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High-Gain Transimpedance Amplifier for Flexible Radiation Dosimetry Using InGaZnO TFTs

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ABSTRACT This paper presents a novel high-gain transimpedance amplifier for flexible radiation sensing systems that can be used as large-area dosimeters. The circuit is implemented with indium-gallium-zinc-oxide thin-film-transistors and uses two stages for the amplification of the sensor signal (current). The first stage consists of cascode current mirrors with a diode connected load that performs current amplification and voltage conversion. Then, the first stage is followed by a voltage amplifier based on a positive feedback topology for gain enhancement. The proposed circuit converts nano-ampere (10 nA) currents into hundreds of millivolts (280 mV), showing a gain around 149 dB and a power consumption of 0.45 mW. The sensed radiation dose level, in voltage terms, can drive the next stages in the radiation sensing system, such as analog to digital converters. These radiation sensing devices can find potential applications in real-time, large area, flexible health, and security systems.

INDEX TERMS Amplifier, a-IGZO TFT, positive feedback.

I. INTRODUCTION

Flexible systems with hybrid technologies are gaining significant interest in consumer electronics and health applications [1]. One of the successful combinations are oxide and organic thin-film-transistors (TFTs) that allows flexible, low-cost, large-area circuits or systems with low weight, suitable for wearable applications [2], [3]. These TFT technologies allow very low-temperature fabrication and large-area uniformity, leading to a direct integration of devices or circuits on the same substrate, resulting in compact integrated systems. Reliable X-ray systems for security purposes can benefit greatly from the possibilities offered by these alternative technologies.

The targeted radiation sensing application can play a vital role in health and security applications, such as, radio therapy for cancer treatment and in nuclear power plants or for laboratory workers, those who work in radiology and oncology departments, where real-time operation is often a demand for status alert. One well known radiation dosimeter is the thermo luminescent detector (TLD) [4]. However, this method is not capable of providing real-time dose measurements. If a sudden rise in radiation-dose levels occurs, either due to accidents or equipment malfunction, life threatening situations or severe system damage may occur. Then this work proposes a transconductance amplifier to achieve a real-time, operationally robust direct X-ray detection system with new functionalities, such as flexibility, large active area coupled to low-weight and low-power consumption. The amplifier is based on IGZO TFT technology owing to its robust performance against radiation dose levels [5], [6], large-area uniformity, relative high mobility, stability and compatibility with low-temperature fabrication [7]. The circuit is designed to match the electrical properties of organic thin film photoconductors acting as radiation sensors [8], [9]. In particular, it targets bis-(triisopropylsilylethynyl) pentacene (TIPS-pentacene) micro-crystalline organic thin films, that exhibit dark current 10-100 nA for bias <1 V and photocurrent ≈ 10 nA under

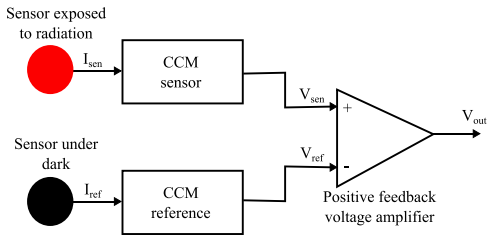


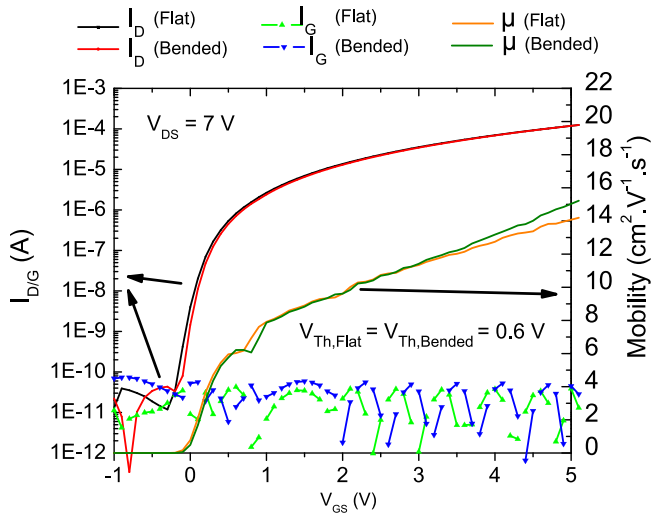
FIGURE 1. Proposed differential two-stage transimpedance amplifier block diagram.

an X-ray beam by a Mo-target X-ray tube with a dose rate of 55 mGys^{-1} [10].

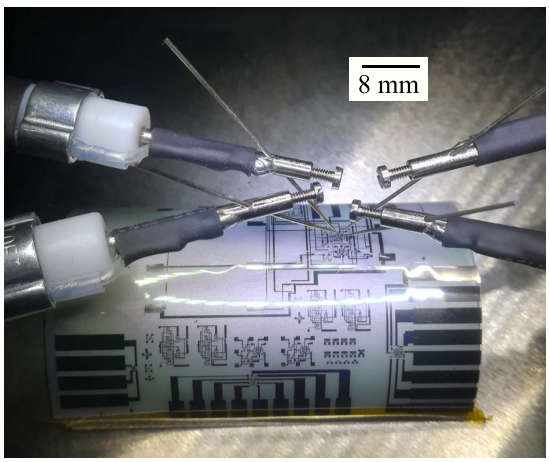
Due to its unique properties, as referred earlier, the demand for circuits based on IGZO TFT technology is increasing day-by-day. Many analog, digital and mixed-signal blocks have been reported, namely, logic gates [11], voltage amplifiers [12], [13], data converters [14] and V_{TH} compensation circuits [15]. However, the work done towards transimpedance amplifier is very limited, and with insufficient gain for the current application — a transresistance gain of 86.5 dBΩ as in [16], or ≈ 21 kΩ, rests well below the current need. The sensors in the current context generate currents in the nA range that need to be translated to hundreds of mV so the signal can be discriminated by ADCs based on oxide TFT technology [17]. Such specification demands a transresistance value of at least tens of MΩ. It should be noted that the radiation sensors (organic crystals) work at very low frequency (in the order of few Hz), therefore, bandwidth is not a stringent requirement [10]. In order to achieve this performance, a two-stage transimpedance amplifier is proposed, in which the first-stage includes cascode current mirrors (CCMs) with a diode connected load. This stage is designed in such a way that it achieves current gain, and the current is subsequently converted to voltage with a diode-load. The second-stage corresponds to a positive feedback voltage amplifier that further enhances the overall gain. The block diagram of the complete circuit is presented in Fig. 1. The amplifier is characterized from measurements at room temperature and atmospheric pressure.

A. DEVICE AND CIRCUIT FABRICATION

For gate, source, and drain electrodes a 60 nm-thick Mo layer was deposited by RF magnetron sputtering in an AJA ATC-1800 system. The oxide semiconductor was a 30 nm-thick IGZO layer, and both the semiconductor and dielectric layers were also deposited by RF magnetron sputtering, in an AJA ATC-1300 system. After annealing of the devices on a hot-plate for one hour at 180°C, a 1 μm-thick parylene-C (poly monochloro-p-xylylene) was deposited by chemical vapor deposition (CVD) in a SCS PDS 2010 system to act as a passivation layer for improving device stability [18]. The patterning of the electrodes and semiconductor was done by a liftoff process, while the dielectric and the passivation layers were etched by reactive ion etching in a Trion



(a)



(b)

FIGURE 2. (a) Drain, Gate currents and mobility of the TFT with and without bending (b) Test setup for measurements with a bending radius of 15mm, which is used to obtain the bending response reported in Fig. 2(a).

Phantom 3 system, with SF_6 and oxygen atmosphere, respectively. No intentional substrate heating was used during any of the deposition processes. Transistors and circuits were fabricated both on glass and 125 μm thick Polyethylene naphtalate (PEN) foil. Transfer characteristics and mobility (μ) of a TFT (width = 320 μm and length = 20 μm) on PEN with and without bending is presented in Fig. 2 (a). It can be noticed that bending is not showing any significant impact on electrical parameters. The devices are showing a threshold voltage (V_{TH}) of around 0.6 V and on-off ratio ≈ 10^7. Test setup with bending is presented in Fig. 2 (b) for a bending radius of 15 mm. Reliable operation of the TFTs with smaller bending radius would require thinner PEN substrates and/or tuning the thickness of the entire device stack (including substrate and encapsulation layer) so the TFT layers would stay closer to a neutral strain plane [19], [20].

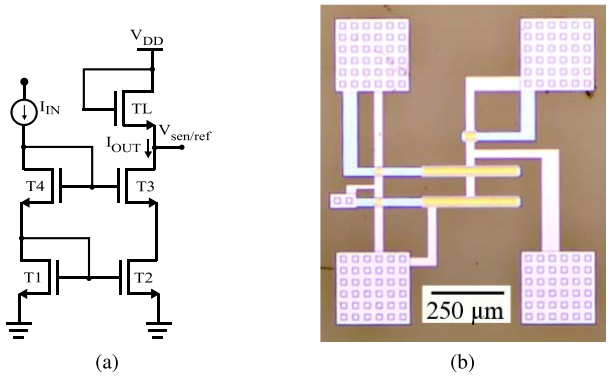


FIGURE 3. First amplification stage (a) circuit schematic (b) Micrograph of fabricated CCM.

II. CIRCUIT DESIGN

The proposed amplifier is targeted to amplify the radiation sensor output, which is in the order of nA. It should be noted that even when the organic sensor is under dark (i.e., not exposed to X-rays), the settling time of the output current can be in the range of minutes due to bias stress effects [10]. When a sensor is exposed to the radiation, its outcome is formed by two current components, one is time dependent and the other is proportional to the dose level. Since the final target is to detect the dose level, time dependent components should be canceled. To achieve this, a differential configuration is considered, where two identical sensors are used, in which one is exposed to the radiation while the other is kept under dark condition for reference generation. The differential current of these two sensors contain only the current that is proportional to the dose level as the time dependent behavior is being canceled out. The differential configuration also minimizes the effect on the amplification effectiveness of small variations occurring in the fabrication of different batches of the organic sensors (as compared to a single ended amplification approach).

The CCM circuit schematic and the micrograph are presented in Fig. 3. The circuit is designed to give current gain by choosing proper aspect ratios of the transistors, achieved by changing their channel widths (W). As it can be noticed from the micrograph, ($W_{T3} = W_{T2} = 320\ \mu$m) > ($W_{T1} = W_{T4} = 16\ \mu$m) and all the TFTs in the circuit have a channel length of 20 μm. The diode-connected load is implemented with a smaller TFT in order to achieve high load impedance ($\approx \frac{1}{g_m}$, g_m being the transconductance). The output current (I_{OUT}) and the output voltage (V_{OUT1}) of the first stage are given by,

$$I_{OUT} = \frac{W_{T2,3}}{W_{T1,4}} \times I_{IN} \tag{1}$$

$$V_{sen/ref} \approx V_{DD} - \frac{1}{g_{mTL}} \times I_{OUT} \tag{2}$$

This stage results in very high transimpedance gain, since the transconductance of IGZO TFT (g_{mTL}) is very small due to two reasons: (i) relative low mobility of the device resulting from amorphous nature of the semiconductor and (ii) small width of the diode connected load (T_L).

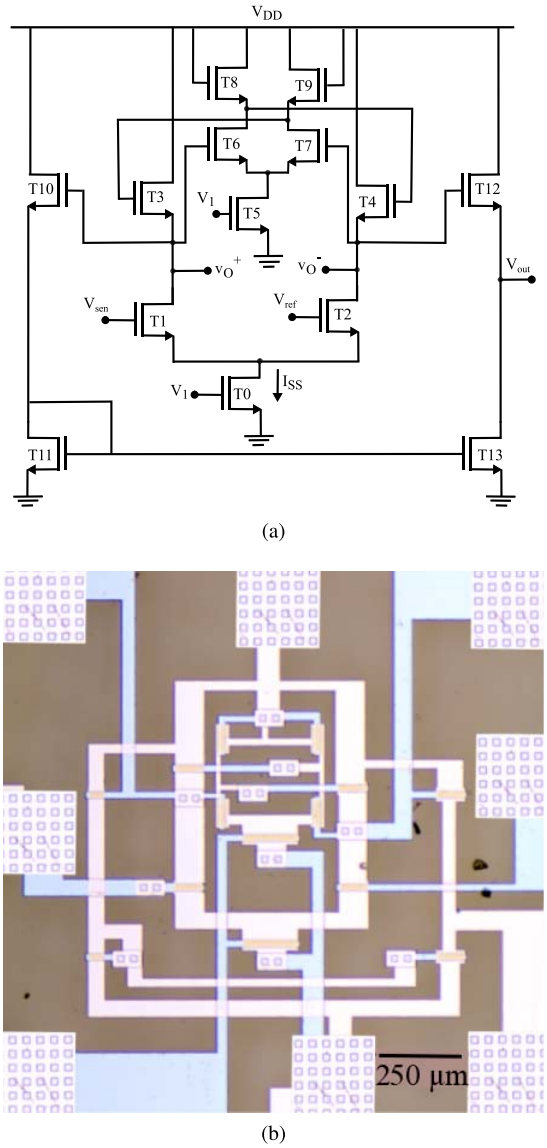


FIGURE 4. Second amplification stage using positive feedback (a) circuit schematic (b) Micrograph of fabricated Opamp.

Two CCMs were employed as first-stage amplifiers, where one CCM input is connected to the sensor exposed to the radiation and the other CCM input to the sensor under dark conditions to cancel out the common mode components.

The output voltages of these CCMs are being connected as inputs to the differential positive feedback amplifier [21], [22], whose circuit schematic and micrograph are shown in Fig. 4. It should be noted that the CCMs output nodes ($V_{sen/ref}$) are being connected to the gates of input transistors (T1 and T2) in Fig. 4(a), so that loading effects on first-stage amplifiers can be minimized as the gate impedance is very high (ideally open circuit). The only component left is the capacitive loading effect of gate-to-source capacitance (c_{gs}) from the input transistors (T1 and T2 in Fig. 4(a)).

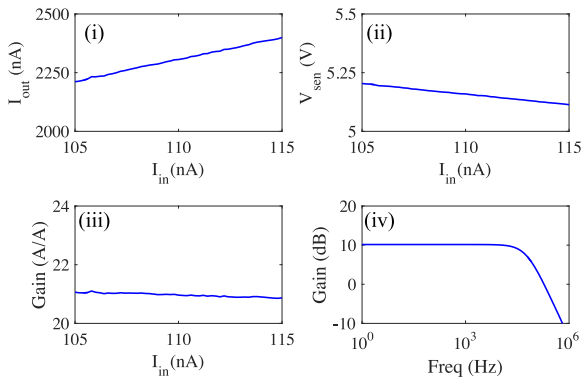


FIGURE 5. Measured amplifier response: (i) Output current (ii) Output voltage (iii) Current gain from CCM (iv) frequency response of the second stage positive feedback amplifier.

Therefore, the second-stage ideally does not load the first-stage at very low-frequency of operation, which is the case of the current application, considering the slow response time of the radiation sensors.

The second-stage positive feedback amplifier works based on g_m cancellation of the load transistors (T3 and T4) in Fig. 4. v_O+ and v_O- are the differential output voltages of the positive feedback amplifier and v_1 is the biasing voltage. The feedback loop formed by transistors T5 – T9 determines the feedback gain (A_f), which plays a critical role in the overall gain of the amplifier. Transistors T10 – T13 are responsible for differential to single-ended conversion, with a gain of almost one. The overall gain (A_{V2}) of this stage is given by,

$$A_{V2} \approx \frac{g_{m1,2}}{(1 - A_f)g_{m3,4} + g_{ds1,2} + g_{ds3,4}} \tag{3}$$

Care should be taken to ensure stability with $A_f < 1$, either by choosing proper aspect ratios or biasing conditions of those TFTs in the feedback loop. If $A_f > 1$, the effective load resistance may become negative leading to instability.

III. RESULTS AND DISCUSSION

The circuit was designed and simulated in Cadence environment, using in-house models of the IGZO TFTs [23] and custom design rules adapted for the fabrication processes established at CENIMAT—I3N. The circuit response reported in this section was obtained from glass substrates. While circuits were also fabricated on PEN foil, the rougher surface compared to glass resulted in high leakage at the input nodes of the positive feedback amplifier. Still, this is currently being addressed by modifying layouts and processes to avoid gate and source-drain layer crossings, by accommodating extra metal layers separated by thick interlevel dielectrics. Moreover, given the demonstrated robustness of individual TFTs under bending (see Fig. 2(a)), the proposed circuit is also expected to be totally insensitive to bending after addressing the fabrication yield issue mentioned above.

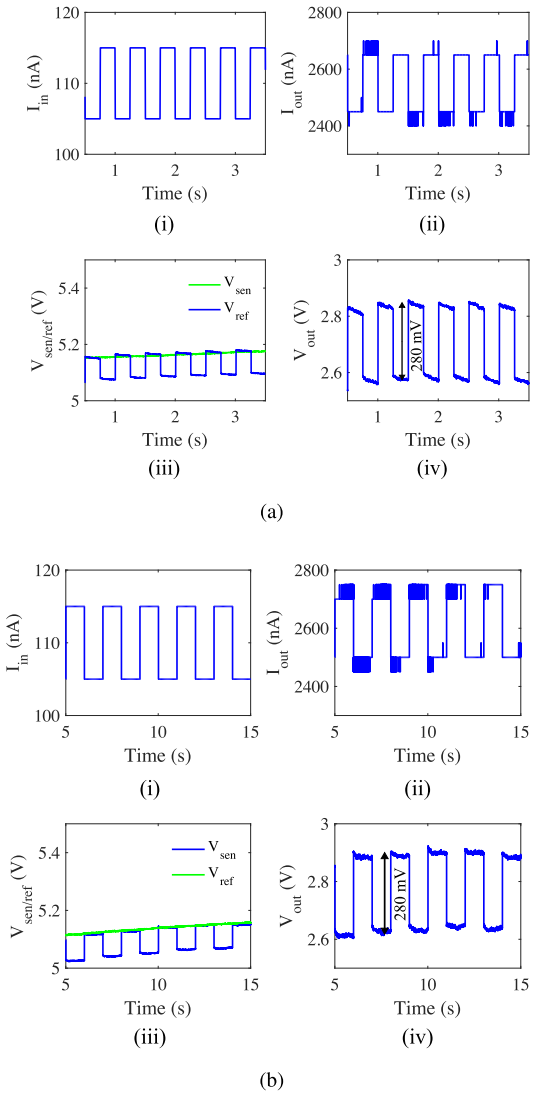


FIGURE 6. Proposed circuit measured response under normal ambient at (a) 2 Hz (b) 0.5 Hz : (i) Input current mimicking the sensor response, when exposed to radiation (ii) Current amplification from the first stage of the CCM sensor in Fig. 1. (iii) First-stage output voltages corresponding to the sensor exposed to radiation (V_{sen}) and sensor under dark conditions (V_{ref}) from Fig. 1 (iv) Final output voltage corresponding to a differential input current of 10 nA.

The main objective of the amplifier is to convert the sensor output current (in the nA range) into hundreds of mV, demanding a gain in the order of tens of MΩ.

However, there is no need for operating frequencies higher than few Hz, given the slow response time of the organic photoconductors [10]. The response of the isolated amplification stages is presented in Fig. 5, demonstrating the output current of the CCM (Fig. 5(i)), output voltage of CCM (Fig. 5(ii)), being able to convert a differential current of 10 nA into almost 95 mV. A current gain of around 20.8 A/A from the first stage can be noticed from Fig. 5(iii), where the masks were designed to obtain a gain of 20 A/A. Whereas, the second stage is providing a gain of 10 dB and gain bandwidth product (GBWP) of around 200 kHz, with

15 pF//10 MΩ. Measured time response is presented in Fig. 6 for two frequencies (2 Hz and 0.5 Hz). Due to differential nature of the amplifier, the impact of the common-mode input signals is minimized, including the bias stress effects of the TFTs (evident from Fig. 6(b)(iii)). It can be verified that V_{out} amplitude is insensitive to the operating frequency, amplifying the 95 mV from the CCM stage into 280 mV. Compared to the state-of-art gain reported for IGZO transimpedance amplifiers (86.5 dBΩ [16]), this work shows a significant improvement, by enabling a gain of 149 dBΩ, with a low power consumption of 0.45 mW at 10 V supply voltage. It should be noted that the overall gain of the amplifier is almost constant down to a supply voltage of 8 V and then the gain starts degrading with decrement in the V_{DD} value. Though very high values of V_{DD} improves voltage swing further, it trades with the power consumption. As a tradeoff between voltage swing and power consumption, the measurements are reported with a 10 V of supply.

IV. CONCLUSION

This work reports a high-gain transimpedance amplifier based on IGZO TFTs fabricated at low-temperature (≤180°C). The proposed circuit is able to convert nA range current into hundreds of mV with a low power consumption of 0.45 mW at 10 V supply voltage. In order to verify that the circuit would be suitable to match the slow response time of organic photoconductor X-ray sensors, its operation is shown to be stable at 0.5 and 2 Hz, revealing ΔV_{out} around 280 mV as a response to a ΔI_{in} of 10 nA. This represents a gain of 149 dBΩ, the highest reported in literature for a IGZO TFT transimpedance amplifier. The presented circuit can also be adapted to higher frequency applications, as suggested by the GBWP around 200 kHz measured for the positive feedback amplifier stage.

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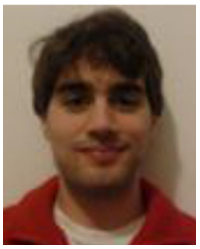

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