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Journal of Semiconductors
(2019) 40, 022402
doi: 10.1088/1674-4926/40/2/022402

# High performance active image sensor pixel design with circular structure oxide TFT

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**Abstract:** We report a high-performance active image sensor pixel design by utilizing amorphous-indium-gallium-zinc-oxide (a-IGZO) thin-film transistors (TFTs) with a circular structure. The TFT, configured with the inner electrode as source and outer electrode as drain, typically exhibits good saturation electrical characteristics, where the device has a constant drive current despite variations in drain voltage. Due to the very high output resistance exhibited by this asymmetric TFT structure with a circular shape, the pixel circuit considered here in common-drain configuration provides a higher gain of operation than a pixel circuit implemented with rectangular a-IGZO TFTs. They can be used as driving TFTs in active image sensor circuits. They are, therefore, good candidates for digital X-ray detectors in applications such as medical diagnostic procedures.

**Key words:** a-IGZO TFT; active image sensor; circular structure; high gain

**Citation:** R Geng and Y X Gong, High performance active image sensor pixel design with circular structure oxide TFT[J]. *J. Semicond.*, 2019, 40(2), 022402. http://doi.org/10.1088/1674-4926/40/2/022402

## 1. Introduction

The potential of amorphous oxide semiconductors (AOS) for applications in large area transparent and/or flexible electronic devices has generated an incredible amount of research devoted to these materials[1]. More specifically, amorphous indium–gallium–zinc–oxide (a-IGZO) is now widely accepted as the most promising material for implementation in large area electronic systems. This is because of its enhanced current drivability compared to hydrogenated amorphous silicon (a-Si:H) and its significant scalability while having a more economical production cost compared to low-temperature polycrystalline silicon (LTPS)[2, 3]. More importantly, the low-temperature processing (room temperature) makes a-IGZO TFTs suitable for large scale integration electronics on flexible substrate[4, 5].

Large scale image sensors also utilize TFT backplane technology which uses amorphous silicon material for the switch TFT and the photodiode in the single pixel[6]. Due to the higher mobility and extremely low off-state current, the use of oxide TFTs will enable a high signal-to-noise ratio (SNR) without pixel amplifiers and allow high-frame-rate imaging sensing such as specialized digital X-ray or infrared detectors[7].

The methods for driving image sensors can be categorized as passive or active. In the passive method, the exposure and readout of the sensors are performed sequentially. The majority of image sensors utilize the passive driving method because of the simple driving schematic; however, this method may introduce image blurring if fast moving objects are captured due to the pixels being subjected to exposure at different times from top to bottom of the sensor array. On the other hand, the active driving method exposes all the pixels simultaneously, and they are read out sequentially, which is favorable for the capture of moving objects. However, after exposure the charge is accumulated in the sensors from exposure until the sensor is read, which will lead to decreased image quality because of the leakage resulting from the off-state current of the shutter TFTs in the pixels. Given the very low off-state current, an active image sensor could easily be realized with a-IGZO TFTs[8, 9]. However, unlike the metal oxide semiconductor field-effect transistors (MOSFETs), a-IGZO TFTs exhibit several unsatisfactory electrical characteristics such as non-saturation and low output resistance, which prevents the pixel circuit output from achieving the desired result[10–12]. This non-saturation and low output resistance manifest as lower gain and errors in gray level.

In this paper, we propose a high-performance active image sensor pixel based on a-IGZO TFTs with a circular structure. The circular a-IGZO TFTs fabricated normally exhibit good performance with a mobility ($\mu_{FE}$) of 14.3 cm$^2$/(V·s), threshold voltage ($V_{th}$) of 3.2 V, and a subthreshold swing (SS) of 242 mV/decade. Compared to rectangular TFTs, circular TFTs exhibit good saturation electrical characteristics and much higher output resistance when configured with inner electrode as source and outer electrode as drain. This configuration results in a higher gain of voltage (close to one) when compared to rectangular TFTs. Given the very high output resistance exhibited by the circular TFTs, they can be used as the driving TFT in an active image sensor circuit. It is, therefore, a good candidate for image sensing applications such as medical diagnostic procedures.

## 2. Circular a-IGZO TFT

Figs. 1(a) and 1(b) show the 3-D schematic views and a microscope image of the circular a-IGZO TFTs in this work. The TFTs comprise a gate, gate insulator, active layer, outer electrode, inner electrode and passivation layer. The fabrication pro-

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Received 16 JULY 2018; Revised 14 SEPTEMBER 2018.

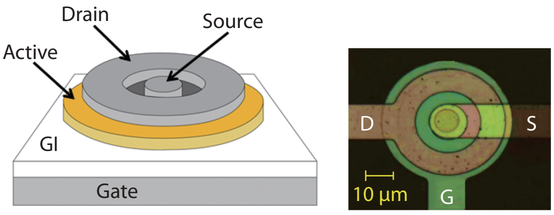


Fig. 1. (Color online) (a) The schematic 3-D views and (b) optical image of the circular a-IGZO TFTs.

cess is the same as the conventional back channel etched a-IGZO TFTs in rectangular shape. The 250 and 300 nm thick $SiO_2$ layers are used as the gate insulator and passivation layer deposited by plasma-enhanced chemical vapor deposition (PECVD) at 300 °C. The 60 and 120 nm thick molybdenum (Mo) layers are used as gate and source/drain electrodes deposited by sputter. A 20 nm thick a-IGZO layer is used as active by sputter deposition at 200 °C, with a target of polycrystalline IGZO ($In_2O_3$ : $Ga_2O_3$ : ZnO = 1 : 1 : 1 mol%) and Ar : $O_2$ gas ratio of 4 : 8. The chemical composition of the active layer deposited is determined to be In : Ga : Zn = 3 : 2 : 1 in atomic ratio. After the whole process, a 2 h thermal annealing must be carried out at 250 °C in vacuum to relieve the stress and achieve stable and reproducible performance.

The typical measurement results of transfer ($I_{DS}$–$V_{GS}$) and output ($I_{DS}$–$V_{DS}$) curves of circular a-IGZO TFTs with inner electrode as source and outer electrode as drain are shown in Figs. 2(a) and 2(b). The radiuses of the outer and inner electrode are 15 and 4 $\mu$m, respectively. The TFT performances in the linear regime ($V_{DS} < V_{GS} - V_{th}$) are very similar to the typical rectangular a-IGZO TFT in terms of the turn-on voltage, mobility from the transfer characteristic and the current level from the output characteristic; in the saturation regime ($V_{DS} > V_{GS} - V_{th}$), the output curve of the circular TFTs becomes flat, which means very high output resistance while the output currents of the rectangular TFT still increase with increasing $V_{DS}$, indicating a low output resistance (inset is the typical output characteristics of rectangular TFT as a comparison). The devices normally exhibited a good performance with a $\mu_{FE}$ of 14.3 cm$^2$/(V·s), $V_{th}$ of 3.2 V, SS of 242 mV/decade, and ON/OFF current ratio > $10^8$ for both structures. The channel length ($L$) of this circular TFT is determined by $L = R_2 - R_1$, where $R_2$ and $R_1$ are the geometrical parameters, the radiuses of the outer and inner electrodes, respectively. By considering a radial electric field, the channel width ($W$) of this structure should be calculated as a function of $R_1$ and $R_2$, it was reported as $W/L = 2\pi/\ln(R_2/R_1)$[11]. $V_{th}$ was determined by a linear extrapolation of the plot of $\sqrt{I_{DS}}$ versus $V_{GS}$. The value of $\mu_{FE}$ was retrieved from the transconductance, $g_m = \partial I_{DS}/\partial V_{GS}$. The SS was taken as the minimum value of $(\mathrm{d}\log(I_{DS})/\mathrm{d}V_{GS})^{-1}$ with $V_{DS}$ = 0.1 V. The transfer curve of the fabricated devices indicates an enhancement mode, which allows simple circuits without requiring voltage level shifting. Current crowding is not observed from the output curve, which indicates a good metal–semiconductor contact. Such good TFT performances are due to the careful and consistent fabrication process, and also the favorable material properties. The circular TFTs also exhibit good uniformity, with all TFTs having a very high output resistance with inner electrode as source and outer electrode as drain (results not shown). Such good saturation electrical characteristics can be attributed to the geometrical factor $W/L$, which is a function of $R_1$ and $R_2$ and is affected only very slightly by the channel length modulation beyond the pinch-off: as $W/L = 2\pi/\ln[(R_2 - \Delta L)/R_1]$, given that $R_2 > R_1$, it can be deduced that $I_{DS}$ increases only very slightly with $\Delta L$.

## 3. Active image sensor pixel design

The schematic of the active image sensor design is shown in Fig. 3(a), while Fig. 3(b) shows the timing diagram of this active image sensor. The single pixel of this active image sensor consists of three TFTs and one photodiode. The shutter TFT is used to control the exposure time and the switch TFT is used to read out the data when the current row is selected. The driving TFT receives the signal from the photodiode through the gate terminal and generates the output signal through the source terminal in a common-drain amplifier configuration to achieve enough drivability and less distortion. The output nodes of the entire column are biased with a single mirror current source to stabilize the output, while the whole current source of each column is mirrored to a single reference current by a single TFT in diode connection. The operation of this active image sensor consists of two steps as shown in Fig. 3(b). The shutter signal goes high and all shutter TFTs turn on, the photodiodes are exposed and the signals are stored at the gate of the driving TFT through the shutter TFT. After the exposure, the shutter TFTs are turned off and the switch TFTs are turned on by row selected for output. This common-source amplifier should have higher gain to achieve the target value of the error in gray scale.

## 4. Results and discussions

The active image sensor pixel performance was measured by swiping a voltage source instead of exposing the photodiodes for simplicity, while maintaining the shutter and switch TFTs in the on state with a consistent bias current. The equivalent circuit for this measurement is shown in Fig. 4(a).

Fig. 4(b) shows good linearity of output and gain by utilizing the circular structure for the driving TFT while maintaining a rectangular structure for the shutter and switch TFTs. It is observed that the offset voltage ($V_{in}$ − $V_{out}$) exists under active load bias because the operation needs an external voltage to overcome the $V_{th}$ of the driving TFT. This offset voltage can be calibrated by external or pixel circuit compensation techniques[13, 14]. By applying low-frequency small-signal analysis to this common-drain amplifier configuration with active load bias, the voltage gain would be higher with larger output resistance. Due to the very high output resistance induced by the circular TFTs compared to the low output resistance exhibited by the rectangular TFTs, a higher gain of voltage (close to one) was achieved, as can be seen in Fig. 4(b), compared to other reported rectangular oxide TFT based image sensors[15]. It should be noted that the voltage gains of the circular TFT-based active sensor approach almost one for all bias condition (results not shown), whereas those of the rectangular TFT-based one are much less than one.

## 5. Conclusion

We proposed a high-performance active image sensor pixel based on a-IGZO TFTs with a circular structure. The fabricated devices typically exhibited good performance with a mobility ($\mu_{FE}$) of 14.3 cm$^2$/(V·s), threshold voltage ($V_{th}$) of 3.2 V, and a subthreshold swing of 242 mV/decade. The circular TFTs, configured with the inner electrode as source and outer electrode

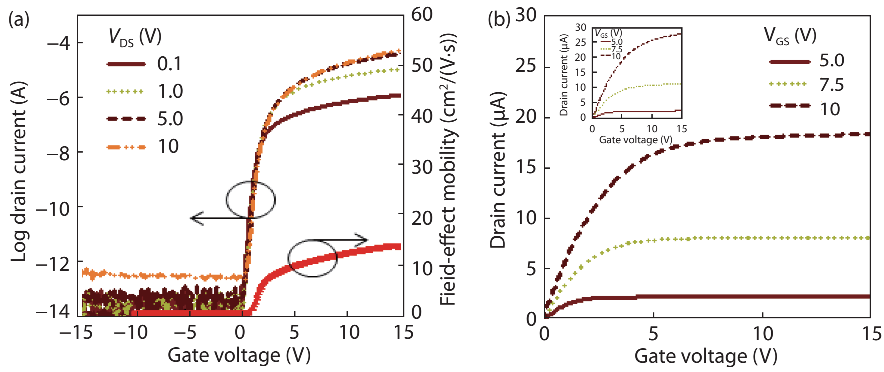


Fig. 2. (Color online) The typical measurement results of (a) transfer ($I_{DS}$–$V_{GS}$) and (b) output ($I_{DS}$–$V_{DS}$) characteristics of the circular a-IGZO TFTs with inner electrode as source and outer electrode as drain (inset is the typical output characteristics of a rectangular TFT).

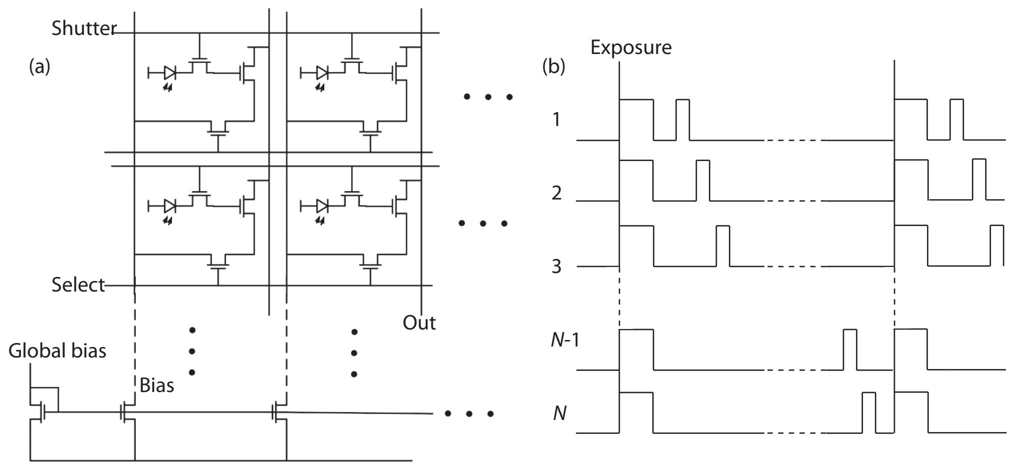


Fig. 3. The (a) schematic and (b) timing diagram of the proposed active image sensor.

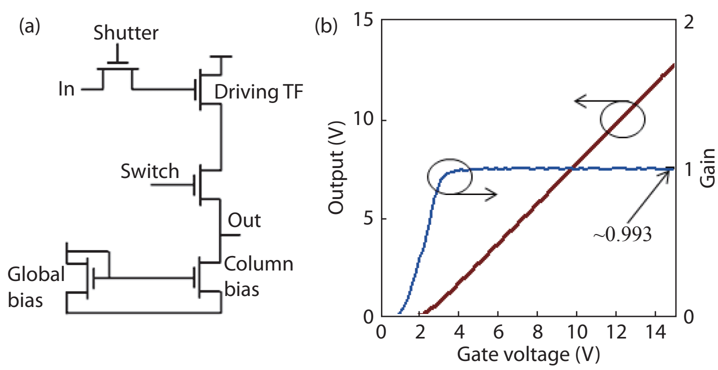


Fig. 4. (Color online) (a) Equivalent circuit, (b) output and gain of the proposed active image sensor pixel with circular a-IGZO TFT.

as drain, exhibited good saturation electrical characteristics and much higher output resistance compared to rectangular TFTs, resulting in a higher voltage gain (close to one). Given the very high output resistance exhibited by the circular TFTs, they can be used as driving TFTs in active image sensor circuits. They are, therefore, good candidates for image sensing applications such as medical diagnostic procedures.

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