Textile-Based IGZO TFTs with 2T1C Pixel Circuits for Wearable AMOLEDs

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Abstract

This study demonstrates flexible IGZO thin-film transistors (TFTs) fabricated on textile substrates using low-temperature processing below 150°C. The TFTs exhibit mechanical reliability under repeated bending with critical strains of approximately 1.6% for single devices and 0.7% for 2T1C circuits, stably driving active-matrix organic light-emitting diodes (AMOLED) for wearable displays.

Author Keywords

Textile based TFT; flexible TFT; a-IGZO TFT; low-temperature process; TFT array; 2T1C circuit; Active-Matrix OLED; textile platform; wearable display; wearable electronics;

1. Introduction

The display industry is evolving toward more human-centered technologies, transitioning from rigid, flat panels to freeform displays that prioritize flexibility and seamless integration into daily life. These advancements reflect a growing demand for displays that enable real-time data interaction while maintaining comfort and accessibility. Textile-based displays that incorporate electronic functionality into woven textiles, have emerged as a key component in this evolution, offering a promising platform for wearable displays [1-3].

Textile-based TFT fabrication approaches can be broadly categorized into fiber-based and planar textile-based methods [4]. Fiber-based TFTs focus on integrating transistors directly onto individual fibers, which are later woven into textiles. While this approach represents a long-term vision for fully fiber-integrated systems, challenges such as geometric complexity, limited scalability, and trade-offs between electrical performance and flexibility remain unresolved [5-6]. Planar textile-based TFTs, in contrast, offer significant advantages in scalability and compatibility with established fabrication processes. Existing TFT fabrication techniques for rigid substrates can be adapted to woven textiles with minor modifications. To address the inherent roughness of textiles, prior studies have introduced solutions such as the transfer technique and planarization layers [7-10].

Building upon these advancements, this study investigates textile-based TFTs from single-unit transistors to two transistor and one capacitance (2T1C) pixel circuits for active-matrix, a critical architecture for driving self-emissive displays. Both configurations were evaluated for mechanical reliability through bending tests, demonstrating their suitability for use in textile-based wearable display systems. Furthermore, the integration of AMOLEDs underscores the potential of this approach in realizing true wearable displays.

2. Results and Discussion

Top-gate staggered structure TFTs, as illustrated in Figure 1a, were fabricated on a textile substrate with surface roughness of tens of nanometers. To achieve this, an ultra-thin planarization layer structure was adopted. Parylene-C served as the planarization layer, while silicon RTV acted as a strain-relief buffer, preventing high strain generated in the textile from being transferred to the planarization layer [11]. Aluminum electrodes for the drain, source, and gate were deposited using thermal evaporation and the IGZO channel was deposited via sputtering, both conducted in a vacuum environment at room temperature. The thin films were patterned using a shadow mask. The only thermal process involved was the deposition of the gate insulator, Al_2O_3, using atomic layer deposition (ALD). Polyester-based textiles exhibited thermal deformation at temperatures exceeding 150°C or under prolonged exposure to temperatures above 100°C.

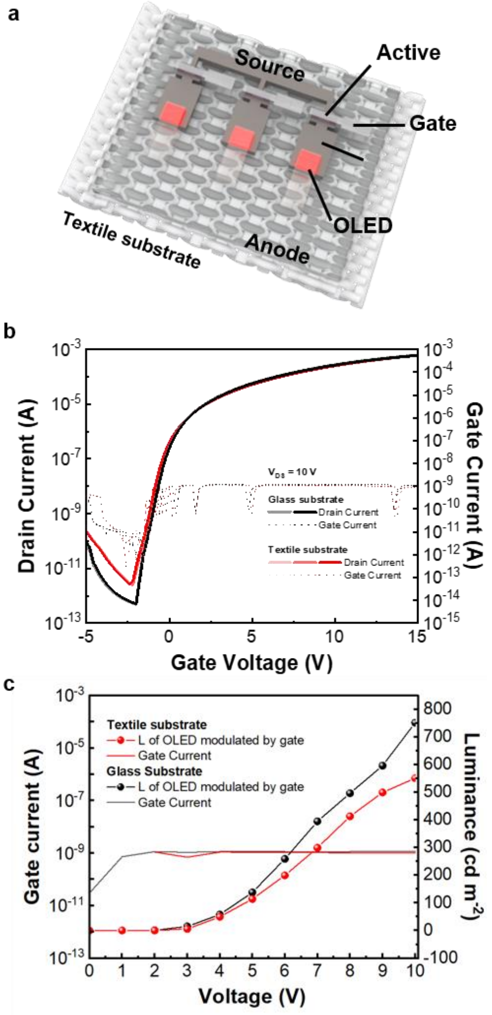

Figure 1 (a) Structural diagram of a textile-based 1TFT-1OLED(1T-1O) system (b) Multi-sweep transfer curves of textile-based TFT and glass-based TFT at Vds = 10 V (c) Variation in OLED luminance and TFT gate current in the 1T-1O system as a function of gate voltage

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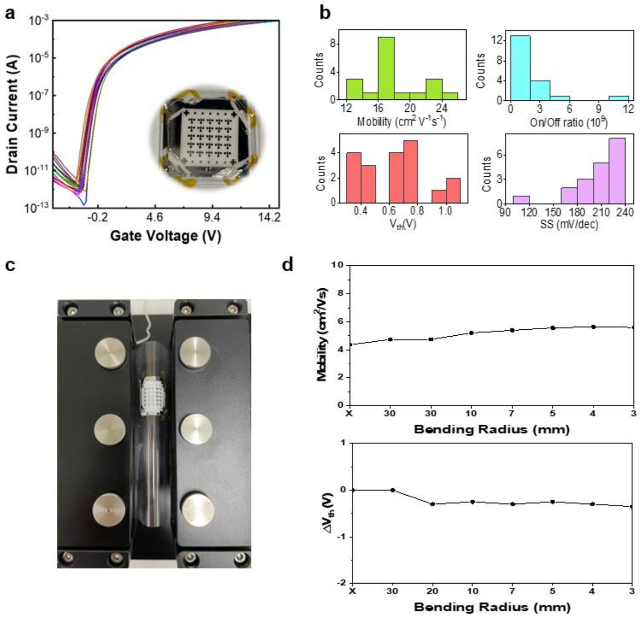

Figure 2 (a) Transfer curves and (b) statistical analysis of mobility, on/off ratio, threshold voltage, and subthreshold swing of 19 out of 25 devices in a textile-based TFT array (c) Image of the textile-based TFT array under bending conditions (d) Variation in mobility and threshold voltage at a minimum bending radius of 3 mm

To address this issue, process conditions were optimized by combining low-temperature Al_2O_3 deposition at 120°C with continuous post-annealing (CPA) to mitigate thermal strain [12]. As result, reliable and stable TFTs were fabricated without requiring additional passivation layers, demonstrating the feasibility of a low-temperature process.

The electrical characteristics of the TFTs were measured under ambient conditions using a Keithley 4200-SCS system. The multi-sweep transfer curves of unit TFTs are shown in Figure 1b. The electrical properties of glass-based and textile-based TFTs fabricated using the same process were as follows: the saturation mobility was 8.12 $cm^2/V{\cdot}s$ and 7.55 $cm^2/V{\cdot}s$, the on/off ratio was 1.2×10^9 and 2.4×10^8, the subthreshold swing (SS) was 234 mV/dec and 347 mV/dec, and the threshold voltage (Vth) calculated using the constant current method (at 1×10^{-7}A) was 0.689 V and 0.761 V, respectively. Both devices maintained a gate current in the low 10^{-9} A range despite increasing gate voltage and provided sufficient on-current exceeding 100 µA. To evaluate the feasibility of the textile-based TFT for driving OLEDs, 1T-1O system was implemented by connecting the drain of the TFT to the cathode of an inverted top-emitting red OLED with the following structure: Al/Liq/$Bebq_2$:$Ir(piq)_3$ /NPB/MoO_3/Ag. Using a spectro scopic radiometer (CS2000) and a source meter (2400 series), as shown in Figure 1c, the luminance of the OLED increased stepwise with the TFT gate voltage sweep. This confirms the stable operation of the 1T-1O system, with the TFT providing sufficient current to drive the OLED. Moreover, the performance of the system fabricated on the textile substrate was comparable to that on a glass substrate, demonstrating the feasibility of achieving stable devices on textile substrates.

Figure 2a shows the statistical transfer curve for the TFT arrays deposited over the entire area of the textile substrate. A statistical analysis of 19 out of 25 devices, as depicted in Figure 2b, revealed a high on/off ratio exceeding 10^9, low SS below 250 mV/dec, and a mean Vth of 0.64 V with a small variation in the range of 0.36 to 1.03 V. Additionally, the average mobility was 17.9 $cm^2/V{\cdot}s$, demonstrating the capability to fabricate high-mobility flexible oxide TFTs across the entire textile substrate[13]. To evaluate flexibility, unit textile-based TFTs were subjected to bending tests using a tensile bending system, as shown in Figure 2c. The devices underwent 1,000 bending cycles at radii ranging from 30 mm to 2 mm. Figure 2d shows the resulting changes in mobility and Vth. For bending radii as small as 3 mm (corresponding to about 1.6% strain, based on analytical modeling of textile substrates), no significant degradation in mobility or Vth was observed after 1,000 cycles, indicating the high mechanical reliability of the textile-based TFTs, as the Al_2O_3 gate insulator layer remained intact under these conditions [14]. However, at a bending radius of 2 mm (approximately 2.1% strain), the devices failed due to cracks in the textile substrate, which caused disconnection of the electrodes and channel, resulting in the loss of switching characteristics.

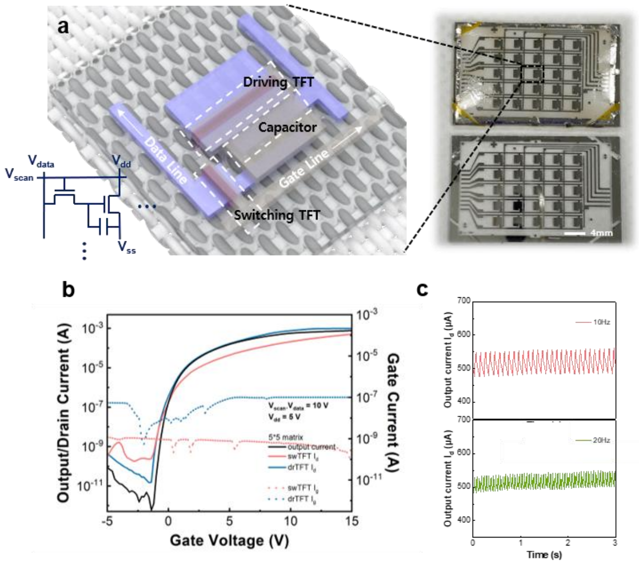

Figure 3 Schematic diagram of a single 2T1C unit and optical images of 5×5 active matrix display driving circuits on textile substrate(top) and glass substrate(bottom) (b) transfer curves of the switching TFT, driving TFT and Output current through driving TFT in the 2T1C structure (c) Output current of the 2T1C pixel circuit at 10 Hz (top) and 20 Hz (bottom)

To verify the feasibility of active matrix driving for textile-based TFTs, a 5✕5 textile-based TFT array was fabricated with a 2T1C pixel circuit structure, as shown in Figure 3a. The circuit was supplied with voltages at four terminal: data line, gate line, source line, and Vdd line. The resulting output current as a function of data line voltage, along with the transfer curves of each TFT, are shown in Figure 3b. Both TFTs in this pixel structure are top-gate staggered-structure devices. To minimize thermal deformation of the textile substrate, a single gate insulator deposition process was employed. Additionally, a small PDMS film was used for masking to connect the source electrode of the switching TFT to the gate of the driving TFT and one electrode of capacitor. As the area of the textile substrate increases, swelling issues from differance of thermal expansion coefficeinct arise due to thermal process. Therefore, the process was optimized to minimize these effects,

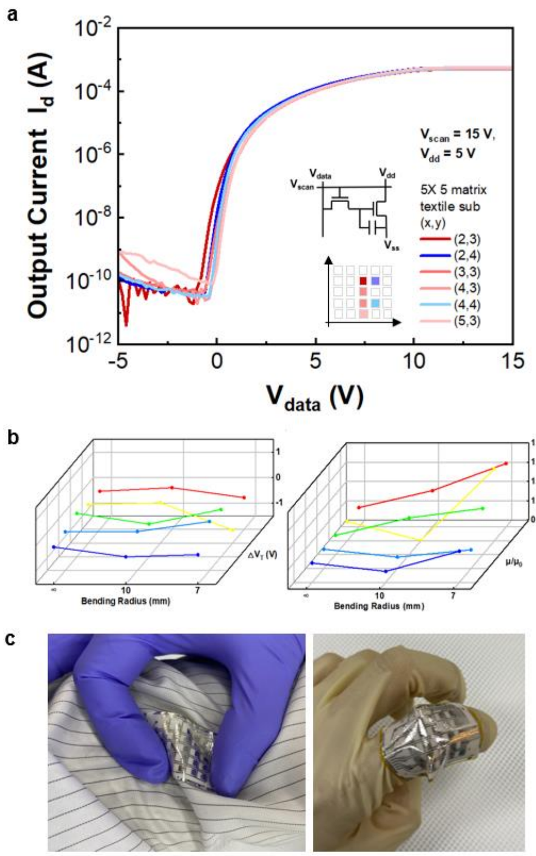

Figure 4 (a) Output driving currents of six selected 2T1C pixels in a 5✕5 active matrix (b) Output current of 5 pixels under different bending radii of ∞(before bending) mm, 10 mm, and 1 mm (c) Demonstration of textile-based TFT flexibility during crumpling on fabric and bending around a finger

ensuring the performance of the devices, with a fine metal mask (FMM) design that accounted for margin to accommodate potential deformations during the process. In Figure 3b, individual TFTs and 2T1C circuit exhibit good switching characteristics. The mobility of the textile-based TFTs in the 2T1C structure was 4.24 $cm^2/V \cdot s$, with an on/off ratio of 2.72×10^9, a subthreshold swing (SS) of 141 mV/dec, and a threshold voltage of -0.137 V, demonstrating very similar electrical performance with glass-based TFTs fabricated using the same process. To assess the suitability of this structure for pulse driving and to evaluate the capacitor's voltage retention ability, pulse voltages were applied with scan voltage and data voltage at duty ratios of 35% and 40%, respectively. As shown in Figure 3c, Even when voltages were applied to turn off the transistor in the gate and data lines, the current was successfully held by the capacitor, demonstrating stable driving of the 2T1C circuit. However, considering the kickback phenomenon, some leakage in the holding current was observed, suggesting the presence of leakage paths in the device, potentially related to contact resistance, surface charge, or mechanical stress. Further analysis of the electrical characteristics of the textile TFT device related to these leakage paths is needed.

In a 5✕5 textile-based 2T1C pixel array, the switching characteristics of the output current were well demonstrated for six selected cells at different positions exhibiting minor variations within a narrow range of the electrical characteristics in Figure 4a. To evaluate the flexibility of the pixel array device, a bending test was performed on five randomly selected pixels, subjecting them to 1,000 bending cycles at various bending radii. The bending stress was classified into three condition: i) compressive/parallel, ii) tensile/parallel, and iii) tensile/perpendicular, based on the type of bending and the relative direction between the bending axis and the channel width. In oxide TFTs, bending typically induce micro-cracks along the bending axis, which can act as defects and leakage paths. Among the characteristics of the oxide channel under mechanical stress, Gaussian donor-like defects are the dominant factor in determining stress severity. When tensile stress is applied and the channel is oriented perpendicular to the bending axis, the channel experiences more severe stress, as observed in both simulations and experiments [15-16]. Based on this trend, it was expected that the critical bending radius would follow the order of i, ii, iii, with progressively smaller radii tolerable for higher stress. However, the results of the bending test on the pixel array showed the opposite trend, with the order of iii, i, ii, indicating the ability to withstand higher bending strains. Figure 4b shows that in case iii, the mobility and threshold voltage of the selected five pixels remained stable without significant fluctuation, even under bending up to a critical bending radius of 7 mm. Bending tests were conducted at bending radii of 10 mm, 7 mm, and 5 mm, corresponding to bending strains of approximately 0.44%, 0.7%, and 1.0%, respectively. For the bending radius of 7 mm (i), 10 mm (ii), and 5 mm (iii), the switching characteristics were no longer observed. The bending test results, coupled with the observation of crack patterns and directions after the tests, highlight a deviation from the expected trend based on the physical stress of the channel. Instead of the channel experiencing the highest stress as anticipated, the limitation of bending strain in the pixel is primarily due to cracks occurring in areas like the electrode lines and capacitor, which can lead to electrical failure or short circuits. This can likely be improved by modifying the material or structural design of these components. Figure 4 c shows a photograph of a textile-based TFT attached to actual clothing or rubber gloves, demonstrating its ability to deform multi-directionally and effectively reflect the curvature of the human body. The characteristics of this textile-based TFT distinguish it as a strong and unique solution in the field of flexible TFTs, offering significant advantages in terms of accessibility and wearability.

The inverted top-emitting red OLED was deposited onto the 5✕5 pixel array, with the cathode of the OLED connected to the drain electrode of the driving TFT in the 2T1C pixel circuit, resulting in the fabrication of the textile-based AMOLED. The driving voltages

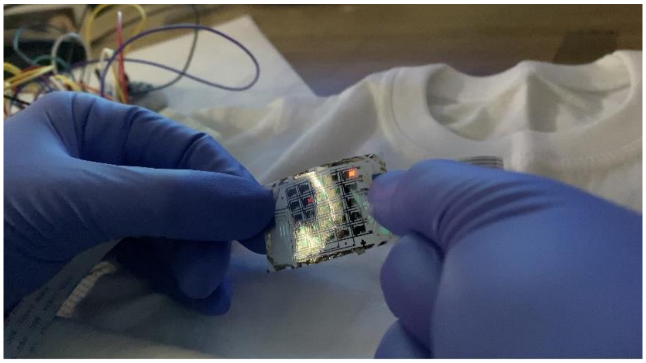

Figure 5 Photograph of a 5✕5 Active Matrix OLED on Textile Substrate Demonstrating Flexibility

for the four terminals were set using an Arduino and supplied to each line through an FFC cable. As shown in Figure 5, the textile-based AMOLED selectively emitted light even under substrate wrinkling, with OLED luminance gradually increasing as the current increased, confirming the stable operation of the TFT and the successful driving of the AMOLED system on the textile substrate**.**

3. Conclusion

Textile-based TFTs with a top-gate staggered structure were fabricated using a simplified process at a low temperature of 120°C. In addition to single TFTs, textile-based 2T1C pixel circuits for active matrix driving were also successfully developed, demonstrating electrical performance comparable to devices fabricated on glass substrates. To minimize substrate deformation caused by thermal stress, process optimization and mask design adjustments were made. These optimizations led to the successful fabrication of textile TFTs with mobilities approaching or exceeding 10 $cm^2/V\cdot s$. The flexibility of the textile-based TFTs was demonstrated through bending tests, which revealed that the unit TFTs withstood 1.6% strain, while the 5×5 2T1C active matrix array endured 0.7% strain. Furthermore, the successful integration of OLEDs with the 2T1C textile-based pixel circuits confirmed the feasibility of textile-based AMOLEDs, validating the potential for realizing a truly wearable AMOLED system with stable performance.

4. Acknowledgements

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5. References

1. Hassan M, Abbas G, Li N, et al. Significance of flexible substrates for wearable and implantable devices: Recent advances and perspectives. *Adv Mater Technol*. 2022;7:2100773.
2. Meena JS, Choi SB, Jung SB, et al. Electronic textiles: New age of wearable technology for healthcare and fitness solutions. *Mater Today Bio*. 2023;19:100565.
3. Choi S, Kwon S, Kim H, et al. Highly flexible and efficient fabric-based organic light-emitting devices for clothing-shaped wearable displays. *Sci Rep*. 2017;7:6424. doi: 10.1038/s41598-017-06733-8.
4. Hwang YH, Kong SU, Kim CY, et al. Organic light-emitting fibers and fabrics for truly wearable smart displays: Recent progress and future opportunities. *J Soc Inf Display*. 2022;30(10):727-747.
5. Park CJ, Heo JS, Kim KT, et al. 1-Dimensional fiber-based field-effect transistors made by low-temperature photochemically activated sol–gel metal-oxide materials for electronic textiles. *RSC Adv*. 2016;6:18596-18600.
6. Park JW, Kwon S, Kwon JH, et al. Low-leakage fiber-based field-effect transistors with an Al_2O_3–MgO nanolaminate as gate insulator. *ACS Appl Electron Mater*. 2019;1(8):1400-1407.
7. Yoon J, Jeong Y, Kim H, et al. Robust and stretchable indium gallium zinc oxide-based electronic textiles formed by cilia-assisted transfer printing. *Nat Commun*. 2016;7:11477.
8. Lee HE, Kim S, Ko J, et al. Skin-like oxide thin-film transistors for transparent displays. *Adv Funct Mater*. 2016;26:6170-6178.
9. Kim JS, Song CK. Textile display with AMOLED using a stacked-pixel structure on a polyethylene terephthalate fabric substrate. *Materials*. 2019;12(12):2000.
10. Park J, Kim CY, Kim MJ, et al. Flexible, transparent, high mobility amorphous In–Ga–Zn–O thin film transistors fabricated on textile. *ACS Appl Electron Mater*. 2023;5(3):1606-1614.
11. Choi S, Jo W, Jeon Y, et al. Multi-directionally wrinkle-able textile OLEDs for clothing-type displays. *npj Flex Electron*. 2020;4:33.
12. Kim CY, Hwang YH, Chang J, et al. High mobility, low off-current, and flexible fiber-based a-InGaZnO thin-film transistors toward wearable textile OLED displays. *ACS Appl Mater Interfaces*. 2024;16(45):62335-62346.
13. Petti L, Münzenrieder N, Vogt C, et al. Metal oxide semiconductor thin-film transistors for flexible electronics. *Appl Phys Rev*. 2016;3(2):021303.
14. Lee J, Gu CY, Chang J, et al. Analytic modeling and validation of strain in textile-based OLEDs for advanced textile display technologies. *npj Flex Electron*. 2024;8:73.
15. Billah M, Hasan M, Jang J. Effect of tensile and compressive bending stress on electrical performance of flexible a-IGZO TFTs. *IEEE Electron Device Lett*. 2017;38(7):890-3.
16. Sheng J, Park J, Choi DW, Lim J, Park JS. A study on the electrical properties of atomic layer deposition grown InOx on flexible substrates with respect to N2O plasma treatment and the associated thin-film transistor behavior under repetitive mechanical stress. *IEEE Electron Device Lett*. 2017;38(7):890-3.