**Oxide semiconductor based deep-subthreshold operated read-out electronics for all-printed smart sensor patches**

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**Abstract**

The ability to fabricate an entire smart sensor patch with read-out electronics using commercial printing techniques may have a wide range of potential applications. Although the solution-processed oxide thin film transistors (TFTs) are capable of providing high mobility electron transport, resulting in large ON-state current and power output, there is hardly any literature report that uses the printed oxide TFTs, at the sensor interfaces. In contrast, here we propose and demonstrate that printed amorphous indium-gallium-zinc oxide (*a*-IGZO) based deep-subthreshold operated TFTs can be used to fabricate an entire sensor analog front-end electronics comprising signal amplifiers, and analog-to-digital converters (ADCs), which can successfully digitalize the analog sensor signal up to frequency range of 1 kHz. In addition, exploiting the high current oxide TFTs, a current drive circuit has been designed, and placed after the ADC unit. This current drive circuit is essential to offer sufficient power output, which can then be used to fabricate an easy-to-detect visual recognition of the sensor signal at a predefined threshold value crossover. Notably, the entire smart sensor patch is demonstrated to operate at a low supply voltage of ≤2 V, thereby ensuring that it can be an on-chip, energy source compatible, and standalone detection unit.

1. **Introduction**

Emerging electronics beyond Si-MOSFETs, which include solution-processed/ printed, and flexible electronics as well, are showing an ever-increasing demand for getting included in the daily-life applications.[1–6] In this regard, Internet of Things (IoT) or smart sensor systems are at the forefront, as there can be a need for high-volume device production, and the possible range of products may also be exceptionally wide.[7–10] However, when focussing on fully-printed circuits or sensor patches, the previous literature reports are quite limited.[11–14] It may be related to the fact that the complexity and reliability of such fully-printed smart tags demands are not easy to realize with the alternative device fabrication techniques, such as printing. For example, a smart sensor tag would require reliable read-out electronics, and wireless communication to transfer the sensor signal, certainly non-trivial to achieve using solution-processed TFTs. The key component of an analog front-end, i.e., the read-out electronics is the analog-to-digital converter (ADC), which is already rare to have fabricated using printing techniques. In fact, the previous reports on amorphous oxide-based ADCs are all realized using vacuum deposition techniques, mostly sputtering.[15–18] Moreover, there the ADC designs are quite complex, which may not be easy to replicate, when TFTs, and the other components are printed. On the other hand, these circuits are designed in a way that the supply voltage requirement is greater than 10 V, which is not compatible with the envisioned power source on-chip, fully printed smart sensor tags.

In an attempt to simplify the readout electronics, one may consider a much simpler ADC design, and an easy-to-detect, on-chip, audio-visual recognition of the sensor signal, as opposed to a complex wireless communication of the digitalized data. However, such audio-visual demonstration of the sensor signal or the ADC output, be it illumination based, a chemical reaction induced colour change of a material, or a small motorized mechanical movement, would always require a supply of large currents. On the one hand, this necessitates a current drive circuit to be placed in series to the ADC unit; on the other hand, the large current requirement ensures that the oxide TFTs become a natural choice, ahead of their organic counterparts.[19–25] However, within the oxide TFTs, there is also a serious performance mismatch between the high performing *n*-type and the low mobility *p*-type transistors.[26–28] Hence, it has often been found that all *n*-type unipolar logics perform way superior to the all-oxide CMOS electronics.[29–36] Nevertheless, it is also important to note that in the case of the proposed standalone smart sensor tag, the on-chip energy source would rather be limited, and consequently, the static, as well as the dynamic power dissipation of the unipolar logics should not be too high. In this regard, it is known that the Schottky contact TFTs can provide high gain with ultra-low power consumption, when operated at the deep-subthreshold regime, i.e., near the off-state of the transistors.[37–39] This strategy has been adopted to fabricate the high gain amplifiers and ADC units, where the DRIVE TFTs are always operated near the OFF-state of the transistors. The steep transfer curve at the deep-subthreshold regime also helps to attain a large signal gain of 140 and excellent noise immunity for the printed inverters, which are then used to realize common-source and differential amplifiers that can amplify the sinusoidal signals with an amplification ratio of 120, and up to an operation frequency of 1 kHz. Therefore, in this study, we primarily demonstrate a sensor, a high signal gain amplifier, an extremely simple design 1-bit ADC unit, with only 4 printed transistors, and a current drive circuit that is fed with the ADC output, and connected to a chemically-induced colour change based visual recognition unit, all printed using a commercial inkjet printer. Here, the visual recognition unit, which is comprised of two printed silver electrodes and a hydrochloric acid based solid polymer electrolyte, turns the shiny silvery colour of the first electrode to blackish-grey silver chloride, when exposed to the high voltage and current flow from the current drive circuit, induced by the change-of-state or switching of the ADC unit. Owing to the use of electrolyte-gated *a*-IGZO based TFTs, the entirely printed analog front-end is found to be operable at a small supply voltage of 1-2 V, thereby, making the all-printed smart tag compatible with on-chip, local energy sources, such as micro-supercapacitors and micro-batteries.

1. **Result and discussion**
   1. **Fabrication and electrical characterisation of electrolyte-gated a-IGZO TFTs and deep-subthreshold operated depletion-load type unipolar inverters**

The inkjet-printed, electrolyte-gated, *a*-IGZO semiconductor channel TFTs have been fabricated on glass substrates. This has been followed by subsequent printing of composite solid polymer electrolyte (CSPE) based gate insulator, and poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) as the top gate electrode.[29,32,40,41] A schematic of the printed bottom-contact, top-gate TFT device is shown in **Figure 1a**, and representative transfer and output characteristic curves are shown in Figure 1b-c, respectively. A statistics plot comprising transfer characteristics of 20 TFTs (*W*/*L*= 20 µm/ 50 µm) is shown in Figure 1d that demonstrates high reproducibility and low variability in device performance, which is quite essential for reliable circuit operation. Here, the ON-state drain current can be noted as 1.2 mA; this is a particularly high value for a *W*/*L* ratio of 0.4. It is only possible due to a conformal semiconductor-electrolytic insulator interface, thereby largely increasing the gating efficiency.[28,42,43] On the other hand, the large electric double layer (EDL) capacitance of the electrolytic insulator can induce strong band bending, and rapidly reduce the ITO/*a*-IGZO contact resistance within a small applied gate potential (~0.5 V) to ensure a semiconductor-electrode Ohmic contact formation.[29] In effect, the recorded subthreshold slope (*S*) is found to be very close to the Boltzmann’s limit (60 mVdecade-1) to support high transconductance efficiency. This contributes to high signal gain in printed inverters, and a large amplification ratio of the printed amplifiers. In addition, the selected large channel lengths (*L*= 50 µm) of the TFTs, immune them from the channel-length modulation effects, which lead to high output resistance (*r*o). In combination, the superior transconductance efficiency and the high output resistance are essential to obtain high intrinsic gain (*A*i), which is again mandatory for efficient, low-power electronic circuits (Supporting Information Figure S2). Here, the devices are found to exhibit very high On/Off ratio of >108, positive average threshold voltage of 0.6 V, and an average linear mobility of 24.3 cm2V-1s-1. In Figure 1 e-h, the important performance parameters of 20 TFTs, printed in a 4×5 array, on an identical substrate is demonstrated; once again, a low variability in the estimated threshold voltage, subthreshold slope, On-Off ratio, and linear mobility ensures that the printed TFT technology is matured to aim at complex circuit demonstration.

Next, using the *a*-IGZO TFTs, deep-subthreshold operated unipolar pseudo-CMOS inverters have been fabricated that show excellent noise immunity characteristics. The schematic of the inverter design is shown in **Figure 2a**. In this case, the DRIVE TFTs are fabricated with a device aspect ratio of *W*/*L*= 20 µm/ 50 µm, whereas, the LOAD TFTs have been designed with *W*/*L=* 50 µm/ 20 µm. The selected large variation in the device aspect ratio for the DRIVE and LOAD TFTs ensures that the DRIVE TFTs always operate at deep-subthreshold regime. A representative voltage transfer characteristics (VTC) of the depletion-load type inverter is shown in Figure 2b. The inverter gain (*η*) is a function of the supply voltage; the correlation of *V*DD with *η* for a particular inverter is shown in Figure 2c. Here, the maximum observed signal gain of the inverter is 140, at a supply voltage of 2 V; the statistics of maximum inverter gain for several inverters is shown in Figure 2d. It may be noted that the transition of the output voltage from the high-state to the low-state is very close to *V*DD/2, resulting in noise margin values i.e., NMH= *V*OH-*V*IH and NML= *V*IL–*V*OL, both to be quite high, as shown in Figure 2e. On the other hand, despite being unipolar logic, owing to the deep-subthreshold operation of the DRIVE TFTs, the dynamic power consumption i.e., *P*OUT= *V*OUT×*I*DD of the devices is found to be very low, in the tens of nW range (Figure 2f).

* 1. **Common-source and differential amplifiers**

A single inverter can also act as a common-source amplifier, as shown in **Figure 3a**; when a very small AC (sinusoidal) signal, the value of which is placed at the maximum gain of the inverter, is superimposed on a DC bias, a large amplification of the input AC signal can be achieved. Figure 3b-c shows the common-source amplifier operation with depletion-load type unipolar inverter; here a peak-to-peak sinusoidal signal of 15 mV at 100 Hz has been superimposed on a DC bias of 0.35 V, and an amplification of the input AC signal to a peak-to-peak output of 1 V has been achieved. The signal gain vs. input signal frequency is shown in Figure 3d. This infers that the amplification capacity of the electrolyte-gated inverters is quite substantial at lower frequency values, and at higher frequency, the amplification decreases to reach unity amplification at 1 kHz, which is a gain-bandwidth product of nearly 1000. However, when such amplifiers are employed at sensor interfaces, the operation frequency of 100 Hz would typically be sufficient for all practical applications; for example, the high gain values at lower frequencies can be used to amplify even the ultra-small electrophysiological signals at µV range to easy-to-record mV level (Supporting Information Figure S5).

Next, it is demonstrated that differential amplifiers may also be fabricated following an identical protocol; here, 4 TFTs are used, two DRIVE (*W*/*L*= 20 µm/ 50 µm) and two LOAD TFTs (*W*/*L*= 50 µm/ 20 µm) are connected to the common supply (*V*DD) and common ground (GND), respectively, as shown in Figure 3e. It operates in a similar manner as the common-source amplifier, the only difference is that the output signal from both the inverters, connected side-by-side, is considered, and differentiated to find out the resultant output signal. In effect, the differential amplifier produces an amplified output signal, which is proportional to the voltage difference of the two input signals (*V*IN1 and *V*IN2) applied to the respective inverters, as shown in Figure 3f. Notably, the differential amplifiers are used to magnify small noisy signal, where the differential input is used to eliminate the noise. Consequently, this circuit is also called a subtractor circuit.

where, *V*O1 and *V*O2 are the output voltage of each individual inverter 1 and 2 respectively, *V*IN1 and *V*IN2 are the corresponding input voltage to the inverter 1 and 2 respectively, A represents the gain of the inverters, which is considered to be equal for both the inverters. Here, the electrolyte-gated differential amplifier is characterized with two different amplitudes of sinusoidal input signal, i.e., the inverters are provided with a peak-to-peak sinusoidal signal of 15 mV and 10 mV, respectively. The differential output voltage (*V*D) is having sinusoidal oscillation of 0.6 V, which is an amplified version of 5 mV differential input (*V*IN1 - *V*IN2) signal, as shown in Figure 3g-i. As the principle of operation of differential amplifier is similar to the common-source amplifier, the amplification in relation to the input signal frequency is expected to be identical. Indeed, a similar trend has been noted (Figure 3j), where up to the input signal frequency of 100 Hz, the high amplification ratio is maintained, and later a quick drop towards higher frequencies is observed.

* 1. **Analog-to-Digital Converter (ADC) based on depletion-load type inverters**

Analog-to-digital converter (ADC) is the key component of any communication system. It is required to convert the analog/ continuous input signal into the digitalized output signal. Here, we demonstrate feasibility of a fully-printed smart sensor tag with printed sensors, common-source/ differential amplifiers, ADCs and a current drive circuit, which can be operated at an on-chip energy source (micro-supercapacitors or micro-batteries) compatible low voltage (1-2 V) values; the scheme of the entire printed sensor tag with on-chip power supply and visual recognition of the sensor signal is shown in Supporting Information Figure S6. In this regard, at first, a simple ADC circuit design is proposed, which would be easy-to-print and offer stable performance, with high reproducibility. The proposed ADC design is schematically shown in **Figure 4a**; initially, only a 1-bit ADC unit is conceived and demonstrated, which would act as a switch and record a predefined threshold crossover of any selected sensor unit. The proposed ADC unit consists of 4 TFTs, in which, the device aspect ratio of the TFTs have been carefully chosen, as shown in Figure 4a. Here, the designed 1-bit ADC unit has two stages (analogous to 2 inverters connected in series), where the DRIVE TFT of the first stage receives the input analog signal from the sensor, while the LOAD transistor is fed with a reference voltage (*V*REF), the value of which controls the position of switching of the ADC output, with respect to the analog sensor signal, as shown in Figure 4b-c. Here, the applied *V*REF determines the input voltage of the T3-TFT, and thereby the voltage distribution between the DRIVE and LOAD TFT, at the second stage, and in turn it controls the output voltage of the ADC unit, with respect to the sensor signal. Therefore, the *V*REF is the tool to control the predefined threshold point of the sensor signal, where the digitalized ADC output would switch from one state to the other. It may also be noted that initially the change in *V*REF from 0.1 V to 0.9 V causes a large shift in the output voltage of the ADC, with respect to the input sensor signal, however, beyond 0.9 V, the degree of the ADC output shift reduces considerably. This is actually related to the transfer characteristic of the T2-TFT; the shift in the ADC output is large, when the transistor channel conductance is in the linear regime, and the shift becomes shallow, when it enters the saturation region. The schematic of the ADC unit with a common-source amplifier to amplify the sensor signal is shown in Figure 4d; with the addition of the amplifier before the ADC unit, the switching characteristics of the ADC output become substantially sharper, as shown in Figure 4e-f. At this point, in order to verify the environmental stability, and shelf-life of the circuit elements, or the printed smart sensor patch, both the ADC unit, and the amplifier plus ADC unit have been re-measured after 1 month to record an identical circuit performance, even when they have not been encapsulated (Supporting Information Figure S8 and S9). Next, the common-source amplifier and the ADC unit are tested together for their switching reliability or stability. Initially, the amplifier alongside the ADC unit is supplied with an input signal sweep between 0 to 2 V, with a constant supply voltage, *V*DD= 2 V. The ADC in response shows digitalized undistorted output data between 0 to 2 V, up to 5 h, after which the ADC output is noted to be distorted, and not completely going back to 0 V (Figure 4g). However, after 10 minutes of idle time, the ADC unit again demonstrates complete switching, as shown in Figure 4h. On the other hand, when the input voltage sweep is reduced to 0 to 1 V, the switching of the ADC unit with respect to the input signal is observed to remain completely unaltered for more than 18 hours (Figure 4i).

The analog-to-digital conversion of a triangular waveform input to a square-wave output is shown in **Figure 5a-b**; with applied triangular input of 1 V, the output voltage swings from 2 V to 0 V, when the input voltage rises above 0.6 V, and it swings back to 2 V, when the input voltage falls below 0.6 V (Figure 5b), thereby, demonstrating a clear analog-to-digital signal conversion. Next, a voltage divider circuit that constitutes a constant resistor (10 kOhm) and a variable resistor in series, is connected before the amplifier unit, where the constant resistor is connected to the supply voltage, *V*DD, and the variable resistor/ rheostat, which controls the voltage to be fed to the amplifier unit, is connected to the ground, as shown in Figure 5c. The entire arrangement must respect one important precondition that the resistance connected across the input of the amplifier unit cannot be more than the gate-source resistance of the receiving transistor. The maximum gate current of the electrolyte-gated TFTs typically varies between 5-10 nA, as shown in Supporting Information Figure S11. Therefore, it is safe to have the series resistance value of the voltage divider circuit up to 10 MOhm. Here, the output voltage of the ADC unit is measured, while the input voltage to the amplifier is controlled by the variable resistor, within a particular voltage range. Figure 5d is showing the digitalized output voltage. An optical viewgraph of the amplifier alongside the ADC unit is shown in Figure 5e. On the other hand, a video of the live experiment is provided as the Supporting Information Movie S1; a still image of the video showing the ADC output voltage variation, in response to the resistance modulation in the variable resistor, is shown in Figure 5f.

* 1. **ADC circuit integrated with temperature sensor**

After observing the performance of the amplifier and the ADC unit with the voltage divider circuit, it has been possible to anticipate that the circuit would work with an actual resistive sensor as well. A resistive sensor is an active material placed between two metal electrodes, whose resistance changes with the change in an external stimulus, which can be anything between temperature, humidity, pressure, proximity, UV, visible light, IR, gas, volatile organic species (VOCs), chemical, metal ions, biological molecules etc. The change in the sensor unit would change the voltage drop across it, which in turn varies the intermediate voltage of the voltage divider circuit, the voltage that is fed to the common-source amplifier (Supporting Information Figure S6). In order to demonstrate the 1-bit ADC trigger by a real sensor unit, a temperature sensor fabricated with Mxene (Ti3C2T*x*) 2D metal sheets, in combination with polyvinyl alcohol (PVA), and polyvinyl pyrolidene (PVP) has been used, as shown in **Figure 6a**. It is observed that the state of the ADC output voltage changes from 0 V to 2 V, when the temperature experienced by the Mxene-based temperature sensor exceeds 75 °C, and it reverses to 0 V, when the experienced temperature by the sensor unit reduces below 77 °C, as shown in Figure 6b-c and Supporting Information Movie S2. The observed 2 °C hysteresis is primarily due to the temperature sensor itself, as shown in Supporting Information Figure S15d. The temperature at which the ADC output switches (from 0 V to 2 V) can be adjusted for the same sensor either by adjusting the resistor connected in series with the sensor unit, thereby changing the input voltage at the common-source amplifier, or by changing the value of *V*REF in the ADC unit. This has been demonstrated with the same sensor unit, where the temperature set-point for the ADC switching has been altered to 32 °C, as shown in Supporting Information Figure S16, and Movie S3. Considering the above experimental results, one can be assertive that the printed sensor-amplifier-ADC combination is working as a switch that can easily detect a certain lower or upper threshold value crossover of any sensor unit. At the next step, multi-bit ADC units may also be fabricated to further discretize the sensor output to multiple ranges (Supporting Information Figure S17).

* 1. **ADC unit alongside the current drive circuit for high current applications**

In order to easily comprehend the switching of the ADC unit at the user-end, it is essential to have a specific work done that would help to visualize the event of the digital switching. This would require a high power output, whereas the ADC output is purely a potential variation with very low current flowing through the inverter-like units, especially when the DRIVE TFTs are always near their Off-state. Therefore, in order to ensure an easy visualization of the ADC switching, a current drive circuit must be connected, after the ADC unit. This current drive circuit may simply be a few high-current oxide TFTs placed in parallel, whose drain electrodes are connected to the supply voltage, and the gate electrodes are connected to the output of the ADC unit, as shown in Supporting Information Figure S6. When the ADC output is 0 V, these current drive circuit TFTs are in their Off-state, however, when the ADC output is 2 V, the large positive gate voltage on these *n*-type oxide TFTs would ensure that they are at ON-state, and therefore a large current would flow through these TFTs. In the present study, the current drive circuit consists of only one TFT; as the printed oxide TFTs can easily carry milliamperes of current, it has been found sufficient for the demonstrator that is shown in this study (Figure 6d-f). Here, the source electrode of the current drive circuit TFT is connected to the visual recognition patch (Figure 6d). The visual recognition patch is comprised of two printed silver circles, and a printed aqueous solid polymer electrolyte based on 3 wt.% of PVA and 1 M HCl, which covers the silver electrodes. While, one of the two printed silver circles is connected to the current drive circuit TFT, and the other one is connected to the common ground (Figure 6d). When the ADC is in its OFF-state, the current drive circuit TFT is also in its OFF-state, thereby the entire supply voltage (*V*DD) drops across that current drive circuit TFT, and the printed silver circle receives 0 V. Therefore, there is no potential difference between the silver electrodes and hence both of them appear shiny silvery in colour. However, when the ADC output changes to 2 V, the current drive circuit TFT switches ON, with minimal resistance and potential drop across it; this also allows a large current to flow. In this situation, a potential difference of 2 V is applied across the printed silver circles, which leads to AgCl formation at the silver circle that is at a higher potential. The AgCl being dark grey in colour, the silver electrode that is connected to the current drive circuit turns blackish grey, thereby providing a clear visual recognition of the ADC switching event (Figure 6e-f).

The VTC plot of the entire circuit is shown in Figure 6g, where the current passing through the circuit is high i.e., around 800 µA, when the output voltage of the ADC unit is high (2 V), and the current passing through the circuit is negligible, when the output voltage of ADC unit is low. Here, with a constant supply voltage of 2 V, when the input voltage of the amplifier is switched continuously between 0 V to 1 V, not only does the output voltage of the ADC change between 2 V to 0 V, but the output current of the current drive circuit also changes in phase with the ADC switching (Figure 6h). The circuit performs well over 3 h without any deterioration in its performance, as shown in Figure 6h and it’s believed that the circuit may perform in the similar manner for more than 18 h, as it has been the case for the ADC unit with the input voltage varying between 0-1 V (Figure 4i). Summarizing it up, in the present study, the idea has been to utilize the voltage-controlled current source mode circuit to identify the pre-defined sensor signal crossover, or the ADC switching, with the help of a visual recognition unit, which may either be electrochromic or LED lighting, or a chemical change induced variation of colour of a material etc. On the other hand, being a one-time event, such printed sensor tags with read-out electronics may also be used as a high-tech, and difficult-to-replicate, anti-counterfeit tag, where, the first-time exposure of the sensor unit to some specific stimulant, e.g., light or air (oxygen or humidity) or a specific chemical substance can be used to trigger the change of state of the ADC unit, which with the help of the visual recognition unit can ensure authenticity of a particular product.

1. **Conclusion**

In summary, a fully-printed smart sensor tag with readout electronics is presented. The analog front-end uses electrolyte-gated oxide TFTs and *n*-type unipolar logics; however, owing to the deep subthreshold operation of all the DRIVE TFTs, the power consumption of the circuits remains low to only a few nW level. On the other hand, the depletion-load type inverter design offers a high signal gain of 140, at a supply voltage of 2 V, and with superior noise immunity. Next, the common-source and differential amplifier are demonstrated with an amplification ratio of 120, and a fairly steady amplification ratio up to 100 Hz, which is certainly sufficient to be used at sensor front-end readout electronics. This follows with an easy-to-realize, four transistors 1-bit ADC design, which can successfully digitalize the input analog signal. Next, with the help of a current drive circuit and visual demonstration unit, it has been possible to demonstrate a fully-printed smart sensor tag, which can identify the crossover of a predefined threshold of the sensor and provide an easy recognition of the event. It may be foreseen that such fully printed sensor tags can have a wide range of applications, for example, at industrial premises, for food and drug safety, as biosensors and medical diagnostic kits, for soil tests, or for various similar applications, where an inexpensive and large volume of reliable smart sensor tags are required.

1. **Experimental methods:**

***Semiconductor ink preparation:***

The inkjet printable 0.03 M *a*-IGZOsemiconductorprecursor ink was prepared (with atomic ratio of In:Zn:Ga= 70:20:10) by dissolving indium (III) nitrate hydrate ([In(NO3)3.*x*H2O], 99.99%, trace metal basis), gallium nitrate hydrate (Ga(NO3)3.xH2O, 99.99%, trace metal basis) and zinc acetate ((CH3CO2)2Zn, 99.99%, trace metal basis) in deionised water, ethanol (C2H5OH, 99.99%) and ethylene glycol (EG, C2H6O2, 99.99%), maintaining a (V/V) ratio of 45:40:15. Here, all the chemicals were procured from Sigma-Aldrich Chemie GmbH and used as-received, without further purification.

***Preparation of Composite Solid Polymer Electrolyte (CSPE) ink*:**

In order to prepare the composite solid polymer electrolyte (CSPE), the 0.3 g of synthetic polymer, poly(vinyl alcohol) (PVA) was dissolved in 5 ml of DMSO, at 90 °C for about 1 h. The supporting electrolyte/ salt, 0.07 g of lithium perchlorate (LiClO4) was dissolved in 1 ml of plasticizer, propylene carbonate (PC) at room temperature. After 1 h of stirring, both the solutions were mixed together and stirred for another 12 h at room temperature, in order to obtain a completely homogeneous CSPE solution. All the chemicals were procured from Sigma-Aldrich Chemie GmbH as used as received.

***Structural and Morphological Characterization*:**

The structural characterization of the *a*-IGZO films was carried out using Rigaku SmartLab grazing incidence X-ray diffractometer with Cu-Kα X-ray source (40 kV, 30 mA), and with a constant grazing incidence angle of 0.5°. The morphological characterization and energy dispersive X-ray (EDX) analysis of the printed thin films were carried out using Ultra55 FE-SEM (Karl Zeiss).

***Device Fabrication*:**

The thin film transistor design is shown in Figure 1a. The source and drain electrodes were defined by lithographically patterned ITO electrodes. The inkjet printing was carried out using Dimatix 2831 functional materials printer. The used 0.03 M *a*-IGZO (In:Zn:Ga= 70:20:10) precursor ink contained 15 vol.% ethylene glycol, which was added to ensure homogeneous, predominantly amorphous film formation. The printing of the *a*-IGZOsemiconductor ink was followed by immediate pre-heating at 90 °C, and a subsequent annealing step at 350 °C for 1 h. Next, printing of the CSPE ink as the gate insulator and the PEDOT:PSS ink as the top gate electrode were carried out on the fabricated semiconductor layer in order to complete the device fabrication process. The detailed printing parameters for each ink, i.e., semiconductor, CSPE and PEDOT:PSS inks are summarized in Table S1 of the Supporting Information. The unipolar NMOS depletion-load inverters, common-source amplifiers, differential amplifiers, analog-to-digital converters (ADCs) and the current drive circuits were printed in an identical manner combining *a*-IGZO TFTs of different aspect ratio, as mentioned in the relevant sections. Notably, prior printing, each and every ink was filtered through 0.2 µm polyimide based hydrophilic filter in order to avoid nozzle clogging and irregular printed patterns.

***Electrical Characterization*:**

All the electrical measurements were carried out at room temperature and in ambient conditions. The electrical characterization was performed using a semiconductor parameter analyzer (KEYSIGHT B1500A) connected to a MicroXact SPS1000-15 DC probe station. For the AC measurements, a function generator (TEKTRONIX AFG1022) was used as the pulse/waveform generator at the input, and a digital oscilloscope (TEKTRONIX TBS1102B) was used to record the output voltage; in this case, the semiconductor parameter analyser (KEYSIGHT B1500A) was used to apply the constant supply/drive voltage, *V*DD. Next, the temperature sensor was integrated with the printed circuit comprising the inverter and ADC, as shown in Figure 6(a-c), and the response was measured using the oscilloscope.

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**Conflicts of interest**

The authors declare no competing financial interest.

**Author Contributions**

J. R. Pradhan and S. Dasgupta conceived the idea and designed the experiments; J. R. Pradhan fabricated the printed EG-TFTs and circuits, measured the devices, and performed most of the characterization and data analysis with the supervision of S. Dasgupta. S. S. Priyadarsini synthesized the Mxene ink, fabricated the temperature sensor, and performed its characterization. M. Singh and S. R. Nibgoor demonstrated the compatibility of the printed read-out electronics, with the ARDUINO and ESP32 board (hybrid electronic). All authors contributed in the manuscript preparation.

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**Figures with caption**



**Figure 1:** (a) A schematic showing the a-IGZO semiconductor channel electrolyte-gated TFT (EG-TFT) device and the constituents of the composite solid polymer electrolyte (CSPE); (b) the transfer characteristics of an archetypal EG-TFT, where the gate voltage (*V*GS) is swept from -1 to 2 V with varying drive voltage (*V*DS) values from 0.5 to 2 V, with a step size of 0.5 V; (c) the output characteristics of EG-TFTs, where the *V*DS is swept from 0 to 2 V with varying *V*GS values from 0 to 2 V, with a step size of 0.1 V; (d) a statistics plot combining the transfer characteristics of 20 EG-TFTs at *V*DS= 2 V, showing very low variability; (e,f,g,h) statistical distribution of threshold voltgae, subthreshold slope, ON/OFF ratio and linear mobility at *V*DS= 1 V, respectively, extracted from an array of 20 (5×4 array) EG-TFTs.

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**Figure 2:** (a) A schematic of depletion-load type inverter based on a-IGZO EG-TFTs, where the LOAD TFT is having *W*/*L*= 50 µm /20 µm and the DRIVE TFT is with *W*/*L*= 20 µm/50 µm; (b) the voltage transfer characteristics (VTC) and the respective voltage gain plot of a typical depletion-load type inverter, where the *V*IN is swept from 0 to 2 V, with varying supply voltage, *V*DD from 0.5 to 2 V, at a step size of 0.5 V; (c) variation of the signal gain of the inverter, with respect to *V*DD; (d) the estimated noise margin of the inverter, NMH and NML for *V*DD= 2 V; (e) the statistics plot of the voltage gain for depletion-load type inverter based on EG-TFTs at *V*DD= 2 V;(f) the dynamic power consumption (*P*OUT= *V*OUT×*I*DD) of the depeltion-load type inverter with repsect to the supply voltage, *V*DD.



**Figure 3:** (a) A schematic of depletion load type inverter based on EG-TFT andthe working principle of a common source amplifier; (b) a sinusoidal input voltage signal (*V*IN) of 15 mV at 100 Hz, which is fed to the common source amplifier; (c) the amplified sinusoidal output voltage signal of 1 V at 100 Hz, received from the common source amplifier; (d) the signal gain vs. frequency plot of *a*-IGZO semiconductor channel EG-TFT derived depletion-load type common source amplifier; (e) the schematic of a differential amplifier based on depletion-load type inverters and the working principle of a differential amplifier; (f) two different sinusoidal input voltage signals of 10 mV and 15 mV, which is fed to the differential amplifier; (g) the amplified sinusoidal output voltage signal of the two different sinusoidal input signal of 10 mV and 15 mV; (h) the difference of the two amplified output signal for the corresponding input sinusoidal signal of 10 mV and 15 mV. (i) the signal gain vs. frequency plot for an a-IGZO semiconductor channel EG-TFT based differential amplifier.



**Figure 4:** (a) A schematic representation of the proposed 4 transistor, 1-bit analog-to-digital converter (ADC) circuit, with selected device aspect ratio for each EG-TFTs; (b,c) VTC of the ADC with respect to the applied reference voltage (*V*REF), varying from 0.1 V to 2 V, with a step size of 0.1 V, respectively; (d) the schematic of the proposed 4-transistor, 1-bit ADC, with a common source amplifier to amplify the input signal; (e,f) the VTC of the ADC with the common source amplifier with respect to the applied reference voltage (*V*REF) varying from 0.1 V to 2 V, with a step size of 0.1 V, respectively, demonstrating a sharper transition of the states with an amplified input signal; (g) the recorded output voltage from the ADC with the common source amplifier circuit, at a constant supply volatge of *V*DD= 2 V, while the input voltage is swept between 0 to 2 V, and it shows a distortion in the output signal, after 18000 seconds; (h) the same circuit demonstrated undistorted ADC output after a 10 minutes of rest time; (i) again, demonstration of undistorted 0 to 2 V digitalized output signal, even after 18 h of continuous biasing, when the input signal is swept between 0 to 1 V.

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**Figure 5:** (a) A schematic of the proposed ADC with the common source amplifier circuit based on EG-TFTs, showing analong input signal to convert to digitalized output signal; (b) the AC measurement of the ADC with the single inveter amplifier circuit, where a traingular input signal is successfully converter to square output; (c) a schematic of proposed ADC with the single inveter amplifier circuit, connected to a voltage divider circuit with a variable resistor; (d) the output voltage waveform of the circuit in response to a change in the resistance of the variable resistor; (e)an optical image of the device comprising the ADC with a single inveter amplifier circuit; (f) an optical image of the live experiment, where the output voltage waveform is being altered continously with the change in resistance at the inverter input by manually changing the resistance of the variable resistor.



**Figure 6:** (a) A schematic of the proposed ADC with the common source amplifier circuit, where the input at the amplifier is from the variable resistance from a Mxene based temperature sensor; (b) the output voltage of the ADC switches from 0 V to 2 V with repect to the change in resistance of the temperature sensor at a preset temperature of 77 °C, defined by the reference voltage set at 1 V; (c) the output voltage again switches back from 2 V to 0 V when the temperature sensor is cooled down below 77 °C; (d) a schematic of the proposed ADC with a common source amplifier circuit that is fed by a voltage divider circuit and the output of the ADC being connected to a current drive circuit for a high current output, and high power based applications; (e,f) demonstration of the visual recognition of ADC switching, two printed silver electrodes with HCl based solid electrolyte, where one is connected to the current drive circuit and other one is grounded; the silver electrodes appear identical when the ADC output is 0 V, however, when the ADC output switches to 2 V, the current drive circuit opens to transfer 2 V alongside large current to the silver electrode at the left, consequently, silver chloride (AgCl) forms on it within 1 minute of operation and the left silver electrode turns black; (g) VTC with output current switch of the current drive circuit, when the ADC output varies between 0 V to 2 V; (h) the current drive circuit under continous dynamic switching, the output voltage of the ADC and the measured current from the current drive circuit is plotted with respect to time, while the input voltage has beenswept between 0 V to 1 V, with a constant reference voltage of 1 V, for more than 3 h of biasing.

**Oxide semiconductor based deep-subthreshold operated read-out electronics for all-printed smart sensor patches**

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Fully-printed read-out electronics to be used at the sensor interfaces are demonstrated. The entirely printed smart sensor patch comprises amorphous indium-gallium-zinc oxide (*a*-IGZO) based deep-subthreshold operated TFTs for common-source amplifiers, and analog-to-digital converters (ADCs). The ADCs can successfully digitalize the analog sensor data and provide easy-to-detect visual recognition. The complete smart sensor patch can operate at ≤2 V, thereby assuring on-chip power source compatibility.

