ZnO flexible high voltage thin film transistors for power management in wearable electronics

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ZnO flexible high voltage thin film transistors for power management in wearable electronics

Wen-Chiang Hong,[1,a)] Yonghui Zhang,[2,a)] Sze-Ying Wang,[1] Yuxuan Li,[1] Navila Alim,[1] Xiaolong Du,[2] Zengxia Mei,[2,b)] and Yicheng Lu[1,c)]
[1]*Department of Electrical and Computer Engineering, Rutgers University, 94 Brett Rd, Piscataway, New Jersey 08854*
[2]*Key Laboratory for Renewable Energy, Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, People's Republic of China*

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A ZnO-based flexible high voltage thin film transistor (f-HVTFT) is fabricated on a plastic substrate. The f-HVTFT shows a blocking voltage of 150 V, on-current of 170 μA, and off-current of 0.01 pA at a drain bias of 10 V. The maximum recoverable bending radius of the device reaches 11 mm, and the blocking voltage is larger than 120 V while it is under bending. The unique center-symmetric circular structure of the f-HVTFT is particularly useful to the wearable systems, which enable one to operate under bending from arbitrary directions. The ZnO-based f-HVTFT is a promising candidate to be used for power management of self-powered wearable electronic systems. *Published by the AVS.* https://doi.org/10.1116/1.5043550

I. INTRODUCTION

The wearable electronics have attracted increasing research interests because they offer broad applications in people's daily life, including personal health and wellness. In wearable systems, electronic components like receivers and sensors are required to be mounted on flexible and bendable surfaces.[1] Furthermore, the mobile devices in a wearable system prefer to have long battery life and span.[2] This motivation has driven intense studies on self-powered portable electronics. Scientists and engineers have investigated different nanogenerators from three major energy sources: (i) biomechanical energy from the movement of human body,[3] (ii) solar energy,[4] and (iii) thermal energy from the temperature difference between human body and environment.[5] However, in the past, most technologies of nanogenerators, such as piezoelectric nanogenerators, could only provide low power due to low efficiency; therefore, they are unable to independently power wearable electronics.[6]

Recently, a triboelectric nanogenerator (TENG)[7] was reported to enable one to drive many electronic components, such as magnetic sensor,[8] liquid crystal display, and light-emitting diode display. A nanopatterned ZnO-/polydimethylsiloxane-/Ag-based triboelectric energy harvester generates over mW energy (120 V and 65 μA) on a textile substrate.[9] However, the typical output voltage of a TENG is about 120 V, which is hard to be directly used to drive the regular electronics.[5] In order to utilize the nanogenerators to power regular electronics, converting high voltage to regular voltage is necessary.[9] Another critical issue is that the energy harvesting from environmental sources usually is not stable. Thus, it needs a power management component to control the storage, conversion, and usage of energy, enabling to provide constant voltage and current to power the regular electronics in a wearable system. The conventional power controllers are bulky and are built on rigid substrates. They are separated from the nanogenerators; thus, it requires extra wiring to make electric connections. For wearable systems, it is desired to integrate nanogenerators with the power control device on a single flexible substrate, like a plastic or fabric textile. Such an integrated self-powered wearable system will not only provide a small size and necessary flexibility by removing external wirings between nanogenerators and the power controller, but will also enable one to recharge flexible batteries and/or directly drive electronic devices under vastly different and varying environmental conditions.

To develop a flexible power management component for wearable electronics, a high voltage transistor fabricated on a flexible substrate at low process temperature is needed. Because the process temperature is limited by the transition temperature of flexible substrates, a low-temperature thin film transistor (TFT) is more suitable than the conventional high-temperature MOSFET as a flexible high voltage device. In order to serve as a high efficient power source, a high voltage transistor has to provide low specific on-resistance at ON state and high blocking voltage at OFF state. The amorphous Si (Refs. 10–16) and polycrystalline Si (Refs. 17 and 18) were utilized as a channel layer for making high voltage TFTs; however, none of them was built on a flexible substrate except for the regular voltage applications. The organic semiconductor materials can be used to fabricate flexible transistors at low process temperature. Recently, Smith *et al.*[19] reported a high voltage organic thin film transistor

[a)]W.-C. Hong and Y. Zhang contributed equally to this work.
[b)]Electronic mail: zxmei@iphy.ac.cn
[c)]Electronic mail: ylu@soe.rutgers.edu

(HVOTFT), which could operate at 400 V. However, the low on-current (~0.3 μA) at $V_{DS} = 100$ V, which means a high specific on-resistance R_{ON} (~$6.67 \times 10^3\ \Omega\,cm^2$) due to low mobility, makes the HVOTFT unable to directly connect to the nanogenerators which have high output current.

Oxide semiconductors, such as indium–gallium–zinc-oxide (IGZO),[20] have also been tried to make high voltage TFTs, primarily on rigid substrates. Recently, Marette *et al.* demonstrated a flexible zinc–tin oxide high voltage TFT for integrated switching of dielectric elastomer actuator arrays.[21] The device could sustain high drain bias (65–1100 V) at ON state; however, the blocking voltage at OFF state was not presented. The on/off ratio of the device is less than 2 orders, and the subthreshold slope (SS) is ~75 V/dec (V_{DS} = 1000 V). Its high R_{ON} of ~$2.76 \times 10^6\ \Omega\,cm^2$ and high off-current of 6 μA would cause serious issues of low power efficiency and high standby power. Furthermore, the device is fabricated at high process temperature up to 450 °C, which is not compatible with the flexible substrates with lower glass transition temperature.[22] It makes this device not suitable for the wearable power management.

In this paper, we report a ZnO flexible high voltage thin film transistor (f-HVTFT) fabricated at low temperature (<110 °C). The unique circular structure of the ZnO f-HVTFTs enables stable and consistent electrical performance under the bending along different directions. The device possesses an on-current I_{ON} ~170 μA at $V_{DS} = 10$ V and a high blocking voltage, V_{block} of 150 V, matching well with the output characteristics of the nanogenerators; therefore, it meets the critical requirement as a power management device for wearable systems.

II. EXPERIMENT

A. Structure design

The ZnO f-HVTFT is designed to have the center-symmetric circular structure. The schematics of its top and cross-sectional view are shown in Figs. 1(a) and 1(b), respectively. The inner and outer radii of the channel region are 252 and 268 μm, respectively. Unlike the conventional rectangular TFT device, in the f-HVTFT, the gate, channel, source, and drain are all in the circular shape so that there is no sharp curvature change at the corners. It avoids the electric field crowding effect; therefore, it eliminates the weak point of the device breakdown at high drain bias.[23] Another advantage of such a center-symmetric circular structure is the stability of the device against random bend directions, which is particularly important for the wearable systems.

B. Device fabrication

Polyethylene naphthalate (PEN) is used as the flexible substrate because of its low coefficient of linear thermal expansion (CTE) of 13 ppm/K in comparison to other popular flexible substrates, such as polyamide (PI; CTE = 17 ppm/K) and polyarylates (CTE = 53 ppm/K), and its high transparency of >85% (PI = 30–60%). Before fabricating the TFT devices, PEN substrates (125 μm thick) were degassed at 110 °C for 12 h to prevent excessive expansion resulted from the heating effect from the subsequent fabrication process. Then, the PEN substrate was encapsulated with a 50 nm Al_2O_3 film using atomic layer deposition (ALD) to protect it from gas

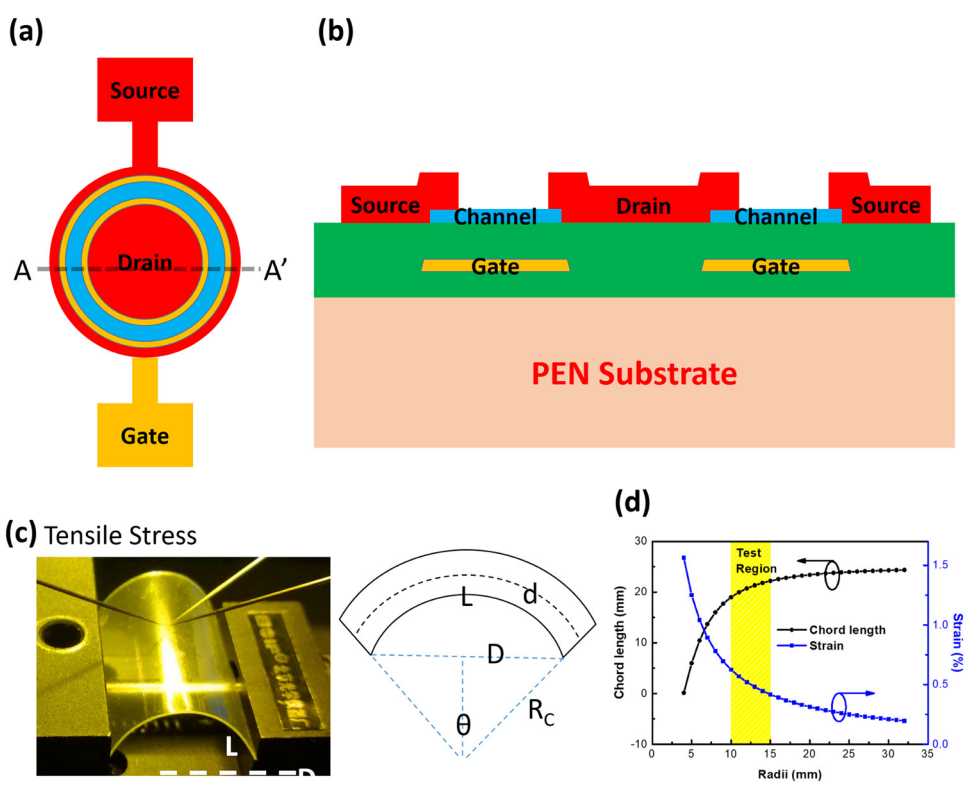

FIG. 1. Schematics of (a) top-view and (b) cross-sectional view (along A–A′) of a flexible HVTFT. (c) The platform of bending test and parameters used in the strain calculation. (d) The bending test region and the corresponding strain vs bending radius.

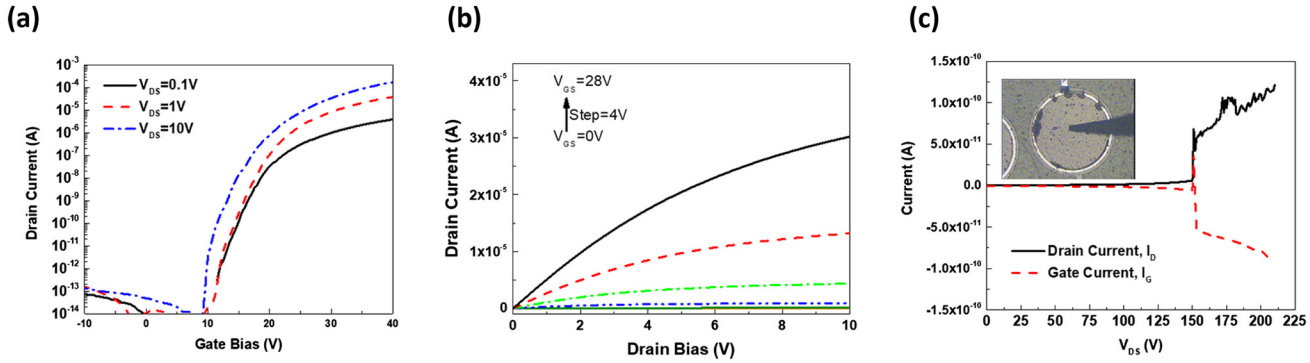

FIG. 2. (a) Transfer characteristics and (b) output characteristics of a ZnO flexible HVTFT. (c) The blocking voltage performance of a ZnO flexible HVTFT. The inset is an optical image which features the burn marks after the device breakdown.

adsorption and to improve the adhesion of the gate metal on the substrate. A 50 nm chromium (Cr) layer was deposited by DC sputtering as the bottom gate electrode, followed by deposition of 200 nm Al_2O_3 as the gate dielectric layer, using ALD at a temperature of ~100 °C. The dielectric constant of Al_2O_3 is ~7.8. Then, a 45 nm ZnO layer was deposited by RF sputtering at room temperature. The ZnO channel has an electron density of $\sim 10^{17}\,cm^{-3}$. The source and drain metallization (100 nm Ti/50 nm Au) was deposited using electron beam evaporation, followed by a normal lift-off process. A photoresist film was coated on top of the f-HVTFT channel, serving as a temporary passivation layer to prevent ambient absorption/desorption during electrical testing.

C. Electrical characterization

The electrical measurements under the low bias were conducted using a Keithley 4200. With the boost from the connection of a pulse generator, the maximum voltage of the Keithley 4200 system was limited to be 210 V. The system with a current resolution of 10 fA was used to measure all transfer characteristics.

In measurements of the f-HVTFTs, the threshold voltage (V_{TH}) is defined as the gate voltage (V_{GS}) value when I_D reaches 10^{-9} A with $V_{DS} = 0.1$ V. The SS is the inverse slope of the $\log_{10} I_D$ vs V_{GS} characteristic in the subthreshold region (I_D: 10^{-12}–10^{-9} A). The turn-off voltage (V_{OFF}) is defined as the gate voltage value when I_D reaches 10^{-13} A with $V_{DS} = 1$ V. The blocking voltage V_{block} is defined as the highest drain bias voltage that a TFT can sustain without a breakdown in the OFF state ($V_{GS} = -10$ V). The specific on-resistance (R_{ON}) is defined as follows:

$$R_{ON} = \frac{V_{ON}}{I_{ON}} \times A_{Channel}, \tag{1}$$

where V_{ON} and I_{ON} are the drain bias voltage and drain current, respectively. $A_{Channel}$ is the area of the channel.

D. Bending test

The bending tests of f-HVTFT were conducted using the platform shown in Fig. 1(c), where the bending radius of the flexible substrate is tuned by adjusting the distance D between two clamps. The bend direction is downward which gives the tensile strain to the devices. The strain values are calculated using the following equation:

$$\text{Strain}\,(\%) = 100 \times \frac{d}{2 \times R_C}, \tag{2}$$

where d is the total thickness of the PEN substrate and TFT and R_C is the bending radius. The corresponding strains and chord are shown in Fig. 1(d).

III. RESULTS AND DISCUSSION

The transfer characteristics of f-HVTFTs are shown in Fig. 2(a). At regular operating condition of $V_{DS} = 1$ V, the drain current (I_D) reaches 38 μA at $V_{GS} = 40$ V (equivalent to the R_{ON} of ~6.88 $\Omega\,cm^2$), and the off-current is as low as 0.01 pA. It is found that the threshold voltage V_{TH} is 16.0 V and the turn-off voltage V_{OFF} is 11.5 V. The SS is ~1.5 V/dec which is much lower than 75 V/dec of flexible zinc–tin oxide high voltage TFT.[21] For higher bias condition of $V_{DS} = 10$ V, I_D can reach 170 μA at $V_{GS} = 40$ V and the off-current keeps 0.01 pA. This f-HVTFT shows characteristics of normally off and low off-current, enabling the low standby power that is suitable for low power applications, such as portable and wearable electronic systems. The output characteristics of a ZnO f-HVTFT are shown in Fig. 2(b). The device shows better saturation behavior at low gate bias; however, under high gate bias conditions, the drain current increases as the drain bias increases. This "kink" effect was also observed in the IGZO HVTFT.[20] It might be related to the channel length modulation and self-heating.[20,24] At this stage, its root cause is not totally clear and is still under investigation.

The testing results of the blocking voltage are shown in Fig. 2(c). The ZnO f-HVTFT has a blocking voltage around 150 V. It is found that the main breakdown results from the burnout of the PEN substrate at the drain side. This could be attributed to the self-heating effect. The poor thermal conductivity of the plastic substrate (~0.2 $W\,m^{-1}\,K^{-1}$) would restrict the heat dissipation from the channel layer. In fact, this has been one of the major issues of the flexible transistors.[25] In our case, the self-heating becomes even more severe because

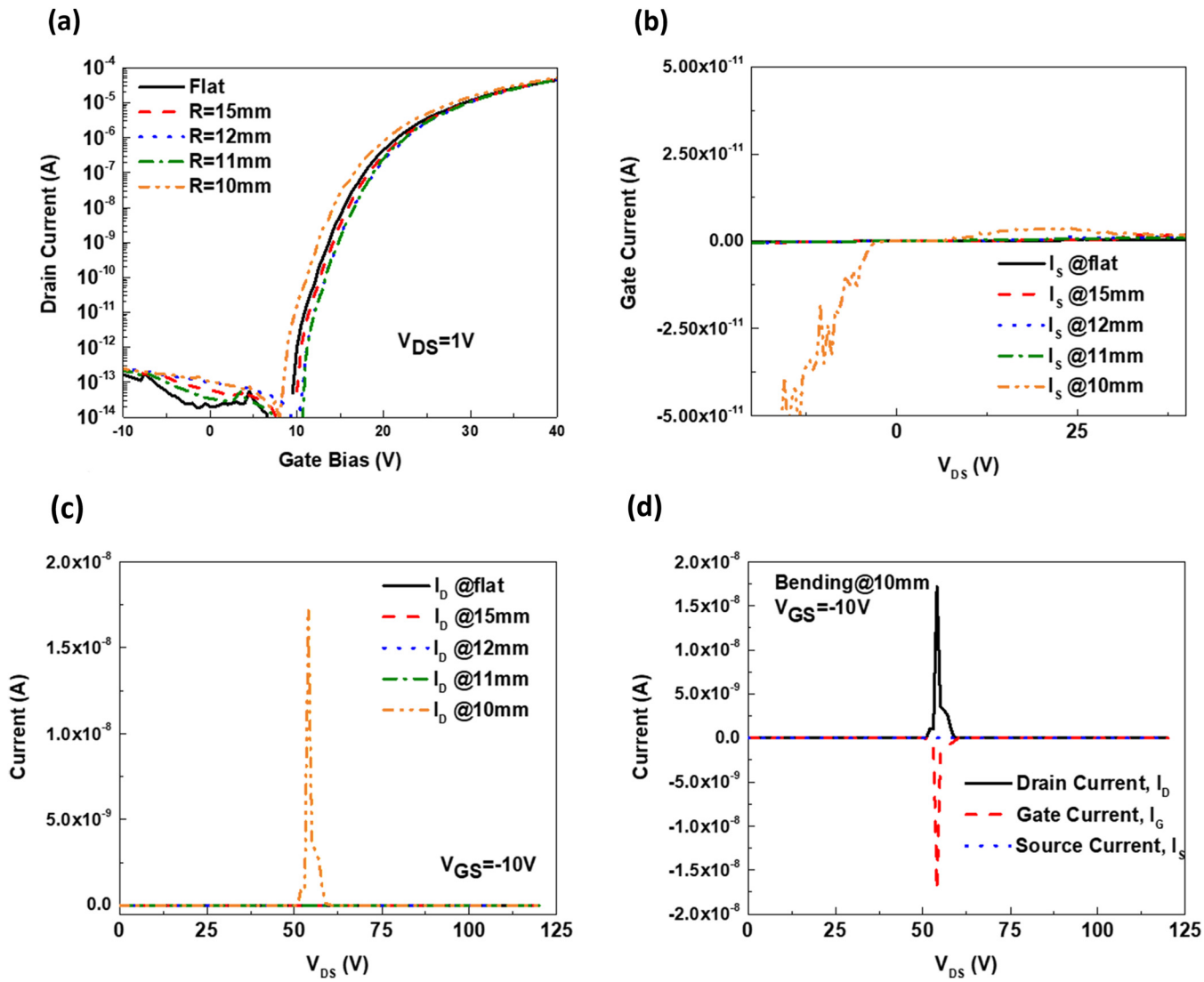

FIG. 3. Testing results of an f-HVTFT under bending: (a) the transfer characteristics show the bending tests under the parallel direction, (b) the gate leakage current, (c) the blocking voltage performance, and (d) drain current, gate leakage current, and blocking voltage characteristics of a ZnO flexible HVTFT under various bending conditions.

the f-HVTFT operates at a much higher voltage than the regular TFT; thus, even a small leakage current under the high drain bias voltage could generate considerable joule heat.

As shown in Fig. 3(a), the transfer characteristics stayed unchanged as long as the bending radius is larger than 10 mm. For the bending radius equal to 10 mm, the ZnO f-HVTFT exhibits the negative shift of threshold voltage and an increase of gate leakage current as shown in Fig. 3(b). Figure 3(c) shows the blocking voltage of the devices under bending at different radii. Both "parallel" (bending along the direction of source and gate contact pads) and "perpendicular" bending (bending vertically to the parallel bending) are performed. The results are essentially the same as expected because the f-HVTFT has the center-symmetric structure. It is found that as the bending radius is larger than 10 mm, the f-HVTFT exhibits a blocking voltage V_{block} of larger than 125 V. While the device is bent at a radius of 10 mm, its blocking capability reduces to V_{block} ~52 V. This lower breakdown was related to the significant increase in the gate leakage current as shown in Fig. 3(d). It is found that the cracks occurred in the bulk of the dielectric layer during the bending process. The cracks could form the leakage paths for electrons to penetrate through the gate dielectric layer.[26] As a result, the breakdown happened at a lower gate bias due to mechanical bending induced gate leakage current.

IV. SUMMARY AND CONCLUSIONS

We have demonstrated the ZnO-based flexible high voltage thin film transistor on plastic substrates. The unique circular design offers the center-symmetric configuration against bending from random directions. The flexible HVTFT offers a high on-current of 100 μA, a low off-current of 0.01 pA, and a blocking voltage up to 150 V. The high blocking voltage and on-current match the output characteristics of the emerging nanogenerators of high impedance, while the low leakage current ensures the low standby power. This flexible HVTFT is promising to serve as the

critically important, but currently missing element—the power controller which transfers energy from the new nanogenerators to other devices and/or rechargeable batteries in wearable systems. The integration of the HVTFT with nanogenerators and other electronic devices on the same flexible substrate/fabric can promote the wearable systems toward small size, lightweight, and stable and sustainable operation.

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