

# A Novel High-Gain Operational Amplifier with Cross-Coupled Pair Based on a-IGZO TFTs

Kyungmin Choi<sup>1</sup>, Donghyuk Kim<sup>2</sup>, Hyunwoo Kim<sup>1</sup>, and Hojin Lee<sup>1,2,3\*</sup>

<sup>1</sup>Dept. of Intelligent Semiconductor, Soongsil University, Seoul 06978, Korea

<sup>2</sup>School of Electronic Engineering, Soongsil University, Seoul 06978, Korea

## Abstract

In this paper, we present a novel operational amplifier (OPAMP) with cross coupled pair (XCP) topology based on amorphous indium-gallium-zinc-oxide (a-IGZO) thin film transistors (TFTs). XCP structure is employed to boost the gain of the common-drain input stage, thus enabling the OPAMP to achieve a high gain of 34.2 dB. From the simulation results, the proposed OPAMP was confirmed to exhibit 3 dB bandwidth of 48.4 kHz, unit-gain frequency of 2.15 MHz, and phase margin of 48°, respectively.

## Author Keywords

a-IGZO; thin-film transistor (TFT); oxide transistor; operational amplifier (OPAMP); cross-coupled pair (XCP); positive feedback

## 1. Introduction

Thin film transistor (TFT) technology occupies an important role in advancing the integration of large-area and flexible electronics, as well as analog and digital building blocks [1], [2]. Among them, amorphous indium-gallium-zinc-oxide (a-IGZO) TFTs have attracted much interest as TFT backplane due to their high field effect mobility, low leakage current, and good electrical stability [3], [4], [5]. These advantages make a-IGZO TFTs suitable for the design of display backplane circuits such as the pixel circuit, scan driver, emission driver, and level shifter. Also, various logic circuits, such as operational amplifier (OPAMP), low dropout (LDO) regulator have been studied and demonstrated based on a-IGZO TFTs [6], [7], [8], [9].

OPAMP is a critical component in display driver integrated circuits (ICs) and mixed signal systems such as LDOs, DC-DC converters and analog to digital converters (ADCs) [10], [11], [12]. In conventional display driver IC systems, due to the relatively poor electrical properties of amorphous silicon TFT (a-Si TFT), display driver ICs including OPAMP, had to be fabricated based on complementary metal-oxide-semiconductor (CMOS) technology fabricated on the single crystalline silicon. However, by employing a-IGZO TFT based OPAMP instead of conventional single crystalline silicon semiconductor, it is possible to reduce manufacturing costs through process simplification and the elimination of additional module assembly steps [13].

In this work, we present a high gain OPAMP with cross-coupled pair (XCP) topology based on a-IGZO TFTs. The XCP topology incorporates a positive feedback structure, enabling the load of the common-drain differential pair to exhibit negative resistance, which significantly boosts the gain. The proposed OPAMP achieves excellent performances including open-loop voltage gain. Furthermore, based on proposed OPAMP, we provide substantial support for the possibility of fabricating other display systems within display driver ICs on a glass substrate by using a single a-IGZO TFT process.

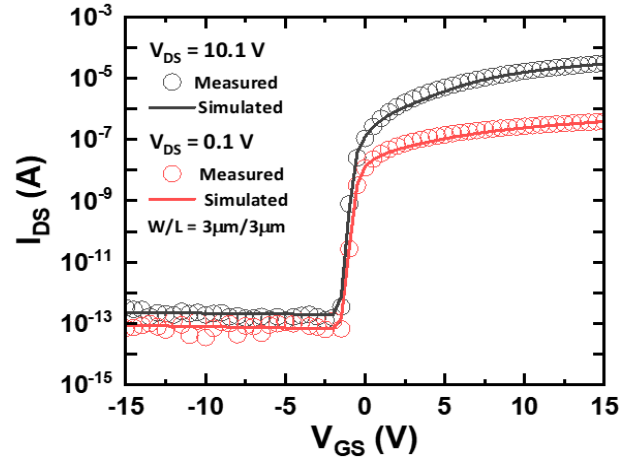


Figure 1. Measured and simulated transfer characteristics of a-IGZO TFT.

## 2. Proposed Op Amp & Simulation Result

The proposed OPAMP consists of eighteen n-type a-IGZO TFTs, and the whole circuit can be divided into three circuit blocks. Fig. 1 shows the measured and simulated transfer characteristics of a-IGZO TFT. The field effect mobility ( $\mu_{FE}$ ) is extracted as 11.53  $\text{cm}^2/\text{V}\cdot\text{s}$ , threshold voltage ( $V_{TH}$ ) is extracted as 0.8 V, and the subthreshold swing (S.S) is extracted as 150 mV/dec. Fig. 2 shows the overall schematic of the proposed OPAMP which consists of only n-type transistors, and table 1 summarizes the geometrical dimensions of TFTs used for the OPAMP.

In the first stage, T1, T2, T3 provides a stable bias voltage to T8 for the tail current to maintain a stable gain. Common drain differential pair (T4, T5) with cross-coupled connected load (T6, T7) is adopted to obtain high gain and high impedance through positive feedback. The XCP structure (T4-T7) can obtain high performance due to the gate and drain nodes of two transistors are intersect in a feedback structure. Thus, the equivalent resistance observed at each drain node in the XCP structure has a negative resistance. T9-T12 is a differential-to-single-ended converter with a current mirror that delivers the signal to the second stage. The second stage is composed of common source amplifier with diode-connected T13 and T14 to obtain high gain and high input impedance. Finally, the third stage acts as an output buffer with pseudo-CMOS inverter (T15-T18) to achieve a stable output node with low output impedance.

The calculated gain of the first stage is given by following equation

$$A_{1st} = A_{v1} \left[ \frac{1}{2} \left( \frac{g_{m11}}{g_{m11} + r_{o11}^{-1} + r_{o12}^{-1}} \right) \left( 1 + \frac{g_{m12}}{g_{m11} + g_{m12} + r_{o11}^{-1} + r_{o12}^{-1}} \right) \right] \quad (1)$$

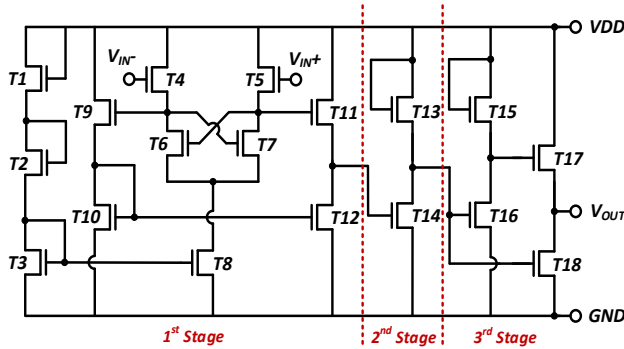


Figure 2. Circuit schematic of the proposed nmos OPAMP.

Table 1. Dimensions of a-IGZO TFTs used for the OPAMP.

TFT	W/L [μm]	TFT	W/L [μm]	TFT	W/L [μm]
T1	3/3	T7	120/3	T13	3/3
T2	3/3	T8	60/3	T14	55/3
T3	30/3	T9	30/3	T15	3/3
T4	24/3	T10	110/3	T16	5/3
T5	24/3	T11	30/3	T17	300/3
T6	120/12	T12	110/3	T18	50/3

Assuming all transistors in the first stage operate in the saturation region and their DC currents are same, the first stage's XCP structure half circuit and its small signal model are shown in Fig. 3(a) and Fig. 3(b). Applying Kirchoff's current law (KCL) at  $V_{OUT}$  in Fig. 3(b), the voltage gain of the XCP structure can be

$$A_{v1} = g_{m5}((g_{m5} - g_{m7})^{-1} || r_{o5} || r_{o7}) \quad (2)$$

$g_{m5}$  and  $g_{m7}$  represents the transconductances of T5 and T7,  $r_{o5}$  and  $r_{o7}$  represents their output resistances. The equivalent resistance observed at each drain node in XCP has a negative resistance. A qualitative analysis of negative resistance is that when current is applied to T7 drain node, the feedback structure causes current to flow in the opposite direction and interferes with the flow of the applied current. Due to the XCP connection of the load transistor T7, transconductance of T7 ( $-g_{m7}V_{OUT}$ ) can be replaced by a negative resistance ( $-g_{m7}^{-1}$ ). By properly adjusting W/L ratio of T5 and T7, some of the current that flows through  $g_{m5}^{-1}$  can be absorbed by  $g_{m7}^{-1}$ . As a result, the transconductance of T5 ( $g_{m5}$ ) is eliminated by the negative transconductance of T7 ( $-g_{m7}$ ), the voltage gain of XCP structure in Eq. (2) can be simplified as

$$A_{v1} = g_{m5}(r_{o5} || r_{o7}) \quad (3)$$

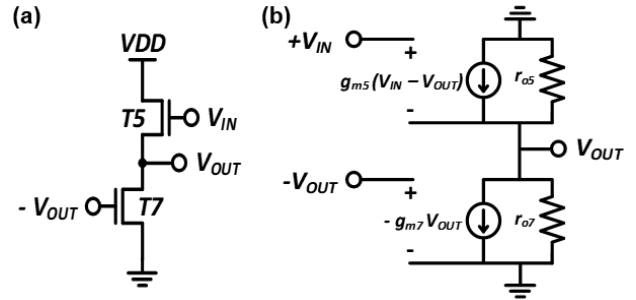


Figure 3. (a) Half-circuit of the common-drain stage with cross-coupled pair connected load, (b) its small-signal model.

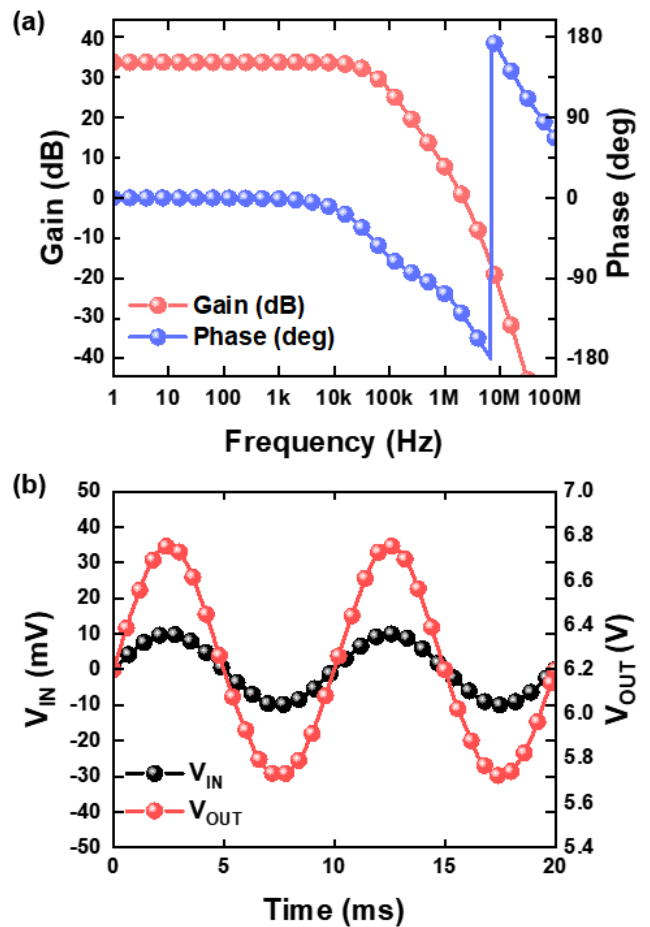


Figure 4. (a) The simulated gain and phase margin in the frequency domain, and (b) Simulated transient waveforms of the proposed OPAMP.

The calculated gains of second and third stage are given by following equation

$$A_{2nd} = -g_{m14}(\frac{1}{g_{m13}} || r_{o13} || r_{o14}) \quad (4)$$

$$A_{3rd} = -\frac{g_{m17}(r_{o17}||r_{o18})}{1+g_{m17}(r_{o17}||r_{o18})} \times (g_{m16} \left( \frac{1}{g_{m15}} ||r_{o5}||r_{o7} \right) + \frac{g_{m18}}{g_{m17}}) \quad (5)$$

By the equations (1)-(5), we can obtain the calculated gain of 19.5 from the first stage. The voltage gain of the first stage is dominant of all stages due to the XCP structure. Common source amplifiers in the second stage had calculated gains of 10.1. Finally, the output buffer with pseudo-CMOS inverter in the third stage had calculated gains of 4.4, resulting in an overall calculated gain of 34 dB.

The proposed OPAMP has been verified through HSPICE simulation tools. Fig. 4(a) shows the simulated frequency response of the proposed OPAMP with the DC supply voltage VDD of 15 V, VSS of ground simulated up to 100 MHz. The results show that the proposed OPAMP can have an open loop gain of 34.2 dB, -3 dB bandwidth of 48.4 kHz, unit-gain frequency of 2.15 MHz, phase margin of 48°. Fig. 4(b) shows the simulated waveforms of the proposed OPAMP for a frequency of 100 Hz.  $V_{IN+}$  is a sinusoidal input of 8V DC offset and 20 mVpp (peak to peak voltage). The waveform of  $V_{OUT}$  is 1.1 Vpp, indicating that the AC gain of the proposed OPAMP reached 34.2 dB.

### 3. Conclusion

We propose a novel high gain OPAMP based on a-IGZO TFTs, which comprises 18 n-type transistors. Negative resistance was obtained by XCP structure in the first stage of OPAMP, and thus boosted the gain of the common-drain input stage, resulting in the overall voltage gain of 34.2 dB from the proposed OPAMP. The simulated 3 dB bandwidth, unit-gain frequency, phase margin were verified to have 48.4 kHz, 2.15 MHz, and 48°, respectively. From the experiment results, we could construct high open loop voltage gain of OPAMP which would play an important role in advanced TFT-based integrated circuits.

### 4. Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT). (No. RS-2023-00218972) and the Korea Institute for Advancement of Technology (KIAT) grant funded by the Korea Government (MOTIE). (P0012451, The Competency Development Program for Industry Specialist) and the BK21 FOUR (Fostering Outstanding Universities for Research, No.2120231314754) funded by the Ministry of Education (MOE, Korea) and National Research Foundation of Korea (NRF).

### 5. References

[1] Muhammad Hassan, et al., "Significance of Flexible Substrates for Wearable and Implantable Devices: Recent Advances and Perspectives", *Adv. Mater. Technol.*, VOL. 7, 2021

[2] Gwon Byeon, et al., "Recent progress in the development of backplane thin film transistors for information displays", *J. Inf. Disp.*, VOL. 24, 2023

[3] Kenji Nomura, et al., "Room-temperature fabrication of transparent flexible thin-film transistors using amorphous oxide semiconductors", *Nature*, VOL. 432, 2004

[4] Liang-Yu Su, et al., "Characterizations of Amorphous IGZO Thin-Film Transistors with Low Subthreshold Swing", *IEEE Electron Device Lett.*, VOL. 32, 2011

[5] Jimin Park, et al., "Oxide thin-film transistors based on i-line stepper process for high PPI displays", *J. Inf. Disp.*, VOL. 24, 2023

[6] Xiang-Lin Mei, et al., "A common drain Operational Amplifier Using Positive Feedback Integrated by Metal-Oxide TFTs", *IEEE J. Electron Devices Soc.*, VOL. 9, 2021

[7] Fanzho Meng, et al., "A Performance Optimized Operational Amplifier Using Transconductance Enhancement Topology Based on a-IGZO TFTs", *IEEE J. Electron Devices Soc.*, VOL. 12, 2024

[8] Pydi Ganga Bahubalindrani, et al., "Analog Circuits With High-Gain Topologies Using a-GIZO TFTs on Glass", *IEEE J. Disp. Technol.*, VOL. 11, 2015

[9] Kenji Nomura, "Recent progress of oxide-TFT-based inverter technology", *J. Inf. Disp.*, VOL. 22, 2021

[10] Kichan Kim, et al., "a-InGaZnO Thin-Film Transistor-Based Operational Amplifier for an Adaptive DC-DC Converter in Display Driving Systems", *IEEE Trans. Electron Devices.*, VOL. 62, 2015

[11] Kichan Kim, et al., "a-InGaZnO TFT Based Operational Amplifier and Comparator Circuits for the Adaptive DC-DC Converter", *SID Symposium Digest of Technical Papers*, 1164-1167, 2014

[12] Daejung Kim, et al., "A Solution-Processed Operational Amplifier Using Direct Light-Patterned a-InGaZnO TFTs", *IEEE Trans. Electron Devices.*, VOL. 65, 2018

[13] Yuanfeng Chen, et al., "High-Speed Pseudo-CMOS Circuits Using Bulk Accumulation a-IGZO TFTs", *IEEE Electron Device Lett.*, VOL. 36, 2015