22.5 dB Open-Loop Gain, 31 kHz GBW Pseudo-CMOS Based Operational Amplifier with a-IGZO TFTs on a Flexible Film

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***Abstract*— This paper presents an operational amplifier based on pseudo-CMOS blocks and integrated in a flexible a-IGZO TFT technology. The circuit consists of only nMOS transistors, and the pair of active loads is in a pseudo-CMOS configuration. These active loads allow various kinds of common mode feedback schemes or cross-coupled connection, typical for CMOS operational amplifiers. The proposed amplifier is fabricated on a flexible film, and characterized with 5 V supply voltage and an output load capacitance of 15 pF. The measured open-loop gain is 22.5 dB, which is the highest reported for operational amplifiers in metal-oxide TFT technology. The measured bandwidth and gain bandwidth products are 5.6 kHz, and 31 kHz, respectively with 160 µW power consumption, which is lowest among flexible operational amplifies.**

Keywords—Flexible; a-IGZO TFT; operational amplifier; active load; low power.

I. Introduction

Recently there has been an increasing interest in realizing analog circuits with flexible electronics, and several differential amplifiers and analog building blocks have been reported [1-7]. In order to obtain a high-gain amplifier, CMOS technologies are obviously preferable: a two-stage operational transconductance amplifier with 51 dB gain implemented in a printed organic CMOS process is presented in [6]. A typical mobility of nMOS organic FET (OFET) is, however, lower than that of pMOS by an order of magnitude. The operation frequency of the circuit, therefore, tends to be limited by the performance of an nMOS OFET.

In order to overcome this imbalance of the mobility, a hybrid organic/solution-processed metal-oxide RFID tag is presented in [8]. The hybrid process, however, currently requires 250 ºC, and therefore, the circuit is fabricated on a rigid carrier. Similarly, it is challenging to realize a high-performance pMOS transistor in a metal-oxide TFT process. One of the high-mobility of NiO-based pMOS TFT is 5.2 cm^2/Vs, which is less than half of an available nMOS transistor [9]. Furthermore, its thermal oxidation process requires around 400 °C, which is unsuitable for flexible plastic films. Thus, design methodologies for both nMOS-only circuits in metal oxide TFTs and pMOS-only circuits in organic FETs are still essential.

Pseudo-CMOS, a design approach suited to flexible electronics, was introduced to realize high-gain logic gates such as inverters and NAND gates [10]. A pseudo-CMOS analog amplifier was also presented [11]. However, the amplifier is basically a logic inverter and cannot handle differential signals. In this context, this paper presents a pseudo-CMOS based operational amplifier implemented with a-IGZO TFTs. The proposed circuitry consists of only nMOS transistors, and the pair of active loads is realized in a pseudo-CMOS configuration.

II. Circuit Design

A. Conventional Topologies

Figure 1 shows the most conventional load configurations for operational amplifiers in flexible electronics. The passive load in Fig. 1(a) is inherently linear and the simplest option. However, a tens kΩ high resistance for each load is required to improve the voltage gain, and its area tends to be large. Diode-connected MOS topologies can reduce the area. The forward-biased MOS diode in Fig. 1(b) is still not optimal for a high gain. The reverse-biased (zero-V_{GS}) MOS diode in Fig. 1(c) is

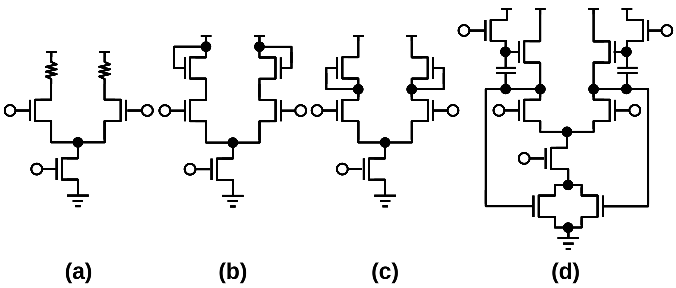

Figure 1. Conventional load configuration of operational amplifiers in flexible electronics. (a) Passive load. (b) Forward-biased MOS diode. (c) Reverse-biased (zero-VGS) MOS diode. (d) Bootstrap with common mode feed back**.**

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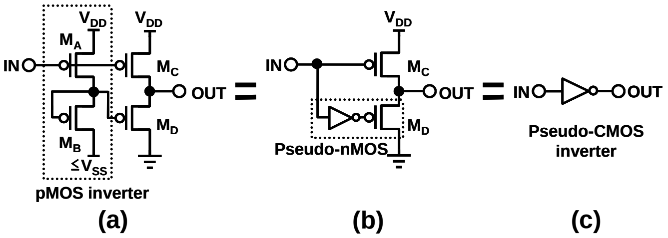

Figure 2. Pseudo-CMOS logic inverter [10]. (a) Original topology. (b) Simplified schematic. (c) Logic symbol.

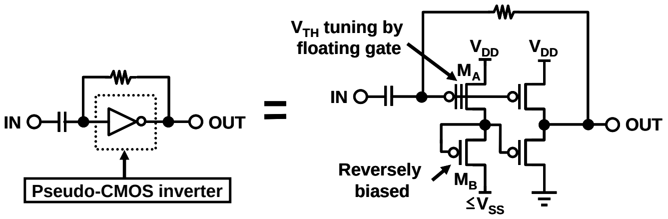

Figure 3. Conventional amplifier based on the pseudo-CMOS logic inverter in [11].

good for a high gain, however, it is more sensitive to process variation. The bootstrap with common mode feedback in Fig. 1(d) was introduced in [4] and is one of the good solutions available. The drawback is its four-transistor stack structure, which is unsuitable for low voltage operation. Therefore, a new active load configuration is desired.

Pseudo-CMOS, a design approach suited to flexible electronics, was introduced to realize high-gain logic gates such as inverters and NAND gates [10]. As shown in Fig 2, the pseudo-CMOS inverter consists of four pMOS transistors. A local "pMOS inverter", which consists of M_A and M_B as shown in Fig. 2(a), and M_D realize a "pseudo-nMOS" as shown in Fig. 2(b). Thus, M_C and M_D operate complementarily. In order to obtain a high inverter gain, the pMOS inverter is reverse-biased with extra voltage lower than V_{SS}.

Although the original pseudo-CMOS inverter was designed for logic circuitry, a pseudo-CMOS analog amplifier in Fig. 3 was also presented [11]. Since the amplifier is a logic inverter with a feedback resistor, which determines the bias point, it cannot handle differential signals. In addition, since M_A and M_B operate in cut off region at the same time, a V_{TH} tuning for M_A by its floating gate is required. In this context, this paper presents a pseudo-CMOS based operational amplifier implemented with a-IGZO TFTs.

B. Proposed Pseudo-CMOS Based Opamp

Figure 4 shows the schematic of the proposed pseudo-CMOS operational amplifier with the dimension of each transistor. The circuit consists of only nMOS transistors, and each active load is based on a pseudo-CMOS configuration. The active loads allow various kinds of common mode feed back schemes or cross-coupled connection as well as typical CMOS operational amplifiers.

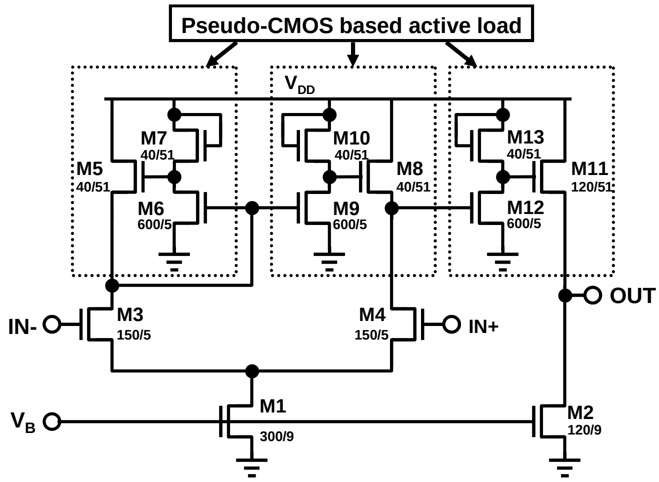

Figure 4. Schematic of the proposed operational amplifier, which has pseudo-CMOS based active loads. Note that the circuit does not require extra bias voltages higher than V_{DD}.

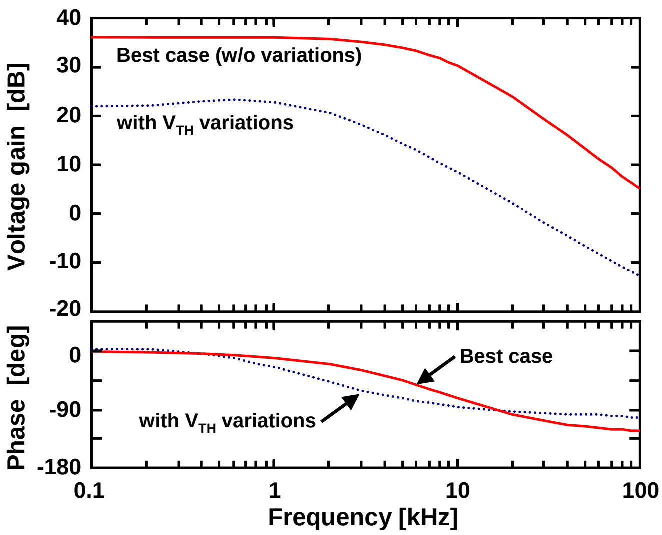

Figure 5. Simulated frequency response by Agilent ADS with our TFT model reported in [12]. Both the best case without any variations and the case with V_{TH} variations are plotted.

In order to reduce the sensitivity to the process variation, the diode-connected MOS transistors (M_7, M_{10} and M_{13}) are forward biased, while conventional pseudo-CMOS circuits use a reverse-biased diode. In addition, no extra voltages exceeding V_{DD} are required. To do so, each transistor size is carefully determined through the simulation with our TFT model reported in [12]. These modifications enable a stable operation of the amplifier, although the maximum open-loop gain and power consumption are slightly degraded.

Figure 5 shows the simulated frequency responses by Agilent ADS. The simulated open-loop gain with V_{TH} variations is approximately 21-23 dB and its bandwidth is 3 kHz with 15pF output capacitance. If there is no process variation, that is, when an adequate V_{TH} compensation scheme

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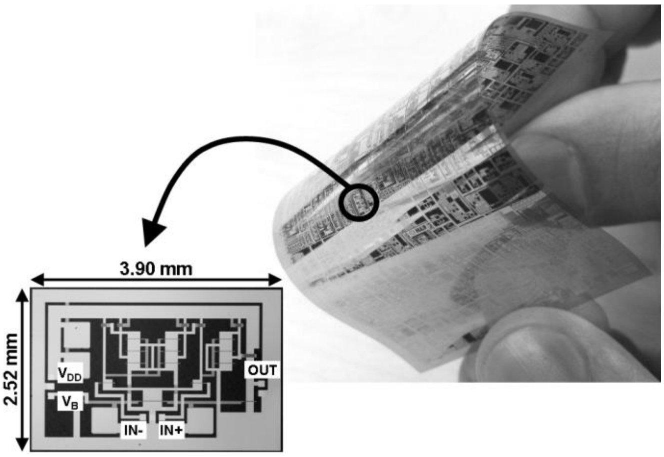

Figure 6. Photograph of the fabricated pseudo-CMOS based operational amplifier on a 50 µm-thick flexible film.

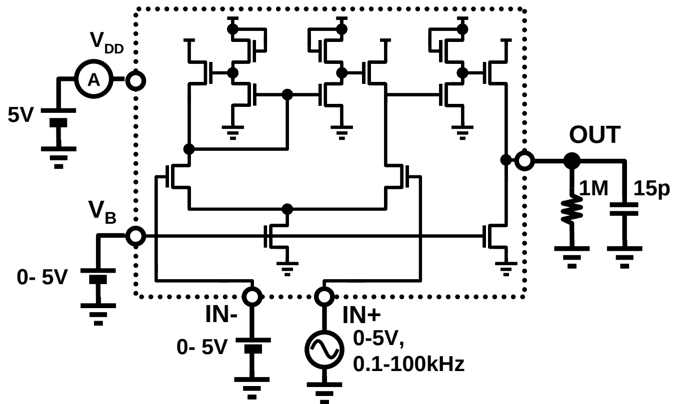

Figure 7. Measurement circuit and configuration.

is adopted to the amplifier, the open-loop gain and the bandwidth will achieve 36 dB and 6 kHz, respectively.

III. Measurement Results

Figure 6 shows a photograph of the operational amplifier fabricated on a 50 µm-thick flexible film using the a-IGZO process in [13]. The total area is 2.52×3.90 mm^2. The measurement circuit and configuration are shown in Fig. 7. The measurement was carried out with 15 pF capacitive load, which comes from the passive probe of the oscilloscope.

The measured time-domain output waveform with 10 mV$_{PP}$, 500 Hz sinusoidal input is shown in Fig. 8. The measured frequency response is shown in Fig. 9. The open-loop gain of 22.5 dB, which is close to the simulated gain with V_{TH} variation, is the highest gain reported for a differential amplifier in metal-oxide TFT, as shown in Table 1. The bandwidth and gain bandwidth products are 5.6 kHz and 31 kHz, respectively.

Although the measured bandwidth does not achieve the best-case simulation result, it is still wider than that by the simulation considering V_{TH} variation. On the other hand, the measured phase margin is not larger than the simulation result.

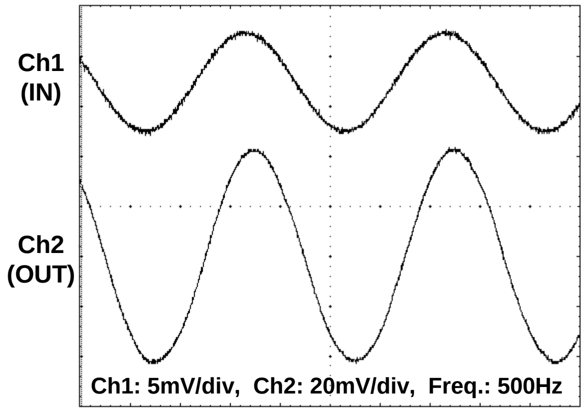

Figure 8. Measured waveform with a 10 mV$_{PP}$, 500 Hz sinusoidal input.

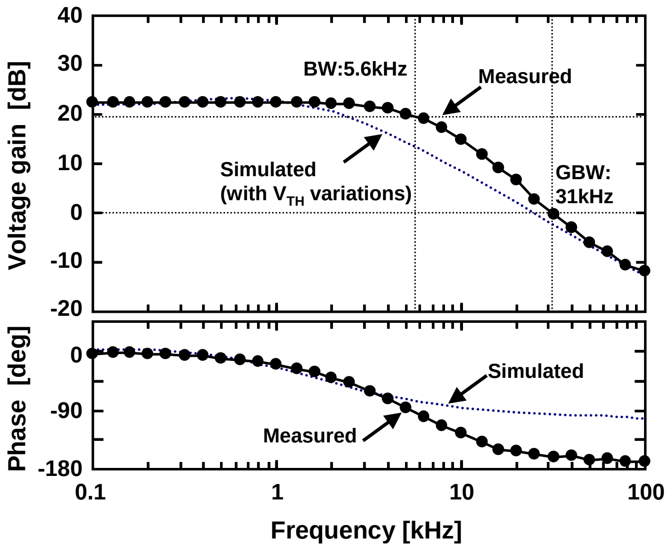

Figure 9. Measured frequency response. The BW and GBW are 5.6kHz and 31kHz, respectively.

This degradation can be improved by reducing layout parasitic capacitance and compensating V_{TH} variations in the TFTs.

This operational amplifier employs three logic inverters enabling the pseudo-CMOS based loads. Since the power consumption by the inverters is dominant in this topology, the total power consumption should be concerned. The measured power consumption of 160 µW with 5 V V_{DD}, however, is the lowest value reported for operational amplifiers. Key performances and comparison are summarized in Table 1 and Fig. 10.

IV. Conclusion

This paper presented a pseudo-CMOS based operational amplifier implemented with a-IGZO TFTs. The proposed circuitry consists of only nMOS transistors, and the pair of active loads is realized in a pseudo-CMOS configuration. The proposed amplifier is fabricated on a flexible film and verified by measurement with 5 V supply voltage. The measured open-

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TABLE I Comparison of differential amplifiers in TFT

	Marien et al., 2012 [4]	Maiellaro et al., 2013 [6]	Tai et al., 2012 [5]	Zysset et al., 2013 [7]	This work
Process	OFET pMOS	OFET CMOS	a-IGZO TFT	a-IGZO TFT	a-IGZO TFT
Substrate	Flexible	Flexible	Rigid	Flexible	Flexible
Load	Bootstrapped pMOS	CMOS	Resistor	nMOS diode	Pseudo-CMOS
V_{DD}	15 V	50 V	10.5 V	5 V	5 V
Open-loop gain	20 dB	51 dB	≈ 21 dB	18.7 dB	22.5 dB
BW	< 30 Hz	20 Hz	< 200 Hz	108 kHz	5.6 kHz
GBW	2 kHz	75 Hz	< 3 kHz	472 kHz	31 kHz
Power	225 μW	325 μW	N.A.	900 μW	160 μW

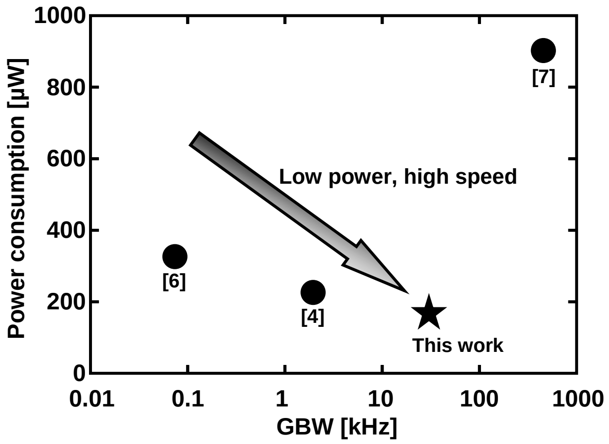

Figure 10. Performance comparison of flexible operational amplifier.

loop gain, bandwidth, gain bandwidth production, and power consumption are 22.5 dB, 5.6 kHz, 31 kHz, and 160 μW, respectively. The proposed active loads allow various kinds of common mode feed back schemes or cross-coupled connection, typical for CMOS operational amplifiers.

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