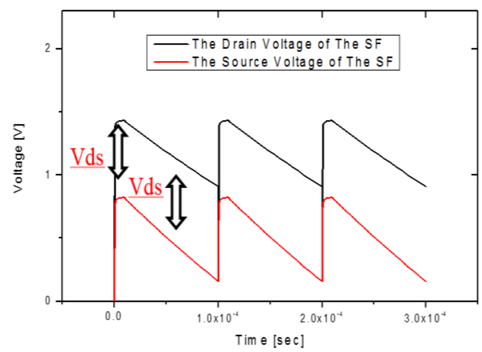


Fig. 4. The structure of a LDSF method

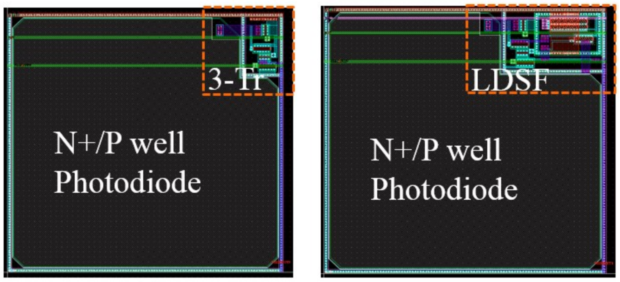


. Fig. 5. The simulation result of the voltage at the source and drain of the source follower

The V_{ds} change as the photodiode voltage decrease is dramatically reduced only using the LDSF method. However, the LDSF method needs additional area in the pixel. It affect fill factor reduce. And the LDSF method also requires an additional current. So it increase power consumption. However, the signal read out without distortion in the source follower is most important in the medical X-ray image field because of the high resolution requirement in the medical image field [3].

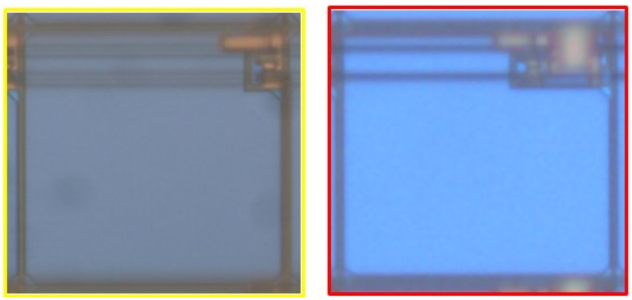
IV. TEST AND RESULTS

The 3-Tr CMOS X-ray pixel without the LDSF method and with the LDSF method is fabricated using 0.18 μm CMOS precess. The pixel size was 50 μm x 50 μm not to be affected by dispersion effect from scintillator. The fill factor without the LDSF method was 86% and the fill factor with the LDSF method was 78%. Using the LDSF method, only 8% fill factor decreased as shown in Fig. 6. The photodiode type was N+/P well type. And the silicide block layer was used to be well absorbed in the photodiode.

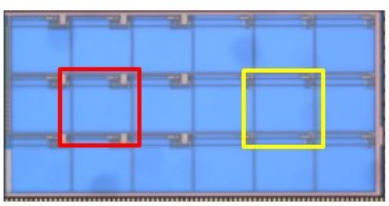


(a) **(b)**

Fig. 6. (a) The layout of the 3-Tr X-ray pixel
(b) The layout of the 3-Tr X-ray pixel with the LDSF method



(a) (b)



(c)

Fig. 7. (a) The chip of the fabricated (a) in Fig. 6.
(b) The chip of the fabricated (b) in Fig. 6.
(c) The fabricated chip using 0.18 μm CMOS precess.

Fig. 7. Shows the fabricated chip using 0.18 μm CMOS precess. The Fig. 7. is taken by a optical microscope. The red box in the Fig. 7. (c) shows 3-Tr CMOS X-ray pixel and the yellow box shows the 3-Tr CMOS X-ray pixel with the LDSF method. These are surrounded by dummy pixels to make circumstance equal [4]. The blue colors in Fig. 7. shows N+/P well photodiode. The fabricated chip used 4 metal layers so Fig. 4. is out of focus.

A test was performed using designed Printed Circuit Board (PCB), Field Programmable Gate Array (FPGA), and signal generator. The test setup is shown in Fig. 8

The manufactured chip was wire-bonded in the mini PCB which is shown on the main PCB in the Fig. 8. The mini PCB is connected to the main PCB. The main PCB has buffers, variable resisters, capacitor, and other circuits to control input signal and output signal. The connector is connected with FPGA to sharing input and output signal which is chip needed. FPGA generated the reset and select signals and the analog output is collected in the data acquisition system. Finally, we acquire the pixel output to confirm the LDSF method.

An output linearity was acquired and plotted as shown in Fig. 9. The red line is ideal pixel output. However, the black line which is simulation output has distortion component. To calculate distortion amount, the variation is selected to compare. The output variance of the 3-Tr CMOS X-ray pixel without the LDSF method was 33.4.

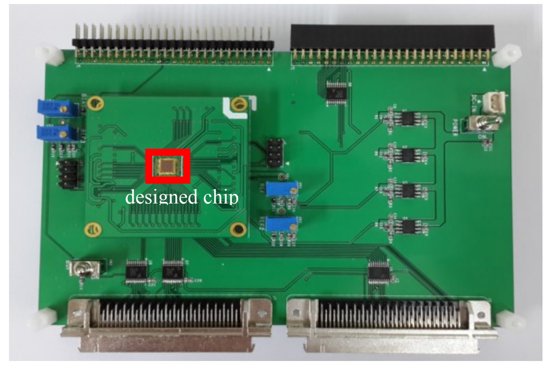


Fig. 8. A test PCB setup

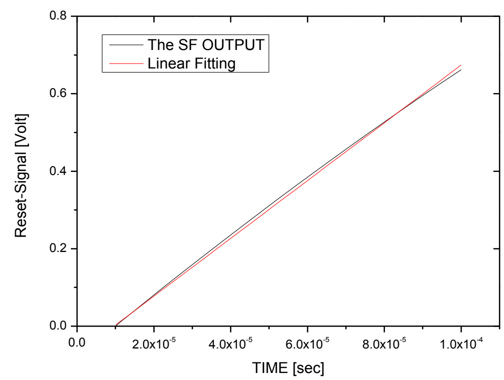


Fig .9. The pixel output without the LDSF method.

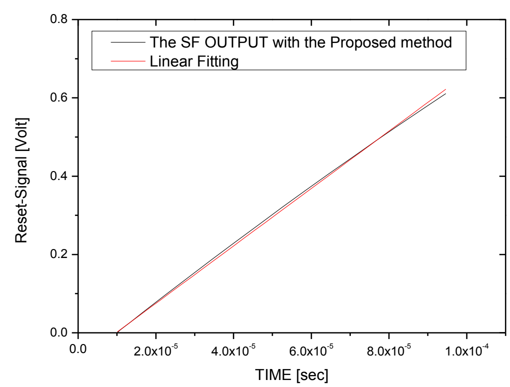


Fig. 10. The pixel output with the LDSF method

The output of the 3-Tr CMOS X-ray pixel is also tested. The variance of the acquired value has 26.9 value. The distortion component decreased 19.5%, using the LDSF method. And the V_{gs} change are observed as shown in Fig. 11. The Voltage peak was observed in the Fig. 11. The voltage peak comes from fast reset Tr transition. The V_{gs} without LDSF method is was changed from 527.5 mV to 426.9 mV. However V_{gs} with the LDSF method was changed from 543.6 mV to 461.8 mV. The V_{gs} was swept from 100.6 mV to 81.8 mV. The V_{gs} range was dramatically reduced by 18.9 %

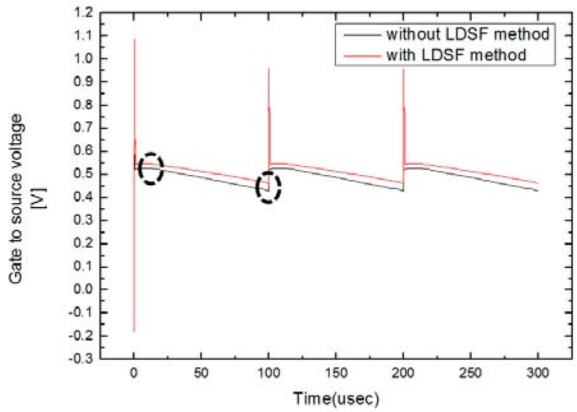


Fig. 11. The Vgs change comparison

V. CONCLUSION

The low-distortion source follower (LDSF) method is proposed and tested. V_{gs} is not dominantly affected by the V_{ds}.

However, the LDSF method will affect when not only the source follower but also the bias current circuit will adapt the LDSF method. This will be fabricated and tested. Even though, total power consumption increased to support LDSF current path and the fill factor in the fixed pixel size decreased 8%.

The distortion of the V_{gs} was reduced 18.9 %, dramatically. The LDSF method will be applied not only the source follower in the 3-Tr CMOS X-ray pixel but also the current source. Those test will be fabricated and tested further.

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