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Fully Transparent Transceiver Using Single Binary Oxide Thin Film Transistors

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Abstract

Using one binary oxide, a fully transparent thin-film transistor (TFT)-based transceiver circuit is presented. The proposed transceiver circuit is fabricated entirely using an atomic layer deposition process. Moreover, the proposed circuit presents two modulation schemes: frequency shift

keying (FSK) and ON/OFF keying (OOK). The fabricated TFTs exhibit saturation mobility, threshold voltage, a subthreshold swing, and an ON/OFF ratio of $18.2 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, 0.9 V, 419 mVdec⁻¹, and 10^9 times, respectively. Finally, the circuit functionality is demonstrated by the word “KAUST” as a Morse code.

Transparent electronics are playing an increasingly important role in consumer electronics. This is because conventional electronic devices need to cope with the application revolution, which is inspired by the requirements of Internet of Things, sensors, and wearable devices. However, these new technologies require an external power supply^[1,2] and communication modules,^[3] which limit their application space. Meanwhile, developing a wireless communication system using these emerging electronic technologies is still challenging due to material constraints. However, some analog mixers and modulators have been developed.^[3-7]

Portable devices raise the demand for low-power consumption, for which transparent conducting oxides (TCOs) are an excellent candidate. Since the transparent material eliminates the need for backlighting in displays, this leads to low-power displays that fit with the current era of low-power electronics. Therefore, many researchers aim to develop transparent oxide semiconductors and contacts.^[8-11] One of the remarkable TCOs is indium tin oxide (ITO), that widely being used in modern age electronics research and industries. However, researchers are seeking a replacement of ITO due to the limited supply and hence, the high cost of indium, which results in increasing the price of consumer’s electronics products. Recently, ZnO-based TCOs, such as aluminum-doped zinc oxide (AZO),^[12] boron-doped zinc oxide (B_nZnO),^[13] gallium-doped zinc oxide (GZO),^[14] and titanium-doped zinc oxide (TiZO)^[15] have been studied extensively as transparent electrodes for thin-film transistors (TFTs) and other electronic devices

due to their low cost, natural abundance, and low toxicity of ZnO. Therefore, developing indium-free oxides is economical and more sustainable. However, ZnO doped with Group-IV elements such as Hf can be a better choice for alternative transparent conducting oxide. Recently, F. H. Alshammari *et al.* reported fully transparent electronics including TFTs comprising one single binary oxide, called HZO (Hf-doped ZnO).^[16] In fact, fabricating the entire TFT device from a single indium-free material can reduce the fabrication cost, thus avoiding the need for different deposition tools for different layers of the TFT.

In contrast, modulation is the process of varying one of the three signal specifications (*i.e.*, amplitude, frequency, and phase) following the message signal. This process is defined as the encoding process of the transmitted data over a periodic signal entitled carrier signal.^[17] For high-speed communication, ON/OFF keying (OOK) is encouraged as a simple and low-cost modulation scheme.^[18] Moreover, OOK is considered one of the forms of amplitude-shift keying (ASK). On the other hand, frequency-shift keying (FSK) is presented due to its robustness against the interference signals, but it is more complicated and has a higher implementation cost.^[18]

This report is the first to present a fully transparent TFT-based transceiver using a single binary oxide ($\text{Hf}_x\text{Zn}_{1-x}\text{O}_{2-\delta}$ or HZO) for all transistor layers. All the TFT layers are developed in a low-temperature (160 °C) atomic layer deposition (ALD) process. Finally, a Morse code message is successfully transmitted with a high data rate, paving the way for a new communication era.

Figure 1 (a) shows the fabricated transparent devices on a glass substrate through which the KAUST logo and ‘beacon’ can be visible clearly. However, the alignment marks (shown as two blurred lines vertically crossed at the center of the substrate) are made with Au for clear

visibility during the lithography process. The whole device stack, including all layers, was further analyzed using a high-resolution cross-section dark-field scanning transmission electron microscopy (STEM), as shown in **Figure 1(b)**. The physical thicknesses of different layers were estimated as ~230, ~130, and ~27 nm for the HZO-contacts (source, drain, and gate), HZO-dielectric, and HZO-semiconductor layers, respectively. Different layers are clearly visible with prominent interfaces between two neighbor layers signifies the well-controlled uniform ALD process and no interlayer diffusion. The change in brightness for different layers in the STEM images depends on the atomic number of the elements and also the electron scattering in different layers.

It is mentioned previously that the research on transparent conducting oxides is vital for future In-free TFTs. Hence, in this study, we focused intensively on the HZO-conducting layer. The transparency characteristics of the HZO-conducting layer was studied using a UV-vis measurement in transparency mode. It can be clearly seen in **Figure 1(c)**, that over 90% transparency was obtained in most of the visible range of the electromagnetic spectrum. Therefore, HZO can be considered as a potential candidate to replace ITO in future transparent TFTs. The optical energy band gap of HZO was estimated as ~3.38 eV from the absorption spectra, as shown inset of **Figure 1(c)**. The value of the bandgap is a little higher as compared to pure ZnO (~3.3 eV), which may be due to the increase of carrier concentration as a result of the doping of Hf^{4+} in ZnO (HZO).

Further, we focus on the crystallinity of HZO-conducting films. The X-ray diffraction (XRD) patterns of the optimized HZO-conducting films are shown in **Figure 1(d)**. Three major peaks were identified (according to JCPDS 00-036-1451) from the XRD spectrum located at the diffraction angle (2θ) of 32.2° (100), 35° (002), and 56.9° (110) with hexagonal wurtzite

polycrystalline microstructure. The significant fact from the XRD study is that the peak characteristics are similar to the pure ZnO film, but a little shift towards the lower diffraction angle sides. Besides, the band-edge emission and defects present in the HZO-conducting films were also studied using photoluminescence (PL) spectra at room temperature by a micro Raman spectrometer (LabRAM Aramis, Horiba) using He-Cd laser source (λ_{ex} : 325 nm), as shown inset of **Figure 1(d)**. It can be seen that no sharp peaks appeared in the PL spectrum, indicating the weaker signals from the near-band-edge emission as compared to the pure ZnO films, where a strong PL signal appears at ~385 nm due to radiative recombination of free excitons. However, in the Hf doped ZnO conducting films, the near-band-edge emission shifted to 360 nm with a weak signal. It is understood that the near-band-edge emission signals reduced significantly due to the substitution of the Hf^{4+} ions in the Zn^{2+} sites.^[19] However, another two peaks appear at the visible range of the spectrum indicating the defects in the films. The peak located at ~422 nm is related to the violet emission due to the transition of electrons from the Zn-interstitials (Zn_i) level near the conduction band to the valence band.^[20] On the other hand, the peak located at ~530 nm is mainly related to oxygen vacancy related defects. This peak may appear from the recombination of electrons with photo-excited holes in singly ionized oxygen vacancies near to the valence band.^[21-22]

The chemical compositions of the HZO-conducting films were studied using X-ray photoelectron spectroscopy (XPS) equipped with a monochromatic Al K_α X-ray source ($h\nu=1486.6$ eV) operating at 150 W. The high-resolution elemental spectra of Zn 2p, Hf 4f, O 1s, and C 1s along with survey spectrum, are shown in **Figure 1(e)**. All XPS spectra are deconvoluted using the standard Gaussian-Lorentzian function after correcting binding energies using C 1s (284.8 eV). However, before deconvolutions, Shirley background correction was

applied to eliminate background signals. The Zn $2p$ spectra show doublets comprising Zn $2p_{1/2}$ and Zn $2p_{3/2}$ at higher and lower binding energy sides, respectively. Moreover, after deconvolution, both Zn peaks show doublets as well. The peaks at 1021.48 and 1044.6 eV represent Zn^{2+} , while peaks at 1021.16 and 1044.17 eV represent nonlattice zinc ions.^[23] The Hf $4f$ high-resolution spectra also show doublets of Hf $4f_{5/2}$ and Hf $4f_{7/2}$. On the other hand, O1s spectra show a combination of a total of three components. The most intense peak at 530 eV can be attributed to O^{2-} ions which are surrounded by either Zn or Hf atoms, while relatively small peaks at 531 and 532 eV are attributed to oxygen vacancies and some surface contaminations (e.g., CO_3 , adsorbed H_2O or adsorbed O_2), respectively. The C1s peak also has three components. The sharp peak at 284.8 eV is related to the adventitious carbon contamination in the ALD deposited films. However, the small peaks at higher binding energy sides located at ~286.2 and ~288.9 eV are related to the carbon contamination appearing from the presence of C=O and C-O (H) bonds.^[24] Moreover, from the XPS analysis, the atomic percentage of Hf doping in the HZO-conducting films is estimated to be ~2.16%. The atomic percentage calculation was done using the area under deconvoluted curves of Zn $2p$, Hf $4f$, and O1s peaks and considering their relative sensitivity factors.^[25]

After studying the material properties, we fabricated fully transparent all-HZO TFTs on glass substrates. The optical image of one such TFT ($W \times L = 50 \times 50$) is shown in **Figure 2(a)**. The overlap of the gate to source/drain is fixed at 10 μm for achieving better stability in the devices, knowing the fact that it may increase the parasitic resistance in the devices. However, for the requirement of circuit applications of the TFTs, the stability of the devices is crucial. Hence, we may compromise the increase of small parasitic resistance in our devices. The dielectric properties of HZO-dielectric films (Zn doped HfO_2) were also studied. The capacitance

1 density of the films is found stable from several Hz to 100 kHz with an average value of ~ 146
 2 nF/cm^2 . On the other hand, the dielectric constant estimated as ~ 22 , higher than the HfO_2 (~ 20)
 3 deposited from the same ALD deposition tool with identical deposition conditions. Therefore,
 4 better TFT performance is expected. **Figure 2 (c)** shows the output characteristics of a typical 50
 5 (W) $\times$ 50 (L) TFT. An excellent saturation at higher drain voltage indicates a good pinch-off
 6 behavior in the channel. The transfer curve of the same TFT is shown in **Figure 2 (d)**, which
 7 shows an excellent switching ratio (ON/OFF) of $\sim 10^9$, with a low gate leakage current (I_{gs}) on
 8 the order of pA. Also, a low subthreshold swing (ss) of $\sim 419 \text{ mVdec}^{-1}$ and a threshold voltage of
 9 $\sim 0.9 \text{ V}$ are achieved. High saturation mobility of $18.2 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ is obtained from these fully
 10 transparent TFTs. It is worth mentioning that the saturation mobility was extracted in the linear
 11 region of the plot of $\sqrt{I_{\text{DS}}}$ versus V_{GS} . Moreover, no hysteresis was visible in the transfer
 12 curve in double sweep measurements, signifies negligible traps in the dielectric/semiconductor
 13 interface. Hence, the mobility of the TFTs under the forward and backward gate bias condition is
 14 similar, which is another essential requirement for circuit applications. Also, it can be seen that
 15 the turn-ON voltage and the sub-threshold region are identical for high and low drain bias
 16 application, implies the stability of the devices for low and also high voltage applications, *i.e.*, no
 17 threshold voltage (V_{th}) shifting found. To further check the stability of our TFTs, constant gate
 18 bias stressing study was carried out at room temperature. The constant positive bias stress (PBS)
 19 of $+10 \text{ V}$, and negative bias stress (NBS) of -10 V was applied to the gate electrode for 500 sec
 20 before measuring the transfer curves. Total stressing time was used as 3000 sec for both PBS and
 21 NBS. The constant gate bias stressing results are shown in **Figure 2(e)** and **(f)**, respectively. It
 22 can be seen that a small turn-ON voltage shifting of 0.22V and almost no shifting of the same
 23 obtained during the PBS and NBS respectively. This signifies the excellent stability of the sub-

threshold region of our devices. In contrast, V_{th} shifting under different bias applications is one of the major issues of concern for TFTs in the circuit applications. Hence, we believe, our TFTs are a good candidate for making electronics circuits knowing their high mobility, high ON/OFF current ratio, low turn-ON voltage, low threshold voltage and most important their stability under different bias conditions.

Using these TFTs, an FSK transceiver circuit, as well as OOK transmitter circuit, is implemented which are presented in **Figure 3** and **4**, respectively. **Figure 3 (a)** portrays different layers of our fabricated TFT. While **Figure 3 (b)** describes the system block diagram of the FSK modulation circuit, where the frequency of an on-chip ring oscillator (RO) circuit is controlled using the message signal. This encoding scheme represents the signal in one of two modes: either a low-frequency or a high-frequency mode. In addition, the FSK transmitter circuit implementation is presented in **Figure 3 (c)** that is composed of a current-controlled on-chip RO circuit. The RO circuit is composed of five NMOS inverters with a unity feedback to maintain an oscillating behavior, while the output node is connected to another inverter circuit to achieve high peak-to-peak voltage. Each stage of the RO circuit consists of a diode-connected transistor as a load resistor and a driver transistor to form an inverter. The RO speed (output frequency) is inversely proportional with both the number of stages and the delay per inverting stage ^[26-28] where the number of stages is optimized to get a clean sine wave. In addition, the delay is inversely proportional to the current consumption. Therefore, the RO circuit frequency is controlled by a current controller, which offers control of the overall power consumption of the modulator circuit as well as a frequency boost for the free-running RO circuit. **Figure 3 (d)** presents the measured frequency while varying current from 0.5 mA to 1.5 mA. This shows how the frequency increases within the same time interval.

Figure 3 (e) shows the circuit implementation of the full FSK transceiver circuit which consists of two main parts: 1) FSK transmitter circuit and 2) a diode-connected transistor M13 of $W/L = 50/50$ as a receiver circuit, which demodulates the output signal. The diode-connected transistor acts as a half-wave rectifier that demodulates the signal and passes the dc-offset associated with the modulated signal, thus forming the receiver circuit. Finally, **Figure 3 (f)** demonstrates the transmission of the text message “KAUST” as a Morse code using FSK modulation techniques, as well as the demodulation of the received message. The output logic is flipped, as sinking less current from the output node results in a higher dc offset at the output node. The proposed transceiver circuit is tested by connecting the output of the RO circuit with a diode-connected TFT device. In addition, an off-chip dc-current source is connected to the ground node of the RO circuit for frequency modulation. Finally, the output frequency varies from 87 kHz to 148 kHz with a current variation from 0.5 mA to 1.5 mA at 20 V_{DD} supply.

Figure 4 (a) presents the conceptional configuration of the OOK transmitter circuit. As shown, this circuit modifies the carrier signal based on the message signal in terms of ones and zeros. Moreover, a detailed circuit implementation is depicted in **Figure 4 (b)**, where the carrier signal (V_{Carrier}) is generated by a RO circuit while the message signal modulates it as an ON/OFF key through one transistor, M13. The core RO circuit is similar to the RO circuit introduced in **Figure 3 (c)**. While the transistor M13 acts as a mixer: its inputs are both the carrier and message signals, and its output is the modulated signal ($V_{\text{Mod Sig}}$).^[5] Finally, the following equation limits the output swing of the modulated signal: $V_{\text{Mod Sig}} = V_{\text{Carrier}} - V_{\text{th}}$, where V_{th} is the threshold voltage of the pass transistor M13. The input message speed is limited to the nominal frequency (f_0) of free-running, where f_0 equals 127 kHz.

Figure 4 (c) presents an experimental demonstration using the message “KAUST” as a Morse code. Adopting Morse code as a character encoding scheme is to increase the data rate of the encoded message since this shows the variety of data that can be sent simply with a low-cost OOK transmitter circuit. The proposed design is tested using a cascade probe station with 6-probes to connect the output of the RO circuit with the pass transistor M13. Finally, an optical image for the fabricated RO circuit is shown in **Figure 4 (d)**, where it occupies an area of 3255 $\mu\text{m} \times 520 \mu\text{m}$.

Finally, **Table I** provides a detailed comparison between this work and the recently published work presented in.^[3-7] The proposed transmitter circuit shows good results compared to others in the literature. In particular, the modulation speed is higher than that in Ref. [3], [4], and [7] by a factor of 12x for OOK and 4x for FSK. This high switching speed is achieved due to the low subthreshold swing (419 mVdec^{-1}), and the high saturation mobility ($18.2 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$) of all-HZO TFTs. Moreover, this work presents a full transceiver circuit, not only a transmitter circuit. Thus, this work combines multiple design aspects (*i.e.*, low cost, simple implementation, transparency, speed, multiple modulation schemes).

In summary, two modulation schemes are discussed where the proposed design is fabricated using a single binary oxide material for all transistor layers. All transistor layers are fabricated by a single atomic layer deposition chamber. A fully transparent ON/OFF keying transmitter circuit is verified and utilized to encode the Morse code message “KAUST” with a maximum operating frequency of 127 kHz. Furthermore, a frequency shift keying transceiver circuit that exhibits a low frequency of 87 kHz and a high frequency of 148 kHz is measured with a 40 kHz input message. These proposed circuits are well-suited for multiple applications as transparent electronic devices for high-speed communication through wireless sensor nodes.

Experimental Section

By controlling the number of cycles of two ALD precursors, Diethylzinc (DEZ) and Tetrakis(dimethylamido) hafnium (TDMAH), different layers of TFTs including HZO-electrodes, HZO-dielectric, and HZO-semiconductor films are prepared at a chamber temperature of 160 °C. The HZO-conducting and dielectric films are made using a DEZ and TDMAH ALD cycles ratio of 15:1 (~2.16 At.% of Hf) and 1:19 (~6.22 At.% of Zn), respectively. The HZO-semiconductor layer is formed of multiple alternating layers of ZnO and HfO₂ (53 cycles of ZnO/5 cycles of HfO₂/53 cycles of ZnO/5 cycles of HfO₂/ 54 cycles of ZnO/5 cycles of HfO₂). For the ALD deposition, deionized water used as the oxygen source for all thin films, and an N₂ flow rate of 20 sccm was used as the purge gas under a chamber pressure of 0.2 Torr. The pulse/purge times for TDMAH, DEZ, and water were 0.2/10, 0.015/10 and 0.015/10 seconds, respectively. The electronics devices are fabricated on a glass substrate subsequently patterned by conventional photolithography. At the end of the fabrication process, the whole device was annealed at 160 °C for one hour on a hot plate. A FEI's Titan G2 60–300 transmission electron microscope was used to collect cross-sectional transmission electron microscopy (TEM) image. The x-ray photoelectron spectroscopy (XPS) studies were carried out in a Kratos Axis Ultra DLD spectrometer equipped with a monochromatic Al K_α X-ray source (hν=1486.6 eV). Current-voltage (I-V) characteristics of the TFTs are measured using a Keysight B1500A semiconductor device parameter analyzer.

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Figure 1. (a) The optical image of the transparent devices fabricated on a glass substrate through which the KAUST logo and ‘beacon’ can be visible clearly. (b) Cross-section STEM image of all-HZO TFT stack, (c) The UV-VIS spectrum obtained from the HZO-conducting layer and inset shows the absorption spectrum from the same film. (d) The XRD spectrum and the PL spectrum (inset) obtained from the similar HZO-conducting thin films. (e) XPS survey spectrum of HZO-TCO thin film and high-resolution elemental spectra of Zn 2*p*, Hf 4*f*, O1*s*, and C1*s*.

Figure 2. (a) The optical image of one of the fabricated all-HZO TFTs. (b) The capacitance and dielectric constant variation under applied frequencies. The (c) output and (d) the transfer curves obtained from the TFT with dimension $W \times L = 50 \times 50$. The (e) PBS and (f) NBS performance of the similar TFTs.

1

2

3 **Figure 3.** (a) Different layers of the fabricated TFT, (b) Modulation Mechanism for Proposed FSK

4 System, (c) FSK Receiver Circuit Implementation, and (d) Low-Frequency Versus High-Frequency

5 Output, (e) FSK Complete Transceiver Circuit Implementation, and (f) Input Message “KAUST”

6 Modulation/Demodulation Demonstration with a Switching Speed of 40 kHz.

7

8

Figure 4. (a) Modulation Mechanism for Proposed OOK System, (b) OOK Transmitter Circuit Implementation, (c) KAUST Demonstration with 40 kHz Switching Speed, and (d) Optical image of the Ring Oscillator.

Table I: Performance Comparison Between this Work and the State-of-the-Art Transmitters

Deposition Techniques	Channel	D/S	G	Dielectric	Transparent	Speed	Modulation	Reference
Double ^x	Graphene	Sc	Ti/Au	Y ₂ O ₃	No	10 KHz	Frequency Doubling	[7]
Double ^x	Graphene	Ti/Au	Si ⁺	SiO ₂	No	4~10 KHz	PSK&FSK	[4]
Double ^y	Graphene	Ti/Au	Ti/Au	Al ₂ O ₃	No	30 KHz	PSK	[6]
Triple ^z	Graphene	Graphene	Graphene	Al ₂ O ₃	Yes	10 KHz	PSK&FSK&4ASK&QPSK	[3]
Single ^t	HZO	HZO	HZO	HZO	Yes	127 / 40 KHz	OOK/FSK	This Work

^x: EBL/E-beam evaporation, ^y: Vacuum evaporator/ALD, ^z: Sputtering/E-beam evaporation/ALD, ^t: ALD,

PSK: Phase Shift Keying, QPSK: Quadrature Phase Shift Keying

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Supporting Information

Fully Transparent Transceiver Using Single Binary Oxide Thin Film Transistors

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The compositions of different layers that obtained from the XPS study are mentioned below.

1 HZO-Conducting layer:

Element name	Amount (%)
Zn	48.17
Hf	2.16
O	49.66

2 HZO-Dielectric layer:

Element name	Amount (%)
Zn	6.22
Hf	28.42
O	65.34

3 HZO-Semiconducting layer:

Element name	Amount (%)
Zn in ZnO	51.12
O in ZnO	48.88
Hf in HfO ₂	32.70
O in HfO ₂	67.29

4

5 The XRD results for the dielectric and the semiconductor layer are shown below.

1
2 Figure S1: The XRD data obtained from the HZO-dielectric layer and from the semiconductor
3 layer (inset).