Metal–Semiconductor Field-Effect Transistors Based on the Amorphous Multi-Anion Compound ZnON

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1. Introduction

Thin-film transistors (TFTs) based on amorphous oxide semiconductors (AOS) triggered part of the evolution observed in the recent development of high-definition displays. Amorphous silicon, initially used within the back-plane of flat-panel displays, exhibits field-effect mobility of about 1 cm² V⁻¹ s⁻¹ limiting the display resolution somewhere between full high definition and ultra-high definition depending on the display’s frame rate. The field-effect mobility of pixel-driving transistors with AOS as channel material is about 20 cm² V⁻¹ s⁻¹, which is still not sufficient for high-end developments (e.g., 3D high-resolution displays) entering the markets nowadays or within a few years. Here, low-temperature polysilicon formed by excimer laser annealing with field-effect mobility of about 100 cm² V⁻¹ s⁻¹ is suited; however, production costs are considerably larger than for AOS-based transistors and homogeneity issues prevail.[1] Ye and co-workers recently demonstrated amorphous metal oxide thin films by a reactive sputtering process at room temperature that showed Hall effect mobility of about 45 cm² V⁻¹ s⁻¹ in the as-grown state which increased to over 100 cm² V⁻¹ s⁻¹ upon annealing at 400 °C.[2] Further, the incorporation of nitrogen in this multi-anion compound shifts the oxygen vacancy state, being a source of bias stress instability and performance changes of multi-cation AOS TFTs under visible light illumination, into the valence band resulting in an inherent stability of zinc oxynitride (ZnON) TFTs under bias stress and/or visible light illumination.[2–4] Besides attracting attention as active channel material in TFTs, ZnON was demonstrated to offer great potential for photosensitive devices with negligible persistent photoconduction due to its low band gap of about 1.0–1.3 eV and the position of the transition level of the oxygen vacancy within the valence band, respectively.[4–6] The issues of reproducibility and long-term stability that are associated with the nitrogen incorporation have been countered by argon plasma treatment,[5] annealing,[2,8,9] and/or encapsulation.[10,11]

So far, amorphous ZnON (a-ZnON) was used as channel material within metal-insulator–semiconductor field-effect transistors (MISFETs)[2–4,8,9,12–14] in this study, we investigate the electrical characteristics of metal–semiconductor field-effect transistors (MESFETs) based on amorphous n-type ZnON channel. MESFETs are especially suited for low-voltage and high-frequency applications due to the missing gate dielectric. Further, this reduces functionalization of the gate contact to the deposition of a metal layer for which a reactive magnetron sputtering process at room temperature is used in the current study. Recently, Schottky diodes and MESFETs based on amorphous zinc–tin oxide (a-ZTO) were demonstrated to be capable of realizing low-voltage operating logic circuits.[15] Combining this device concept with high-mobility a-ZnON seems to be a very promising approach for future sustainable integrated circuit based on AOS. Besides, Schottky diodes can be used for characterization of basic material properties by, e.g., thermal admittance spectroscopy or deep level transient spectroscopy.

2. Results and Discussion

Hall effect measurements at room temperature reveal a free electron concentration of \( n = 1.5 \times 10^{17} \) cm⁻³ and a Hall mobility of \( \mu_{\text{Hall}} = 100 \) cm² V⁻¹ s⁻¹ for the as-received a-ZnON thin film.

Figure 1a shows the Schottky diode \( j/V \) characteristic at room temperature with a rectification ratio of \( 3.8 \times 10^3 \) at ±2 V. Modelling of the diode forward current according to the Shockley equation

\[
j = j_n \left[ \exp \left( \frac{e(V - IR_s)}{nk_BT} \right) - 1 \right] + \frac{V - IR_s}{AR_p}
\]
yields an ideality factor $\eta \approx 1.43$ (backward voltage sweep). $A$ denotes the diode area, $R_s$ the series resistance, $R_p$ the parallel resistance, $j_s$ the saturation current density, $k_B$ the Boltzmann constant, and $T$ the absolute temperature. By considering thermionic emission (TE) theory only, an effective Schottky barrier height of $0.85 \pm 0.05$ eV has been derived from the saturation current density. But the increased ideality factor, compared to unity in the ideal case, as well as the deviation of the diode reverse current from the model indicates that the current transport cannot be described exclusively with the standard TE theory.

Also thermionic-field emission (TFE) theory,\cite{16} which describes tunneling of thermally excited carriers seeing a thinner Schottky barrier, cannot simulate the current in reverse direction (Figure S3, Supporting Information).

However, many researchers observed a trap-limited conduction transport in a-ZnON TFTs due to a high density of localized tail states near the conduction band minimum.\cite{12,17} Such trap states, distributed in the space-charge region, enhance the tunneling probability through the Schottky barrier giving rise to a voltage- and temperature-dependent diode reverse current. The evaluation of temperature-dependent IV measurements, shown in Figure 1b, yields a non-Arrhenius activation of the reverse diode current as expected in case of amorphous semiconductors with a broad activation energy distribution of subgap states (Figure S4, Supporting Information).

In agreement with these results, CV measurements reveal a frequency-dependent space-charge region capacitance indicating a broad distribution of subgap states acting as carrier traps (Figure 2a). In a semiconductor with a distinct defect level, one would obtain a capacitance plateau for frequencies below cut-off. However, in amorphous semiconductors the influence of subgap trap states falsify results of CV measurements as the depletion region also reveals ionized atoms that do not contribute to the free carrier concentration.\cite{18,19} A reliable extraction of the net doping density and the built-in voltage for the a-ZnON Schottky diodes is therefore not possible. An evaluation of the respective quantities from Figure 2b would yield a $V_{bi} \approx 10$ V and $N_d \approx 10^{18}$ cm$^{-3}$ (Figure S5, Supporting Information), whereas the latter is often interpreted as the subgap trap density.\cite{20} In summary, all the results intimate that current transport in the a-ZnON Schottky diode is enhanced by trap-assisted tunneling. Certainly, further investigations are needed to fully understand the transport mechanisms in these devices.
necessary to clarify this. Similar observations were reported for GaN Schottky diodes\cite{21} and also ZTO Schottky diodes\cite{22}.

We note that the numerical modeling of trap-assisted tunneling transport is beyond the scope of this work. However, an improvement in rectification ratio was recently demonstrated for ZnON diodes comprising a very thin insulating layer between metal and semiconductor, which reduces the defect trapped charge density and with that the reverse leakage current\cite{12}.

**Figure 3a** shows a typical transfer characteristic of the investigated MESFET at a drain-source voltage of $V_{DS} = 2 \text{ V}$ and the respective absolute gate current $I_G$. The drain current $I_D$ can be controlled over more than five orders of magnitude from 0.6 mA for a gate voltage of $V_{GS} = 2 \text{ V}$ to $2.6 \times 10^{-9} \text{ A}$ for $V_{GS} = -2 \text{ V}$. It is evident that the transistors off-current is dominated by the gate leakage current, thus limiting the drain-current on/off ratio. The influence of the gate current on the device characteristics is also visible in the output characteristic depicted in Figure 3b leading to a negative drain current for $V_{DS} \rightarrow 0 \text{ V}$ if $V_{DS} << V_{GS}$.

Despite the high gate diode reverse current ascribed to trap-assisted tunneling at the gate–channel interface, as already discussed, our obtained drain current on/off ratio is in the typical range for AOS-based MESFET devices ($10^{5} - 10^{7}$ for indium-gallium-zinc oxide (IGZO)\cite{24-26} $10^{4} - 10^{6}$ for ZTO\cite{27,28}).

The subthreshold swing $S$ was extracted as the minimum value of the inverse slope of the transfer characteristic log $I_D$ versus $V_{GS}$. A value of $S = 112 \text{ mV dec}^{-1}$ was determined from the transfer characteristic depicted in Figure 3a. This $S$ value is much lower than typical values reported for ZnON-based MISFETs being in the range of several hundreds to thousands mV dec$^{-1}$ (Table 1)\cite{2,3,9,29,30}.

Deriving the threshold voltage $V_{th}$ from a $\sqrt{I_{DS, sat}}$ versus $V_{GS}$ plot yields a near-zero value of 0.44 V.

From the transfer characteristic, also the saturation field-effect mobility can be derived as

$$\mu_{sat} = \frac{\left(\frac{\partial (\sqrt{I_{DS, sat}})}{\partial (V_{GS})}\right)^2 2dL}{W\varepsilon_S \varepsilon_r}$$

where $I_{DS, sat}$, $W$, $L$, and $d$ are the drain current in saturation regime, the gate width, the gate length, and the channel thickness, respectively. For the static dielectric constant $\varepsilon_r$ of a-ZnON a value of 11 was assumed\cite{12}.

The calculated saturation field-effect mobility $\mu_{sat}$ obtained from the transfer characteristic depicted in Figure 3a is 130 cm$^2$ V$^{-1}$ s$^{-1}$ for a channel thickness $d$ of 60 nm and $W/L = 430/10$. That this calculated value is higher than the measured Hall mobility of $\mu_{Hall} = 100 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ can be explained by the non-negligible contribution of the gate forward current in the transistors on-regime leading to an overestimation of the “actual” channel mobility. Such behavior is inherent in MISFETs, especially if the transistors turn-on voltage is in the onset regime of the diode forward current, rendering the ideal transistor equations invalid as they neglect the gate voltage dependence. Additional error is introduced by channel length modulation in saturation regime as the effective channel length is smaller.

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**Table 1.** Averaged electrical MESFET parameters, extracted from 34 transfer characteristics, and best device compared to literature values of ZnON-based MISFETs: channel thickness $d$, saturation field-effect mobility $\mu_{sat}$, subthreshold swing $S$, drain current on–off ratio $I_{on/off}$, threshold voltage $V_{th}$, switching voltage $\Delta V$.

| Type  | $d$ [nm] | $\mu_{sat}$ [cm$^2$ V$^{-1}$ s$^{-1}$] | $S$ [mV dec$^{-1}$] | $I_{on/off}$ | $V_{th}$ [V] | $\Delta V$ [V] | Ref.  |
|-------|---------|------------------------------------|----------------------|-------------|-------------|----------------|-------|
| MES   | 60      | 92                                 | 114                  | $1 \times 10^4$ | 0.41        | 2              | This work (av.) |
| MES   | 60      | 130                                | 112                  | $5 \times 10^4$ | 0.44        | 2              | Best device    |
| MIS   | n.a.    | 10                                 | 800                  | $4 \times 10^4$ | 0.5         | 10             | [2]             |
| MIS   | 50      | 43                                 | 1200                 | $10^6$       | 5.4         | 40             | [3]             |
| MIS   | 30      | 52                                 | 420                  | $>10^6$      | 2.8         | 20             | [29]            |

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\(\varepsilon_{Si} \approx 128, \varepsilon_{SiO_2} \approx 3.9, \varepsilon_{Si} \approx 11\)
than the gate length $L$, also leading to an overestimation. Extracting the channel mobility from the maximum transconductance $g_{\text{max}} = \mu n d W / L$ with the free carrier concentration obtained from Hall effect measurements $n = 1.5 \times 10^{17} \text{cm}^{-3}$ yields a value of $75 \text{cm}^2 \text{V}^{-1} \text{s}^{-1}$. This method usually underestimates the carrier mobility in the MESFET channel since the theoretical maximum transconductance is not reached, also due to the non-negligible gate current. Moreover, this method does not account for the voltage dependence of the free carrier concentration in the channel, as it should be considered in case of a trap-limited conduction process, and can therefore only give a rough estimation.

Table 1 summarizes the averaged electrical parameters extracted from 34 transfer characteristics of the investigated MESFETs. Histograms of these parameters are shown in Figure S6 (Supporting Information).

The photostability of the device under visible light was investigated under illumination with a halogen lamp focused onto the device under test through a microscope during measurements. The temperature changes due to light exposure were negligible. In Figure 4a the TFTs transfer characteristics measured in dark and under illumination with an irradiance of $E = 9.6 \text{mW cm}^{-2}$ are compared. The a-ZnON-based MESFETs exhibit negligible threshold voltage shift under light exposure and low photocurrent ($\approx 10^{-9} \text{A}$), which is not persistent (Figure 4b). For irradiance below $2.6 \text{mW cm}^{-2}$ there was even no effect on transfer characteristics observable.

3. Conclusion

In summary, we demonstrated the first MESFETs based on amorphous ZnON channels. As gate reactively sputtered platinum formed a Schottky junction. Best MESFET devices have drain-current on/off ratios of $5 \times 10^5$ and a minimal subthreshold swing of $112 \text{mV dec}^{-1}$ within a gate voltage sweep of less than $2 \text{V}$ rendering such devices favorable for inexpensive low-voltage applications. Certainly, future work should concentrate on reducing the gate leakage by decreasing the trap state density in a-ZnON. However, the main advantage compared to MESFETs based on multi-cation AOS like IGZO$^{[26]}$ and ZTO$^{[27,28,31]}$ is the much higher saturation field-effect mobility reached in a-ZnON field-effect transistors as well as the device stability under illumination.

![Figure 4](image_url)  
**Figure 4.** a) Transfer characteristic of ZnON channel MESFET under illumination with a halogen lamp of $9.6 \text{mW cm}^{-2}$ intensity. b) Drain current as a function of time as illumination is turned on and off during a gate voltage sweep from $-1.8$ to $-0.3 \text{V}$.

![Figure 5](image_url)  
**Figure 5.** Laser microscope image (top view) and schematic device structure (side view) of a,c) the Schottky diode on 100 nm-thick ZnON thin film and b,d) the transistor with 60 nm-thick ZnON channel mesa.
4. Experimental Section
DC-sputtered a-ZnON thin films on glass substrates were supplied by Y. Ye. Details on the fabrication process were reported by Ye et al.[2] The amorphous nature of the ZnON thin film was confirmed by means of wide angle as well as grazing incidence X-ray diffraction using a Philips X’Pert diffractometer with Cu-Kα radiation (Figure S1, Supporting Information). The average chemical composition of the as-received ZnON thin film estimated by energy-dispersive X-ray (EDX) spectroscopy is 51 at% Zn, 15 at% O and 34 at% N.

The electrical properties of the thin films were investigated by means of Hall effect measurements using a four-probe van der Pauw technique with a magnetic field of 0.43 T. Thin gold layers, placed on the corners of the sample, were DC-sputtered under Ar atmosphere providing ohmic contacts, as confirmed by current-voltage (IV) measurements (Figure S2, Supporting Information). The IV characteristics of the diodes and TFTs were measured using an Agilent 4155C Semiconductor Parameter Analyzer in connection with a SÜSS wafer prober system. Electrical characterization was conducted under dark conditions in ambient air. Capacitance-voltage (CV) measurements were performed using a Precision Impedance Analyzer (Agilent 4294A).

Circular diodes with different diameters between 150 and 750 μm as well as top-gate TFT structures with different gate width-to-length ratios W/L were processed by means of standard photolithography and lift-off. Defined 60-nm-thick channel mesas were formed by wet chemical etching of ZnON in diluted hydrochloric acid (1:100). The source and drain electrodes were fabricated by DC sputtering of 40 nm-thick Au and patterned using lift-off technique. The Schottky barrier diode was realized by reactive DC sputtering from a metallic platinum target in Ar/O2 atmosphere at room temperature and p = 1 × 10−2 mbar. Subsequently, a ~10 nm-thick metallic Pt capping layer was DC sputtered under Ar atmosphere serving as gate electrode. A schematic view of the investigated device structures is depicted in Figure 5.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements
The authors would like to thank Y. Ye for preparing the ZnON thin films. They also thank Jörg Lenzner for EDX measurements. This work was partially funded by Deutsche Forschungsgemeinschaft within Schwerpunktprogramm SPP 1796 “High Frequency Flexible Bendable Electronics for Wireless Communication Systems (FFLexCom)” (GR 1011/31-1 and GR 1011/31-2) and within the ANR-DFG project “Zinc magnesium Oxynitrides (ZONE)” (GR 1011/36-1). We acknowledge support from Leipzig University for Open Access Publishing.

Conflict of Interest
The authors declare no conflict of interest.

Keywords
amorphous oxide semiconductors, metal–semiconductor field-effect transistors, Schottky diodes, zinc oxynitride

Received: October 1, 2019
Revised: February 12, 2020
Published online: March 3, 2020

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