A high-gain two-stage amplifier using low-temperature poly-si oxide thin-film transistors with a Corbino structure

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ABSTRACT

This paper proposes a complementary metal-oxide-semiconductor (CMOS) amplifier using low-temperature poly-Si oxide (LTPO) thin-film transistors (TFTs). The Corbino structure used in the proposed amplifier has a higher output resistance than conventional amplifiers. The proposed circuit is composed of two CMOS inverters, one CMOS switch, and one input capacitor. It was possible to determine the operating point where the voltage gain could be kept high, regardless of the device variation, by shorting the gate input and output of the first amplifier. The alternating current component of the input signal was increased because the input signal was transferred to the first amplifier via the capacitor. The function of the second amplifier was to increase the total voltage gain. When a peak-to-peak voltage sine wave of 2 mV was applied at a frequency lower than 500 Hz, the proposed circuit showed an average voltage gain of 60.6 dB, which is the highest among the previously published TFT amplifiers.

ARTICLE HISTORY

Received 15 June 2022
Accepted 6 July 2022

KEYWORDS

Low-temperature poly-si oxide thin-film transistors; two-stage amplifier; Corbino inverter

1. Introduction

Currently, various backplane technologies have been used in display applications. For instance, thin-film transistors (TFTs) made of n-type hydrogenated amorphous silicon (a-Si:H) have been widely used in liquid crystal display panels. TFTs made of low-temperature polycrystalline silicon (LTPS) exhibit high mobility, thereby allowing for high-speed operation. N-type amorphous indium-gallium-zinc oxide TFTs, also known as oxide TFTs, have extremely low leakage currents and uniform device performance. LTPS and oxide TFT technologies have been widely used in mobile and large area displays, respectively. Recently, low-temperature poly-Si oxide (LTPO) TFT technologies have been actively studied for mobile applications [1]. The low leakage current of oxide TFT contributes to the realization of a variable refresh rate and low power consumption in display applications. As a result, various studies adopting the LTPO technology have been conducted, such as pixel circuits for displays using organic light-emitting diodes [2–5], liquid crystals [6–9], and micro-light-emitting diodes [10]. In addition to pixel circuits, LTPO technology has been studied in display circuits, such as gate drivers [2,11–13], level shifters [14], and inverters [15–19].

TFT-based amplifiers have become increasingly important as biometric data measurement via wearable devices has been actively studied [20–25]. Biosignal measurement, such as electroencephalogram (EEG), has made it possible to evaluate emotion [21–24] or stress [25]. EEG signals have frequencies below 100 Hz and amplitudes in the order of microvolts [26]. Therefore, an amplifier is required since the biosignals are remarkably weak. The amplifier must be located close to the signal source in order to amplify a small signal with less noise. Biosignals are detected on human skin or organs with uneven surfaces, indicating that a detection system implemented on a flexible substrate is the best solution. Therefore, flexible electronics have received a lot of attention [27,28]. TFT technology can be used to implement a biosignal acquisition system that includes amplifiers on a flexible substrate.

Among the TFT-based amplifiers, oxide TFT-based amplifiers have been continuously studied due to the advantages of oxide TFT such as low leakage current and low manufacturing cost. Voltage gains of complementary metal-oxide-semiconductor (CMOS) amplifiers using LTPO TFTs [16–19] ranged from 36.7–50.7 dB. Pseudo CMOS amplifiers [29, 30] exhibited voltage gains of 22.5 dB.
and 19.4 dB. It was reported that the voltage gain of an amplifier adopting n-type oxide TFTs was 23.52 dB [31].

This paper proposes a new amplifier using LTPO TFTs with a Corbino structure. The circular-shaped Corbino TFT features a very high output resistance [32], thus allowing for a high amplifier gain. The proposed amplifier adjusts the operating point of the inverting amplifier in order to amplify the signal regardless of the direct current (DC) component of the input signal. In addition, the proposed amplifier achieves a higher gain by connecting the two inverting amplifiers.

2. Proposed circuit

Figure 1 shows the proposed circuit and timing diagram of the control signals. The proposed amplifier is composed of two CMOS inverting amplifiers (M1–M4), a CMOS transmission gate (M5, M6), and a capacitor (CIN). The output of the first amplifier, VOUT1, is connected to the input of the second amplifier. Since the input signal VIN enters CIN, the proposed amplifier can only amplify the alternating current (AC) signal regardless of the DC component.

Switches M5 and M6 determine the input operating point of the first amplifier. The two control signals, Con and Conb, have opposite polarities, as shown in Figure 1(b). If both switches are turned on, VG and VOUT1 are connected.

Figure 2 shows the operating principle of the first amplifier. The red solid line represents the ideal transfer characteristics of the CMOS inverter. The green and blue lines are obtained by shifting the red solid line. Meanwhile, the black dashed line represents the relationship between VOUT1 and VG. VOUT1 = VG indicates that the inputs and outputs are shorted. The symbols shown in Figure 2 are the intersections between the dashed line and the three colored lines. In particular, VG can be initialized by shorting the input and output of the amplifier. A small input signal is transferred through CIN, as shown in Figure 1(a). The DC operating voltage of VG must be determined before transferring the input signal. This can be accomplished by shorting V G and VOUT1. The voltage gain is also calculated as the slope at the intersection between the transfer curve and the dashed line. The stiffer the slope, the higher the voltage gain. Higher output resistances of M1 and M2 result in a stiffer slope. As such, we used Corbino structures for the amplifier TFTs. The variation in device characteristics causes a shift in the transfer curve, as shown in Figure 2. Shorting V G and VOUT1 may result in a high slope, as shown in Figure 2. Therefore, the proposed amplifier can amplify a signal with a high voltage gain regardless of inverter characteristics.

The proposed circuit has an additional inverter amplifier connected to VOUT1. The second amplifier enhances VOUT1, which is the output of the first amplifier, thus achieving a significant voltage gain. VIN and VOUT2 are in phase when two inverting amplifiers are used.

3. Measurement results and discussion

The circuits were fabricated using an LTPO TFT process. The image on the left of Figure 3(a) shows the first
amplifier with $C_{\text{IN}}$ and switches. The second amplifier, shown on the right, is a simple inverter. The proposed amplifier was implemented by connecting the $V_{\text{OUT1}}$ of the first amplifier, as shown in Figure 3(a), to the input of the second inverter using two shorted probes.

Figure 3(b) shows the output characteristics of oxide TFTs with Corbino and conventional structures when $V_{\text{GS}}$ is 2 V. $R_1$ and $R_2$ of the n-type Corbino TFT ($M_4$) were 72 and 57 μm, respectively, in Figure 3(b), (c), and (d). The effective $W/L$ of the Corbino TFT was 26.9. The $W/L$ of the conventional TFT was 50 μm /10 μm. The red solid line and blue dashed line represent the drain currents of the outer and inner drain connections, respectively. An inner or outer drain indicates that the inner or outer circular electrode acts as a drain. The black dashed line shows the output characteristics of the conventional TFT. The measured output resistance $r_o$ of a conventional bar-type TFT was $42 \, \Omega$. The measured $r_o$ of the Corbino TFT with an outer drain was $403 \, \Omega$, which was higher than the inner drain with a value of $136 \, \Omega$. The measurement results confirm that the Corbino TFT has a much higher $r_o$ than the conventional TFT. Figure 3(c) shows the measured transfer curves of the p-type LTPS and n-type oxide TFTs with a Corbino structure when $|V_{\text{DS}}| = 0.1 \, \text{V}$. Figure 3(d) shows the output curves when $|V_{\text{GS}}| = 5 \, \text{V}$. The threshold voltages ($V_{\text{TH}}$) of the p-type and n-type TFTs were $-0.0$ and $0.2 \, \text{V}$, respectively. $R_1$ and $R_2$ of the p-type LTPS TFT were 25 and 10 μm, respectively, in Figure 3(c) and (d).

The circuit information for the proposed amplifier, as shown in Figure 1, is listed in Table 1. Transistors $M_1$–$M_4$ were of the Corbino type, whereas switching transistors

![Figure 3. (a) Micrograph of the fabricated circuit, and (b) measured output characteristics of the n-type Corbino TFT with ($R_1$, $R_2$) = (72, 57 μm) and conventional bar-type TFT with $W/L = 50 \mu m \/ 10 \mu m$, (c) transfer curve, and (d) output curves of the n-type Corbino TFT with ($R_1$, $R_2$) = (72, 57 μm) and p-type Corbino TFT with ($R_1$, $R_2$) = (25 μm, 10 μm).](image-url)
Table 1. Design parameters of the manufactured circuit.

| Devices | Value |
|---------|-------|
| M1      | W/L (R1, R2) 7.4 (14 µm, 6 µm) |
| M2      | 22.6 (33 µm, 25 µm) |
| M3      | 6.9 (25 µm, 10 µm) |
| M4      | 26.9 (72, 57 µm) |
| M5      | W/L 6 µm/6 µm |
| M6      | 6 µm/6 µm |
| CIN     | 3 pF |

Signals & power

| Range   |
|---------|
| Con, Conb from −5 V to +10 V |
| VDD/VSS | 10 V/0 V |

M5 and M6 were of the conventional (bar type). The W/L ratio of the Corbino TFT was calculated by using the following equation [33]:

\[
\frac{W}{L} = \frac{2\pi}{\ln \frac{R_2}{R_1}}
\]

where \( R_1 \) and \( R_2 \) are the inner and outer radii of the corresponding TFT, respectively. The definitions of \( R_1 \) and \( R_2 \) are shown in Figure 3(a). The \( R_1 \) and \( R_2 \) values for each Corbino TFT are shown in parentheses in Table 1. The voltage range of the two control signals was from −5 to 10 V. The turn-on time of M5 and M6 was 200 µs.

Figure 4 shows the measurement results of the proposed amplifier when an input signal with a frequency of 100 Hz was applied. The red and green lines represent \( V_{OUT2} \) and \( V_{IN} \), respectively. The initialization of \( V_G \) was conducted within 200 µs at 0 ms. The peak-to-peak voltage (\( V_{PP} \)) of the \( V_{IN} \) and \( V_{OUT1} \) were 2.1 and 18.7 mV, respectively. The \( V_{PP} \) of \( V_{OUT2} \) was 2.26 V. As a result, the voltage gain of the proposed amplifier was 1091.5 V/V (60.8 dB). The voltage gains of the first and second amplifiers were −9.1 and −120.3 (V/V), respectively.

During the initialization period, the \( V_G \) and \( V_{OUT1} \) were 5.24 V. Based on Figure 2, the voltage gain of the first amplifier is expected to be significantly high due to the 5.24 V operating point. However, the measured voltage gain of the first amplifier was −9.1 V/V because the AC component of the input signal, \( V_{IN} \), was not transmitted completely to the first amplifier. The actual voltage gain \( V_G/V_{IN} \) was less than one because of the input capacitances of M1 and M2. Therefore, the voltage gain of the first amplifier was only −9.1 V/V.

A second amplifier can be used to compensate for this issue. The red line in Figure 5 shows the measured voltage-transfer characteristics of the second amplifier. The black line indicates the calculated voltage gain, and it has the highest gain of −367.9 V/V when \( V_{OUT1} \) is 4.83 V.

Figure 6 shows the voltage gain as a function of the signal frequency. When the \( V_{PP} \) of the input signal was 2 mV, the proposed amplifier showed voltage gains of 60.1, 60.8, 60.0, 60.8, 61.3, 60.4, and 57.7 dB at frequencies of 10, 20, 50, 100, 200, 500, and 1,000 Hz, respectively.
Despite a low power supply of only 10 V, the voltage gain of 61 dB was the highest among the previous studies on LTPO TFT amplifiers [16–19].

The proposed amplifier features an LTPO process. The LTPO process is now available for flexible substrates. Furthermore, the amplifier adopts a Corbino structure and two-stage inverting amplifiers, which enable the highest voltage gain over previously published results. We believe that our amplifier can be used as a high-gain amplifier in a biosignal acquisition system implemented on uneven human skin.

4. Conclusion

A high-gain two-stage amplifier using LTPO technology was proposed. The proposed circuit is comprised of two CMOS inverter amplifiers, a CMOS switch, and an input capacitor. The voltage transfer characteristic exhibited a steep slope when using a Corbino-type TFT with a large output resistance of 403 MΩ. The first amplifier can be operated in the steep-slope region by shorting the input and output. Only a very small AC component of the input signal was amplified by using a two-stage inverter amplifier and an input capacitor. The measured voltage gain was 60.8 dB when a 100 Hz sine wave with a 2 mV VPP was applied. The proposed amplifier can be manufactured by using an LTPO process and integrated into wearable smart devices to measure biosignals.

Acknowledgement

This work was supported in part by the Basic Science Research Program through the National Research Foundation (NRF) under Grant NRF-2020R1I1A3A04037918 and in part by the BK21 FOUR Program through the Ministry of Education (MOE), South Korea. The EDA Tool was supported by the IC Design Education Center.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by National Research Foundation of Korea: [Grant Number NRF-2020R1I1A3A04037918].

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