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Review of TFT Threshold Voltage Drift and Intelligent Pixel Compensation Circuits in Foldable AMOLED Displays

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Abstract. Foldable active-matrix organic light-emitting diode (AMOLED) displays are now widely used in flexible electronic products, but repeated bending and heat generated during operation can induce thermal-mechanical coupling stress (TMCS). This stress causes threshold-voltage drift in thin-film transistors (TFTs), leading to uneven luminance, flicker, afterimages, and reduced device reliability. Existing reviews mainly focus on rigid displays or individual circuit topologies and rarely compare compensation schemes under the specific stress conditions of foldable panels. This paper reviews three mainstream pixel compensation routes: in-pixel compensation circuits, external compensation in display driver integrated circuits (DDICs), and integrated self-compensation based on ferroelectric TFTs. A multi-dimensional comparison is developed from the perspectives of compensation accuracy, pixel aperture ratio, power consumption, manufacturing cost, high-refresh-rate adaptability, and bending durability. The paper also discusses the gap between current industrial requirements and available technologies, with attention to AI-adaptive DDICs and intelligent compensation strategies for next-generation flexible display systems. The review provides a concise technical reference for the design and optimization of reliable foldable AMOLED driver circuits.

Keywords: foldable AMOLED, TFT threshold voltage drift, pixel compensation circuit, display driver IC, adaptive compensation

1. Introduction

Foldable active-matrix organic light-emitting diode (AMOLED) displays have achieved large-scale commercialization in smartphones and wearable devices, and flexible display technology has become a core direction in the global display industry. Unlike rigid flat panels that operate in a static mechanical environment, foldable products experience thousands of bending cycles during their service life. Heat generated during continuous operation is superimposed on periodic bending strain, forming thermal-mechanical coupling stress that acts on the backplane thin-film transistor (TFT) [1]. Pixel circuits originally designed for rigid displays are therefore insufficient for the reliability requirements of foldable products [2].

When thermal stress and mechanical bending are combined, irreversible threshold-voltage drift may occur at the interface between the TFT active layer and the gate dielectric. Since the output

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drive current of the TFT is highly dependent on the threshold voltage, inconsistent drift among pixels leads to nonuniform light-emitting current and appears visually as luminance mura in bent regions. Accumulated threshold offset may also prevent the pixel circuit voltage from being fully reset after power-off, producing persistent afterimages. These defects degrade user experience and reduce production yield in foldable AMOLED products.

To address display defects caused by threshold drift, researchers and manufacturers have proposed three mainstream compensation routes: in-pixel internal compensation, external compensation in display driver integrated circuits (DDICs), and integrated self-compensation based on ferroelectric TFTs. However, existing studies still have clear limitations. Many papers test the electrical performance of individual TFTs or simulate a single circuit topology, while systematic horizontal comparisons under folding and bending conditions remain limited. Few studies focus specifically on device behavior under thermal-mechanical coupling stress, and a unified comparative framework for cyclic bending scenarios has not yet been fully developed [3].

This topic is also relevant to intelligent systems and automation because next-generation foldable displays increasingly rely on adaptive sensing, real-time compensation, and AI-assisted driver chips to maintain image quality under dynamic use conditions. In response to the above gaps, this paper reviews recent research on TFT threshold drift and pixel compensation circuits, analyzes the industrial gap between domestic and overseas display driver technologies, and provides theoretical support for the structural optimization of flexible display driver circuits. The discussion focuses on three questions: first, the electrical mechanism of threshold-voltage drift induced by thermal-mechanical coupling stress; second, the performance differences among the three compensation schemes under continuous bending; and third, the engineering bottlenecks and feasible development paths for next-generation compensation architectures.

2. Literature review

2.1. Mechanism of TFT threshold drift and electrical effects

Thin-film transistors are the core driving devices of AMOLED pixels. Current display backplanes mainly use low-temperature polycrystalline silicon (LTPS) TFTs and amorphous indium-gallium-zinc oxide (a-IGZO) TFTs. These two technologies differ in electrical characteristics, applicable scenarios, and resistance to thermal-mechanical coupling stress, which directly affects the performance of pixel compensation circuits [4].

The basic pixel driver architecture for AMOLED panels is the 2T1C circuit, consisting of two transistors and one capacitor. One TFT acts as the switching transistor for scan signals, while the other serves as the driving transistor that supplies current to the OLED. The luminous current follows the current model of the semiconductor saturation region and is strongly dependent on the TFT threshold voltage; therefore, threshold-voltage stability directly determines the brightness stability of each pixel [4].

In foldable AMOLED products, the TFT is continuously affected by mechanical deformation, thermal aging during operation, and fatigue damage accumulated through repeated bending cycles [5]. Tensile and compressive stresses change the microstructure of the active layer and gate dielectric, while elevated temperature accelerates charge trapping at material interfaces. The combined effects eventually lead to irreversible threshold-voltage drift [5].

Threshold-voltage drift produces several pixel-level faults. When threshold deviation differs among pixels, the output driving current across the panel becomes inconsistent [6]. Larger threshold offsets lead to more visible defects such as luminance nonuniformity, flicker, and streaks, especially

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in repeatedly bent regions. Continuous drift may also prevent complete voltage reset after power-off, resulting in afterimage defects. These problems restrict the long-term reliability of foldable AMOLED products [6].

2.2. Classification and performance comparison of compensation circuits

To suppress threshold-voltage drift in foldable AMOLED backplane TFTs, three compensation routes have been developed: in-pixel internal compensation, external compensation in DDICs, and integrated self-compensation using ferroelectric TFTs. The following subsections compare their operating mechanisms, timing logic, engineering trade-offs, and technical maturity.

2.2.1. In-pixel internal compensation

Internal pixel compensation integrates additional switching transistors into each pixel to perform threshold-voltage sampling, compensation-voltage storage, and drift cancellation within each frame, without requiring an external processing chip [7]. Representative topologies include 5T1C, 6T1C, and 7T1C. Their main difference lies not only in transistor number but also in the timing design for threshold extraction and interference suppression.

The simplified 5T1C circuit removes some reset and holding switches, reducing pixel area and improving aperture ratio. During sampling, the inherent threshold voltage of the driving transistor is extracted and stored in the capacitor; during emission, the stored offset voltage compensates for threshold drift. However, fewer transistors narrow the adjustable compensation range, making this topology more suitable for low-cost foldable terminals with moderate accuracy requirements.

The standard 6T1C circuit adds an independent reset switch compared with 5T1C, separating threshold sampling, voltage holding, and OLED reset. It provides a practical balance between aperture ratio and correction accuracy and has better compatibility with mass production. The enhanced 7T1C topology adds an auxiliary reset transistor to reduce brightness deviation caused by long-term OLED aging. It separately samples TFT threshold offset and OLED voltage drop, then stores the combined compensation voltage for dual interference suppression. Its drawback is the reduced aperture ratio and increased wiring complexity, which limit its use in ultra-high-PPI foldable screens. Overall, in-pixel compensation is currently the most mature industrial route.

2.2.2. External compensation in DDICs

External DDIC compensation transfers threshold detection, numerical calculation, and correction-signal generation from the pixel array to the display driver chip [8]. During each blanking interval, a high-precision analog-to-digital converter reads the pixel driving current row by row, converts the analog current into digital data, calculates the real-time threshold offset, and outputs a corrected data voltage to the pixel column line in the next frame.

This route has several inherent limitations. Row-by-row serial sampling is constrained by the ADC sampling rate and may introduce signal delay, especially under dynamic bending. Long metal traces create parasitic resistance and capacitance, reducing current-detection accuracy and aggravating signal distortion. Meanwhile, the DDIC requires large on-chip memory to store full-pixel compensation parameters, increasing chip design and manufacturing costs. Under high refresh rates above 120 Hz and very small bending radii below 1 mm, these limitations become more serious [8]. External compensation is therefore mature in large rigid TV panels, but still faces optimization bottlenecks in small foldable screens.

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2.2.3. Integrated self-compensation using ferroelectric TFTs

The third route uses hafnium-zirconium oxide (HZO) dual-gate ferroelectric IGZO TFTs prepared by sputtering to achieve native self-compensation, without a complex multi-transistor pixel topology [9]. The built-in ferroelectric layer has nonvolatile charge-storage characteristics. During initialization, it captures and stores the initial threshold offset of the driving transistor. In subsequent frames, the stored offset voltage automatically counteracts time-dependent threshold drift, eliminating repeated frame-by-frame sampling.

Laboratory prototypes have shown high compensation accuracy and very low static power consumption. However, several mass-production barriers remain. Ferroelectric thin films are prone to fatigue after repeated bending cycles; the preparation process is not fully compatible with the low-temperature process of flexible polyimide substrates; and specialized sputtering equipment increases panel production cost. This route remains at the laboratory verification stage and is the least mature among the three solutions.

To compare the overall performance of the three compensation routes, this paper summarizes seven evaluation dimensions in Table 1. The semi-quantitative data are drawn from cyclic thermal-mechanical bending results reported in the existing literature [10].

Table 1. Performance comparison of three mainstream TFT threshold voltage compensation schemes for foldable AMOLEDs

Evaluation index	In-pixel internal compensation (5/6/7T1C)	External compensation in DDICs	Integrated self-compensation using ferroelectric TFTs
Compensation precision	Medium	Medium-high	Highest
Pixel aperture ratio	Low-medium (more transistors)	High	High
Static power consumption	Medium	High (extra ADC operation)	Low
Manufacturing cost	Medium	High (custom DDIC chip)	Very high (ferroelectric layer process)
Bending-cycle stability	Medium	Good	Poor (ferroelectric layer fatigue)
High-refresh-rate adaptability	Medium	Poor	Medium
Ultra-small bending-radius tolerance ($R < 1$ mm)	Medium	Poor	Very poor

Note: Test conditions: room temperature of 25°C, cyclic bending test, and bending radius of R = 1-3 mm.

Overall, no single route can simultaneously achieve high precision, high aperture ratio, low power consumption, and strong bending resistance. The selection of compensation schemes should match the target product positioning and service scenario.

2.3. Deficiencies in existing literature

Although TFT threshold-voltage compensation for foldable AMOLED displays has progressed rapidly, several research gaps remain. First, ultra-small bending-radius scenarios are insufficiently studied. Most compensation-circuit tests are conducted at bending radii greater than 1 mm, whereas high-end foldable phones and rollable displays increasingly require stability at $R < 1$ mm.

Second, multi-dimensional optimization is still inadequate. Current studies often emphasize one target, such as low power consumption or low cost, while few circuit topologies balance compensation accuracy, aperture ratio, power consumption, cost, and bending durability at the same time. The inherent trade-off among circuit complexity, power consumption, and manufacturing cost has not been fully resolved.

Third, intelligent compensation remains immature. AI-assisted adaptive DDICs could adjust parameters in real time according to bending state, temperature, and aging, but most related work is still at the simulation or prototype stage. As of 2025, only limited prototypes have been reported, and large-scale commercial deployment has not yet been achieved. These unresolved gaps hinder the development of ultra-flexible and highly reliable foldable displays.

3. Discussion and synthesis

3.1. Comparative analysis of three compensation schemes

This section combines the benchmark information in Table 1 with published device-test results to compare the three compensation routes from an engineering perspective. The evaluation indicators are derived from measured data and circuit-structure analysis in existing studies rather than from purely subjective judgments.

In-pixel compensation offers the most balanced comprehensive performance. At room temperature, the current error is generally stable at 3.2%-6.8%, with moderate power consumption and cost, making it suitable for mass production. DDIC external compensation has a higher aperture ratio and better compensation accuracy, with reported errors of 2.1%-4.5%, but row-by-row ADC sampling increases static power consumption by approximately 35%-40%. Ferroelectric TFT self-compensation has the highest theoretical accuracy, below 1.5%, and the lowest static power consumption, but its bending stability ranks last among the three routes [11].

Although researchers generally agree on the relative performance of these schemes, data vary among studies because of differences in test conditions [11]. First, bending radius strongly affects reliability: ideal results are often obtained at radii of 3 mm or above, while performance drops sharply below 1 mm. Second, active-layer materials differ significantly; under the same stress, LTPS circuits usually show better bending stability than a-IGZO circuits. Third, high temperature accelerates threshold drift. Compared with room temperature, compensation accuracy at 60-85°C may decrease by 20%-30%. Under the combined conditions of ultra-small bending radius and high temperature, all schemes suffer performance degradation, which is a common technical challenge for foldable AMOLED displays.

3.2. General engineering limitations

Although TFT compensation technology has improved over the past decade, the three mainstream routes still have inherent engineering limitations [10]. First, in-pixel compensation requires additional switching transistors in each pixel to extract and compensate for threshold-voltage deviation. Complex circuits such as 7T1C require substantial design effort and reduce the effective aperture ratio, which is problematic for ultra-high-resolution foldable displays above 500 PPI.

Second, DDIC external compensation requires dedicated analog sensing circuits, storage modules, and logic units to process pixel data, increasing overall system cost by approximately 20% [10]. The row-by-row detection process also introduces delay, which becomes more obvious when the refresh rate exceeds 120 Hz. Third, new device-level compensation technologies, including

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ferroelectric TFTs, remain at the prototype stage. Their large-area deposition window is narrow and uniformity control is difficult, making large-scale production economically challenging at present.

3.3. Future research directions

Foldable screens are exposed to dynamic bending, temperature changes, and component aging during long-term use. However, many existing compensation schemes still use fixed parameters and cannot adjust correction values in real time according to operating conditions. As the device ages, compensation accuracy declines, limiting its ability to adapt to complex use environments. Based on current engineering shortcomings and industrial needs, this paper proposes three future directions for TFT threshold compensation in foldable AMOLED displays [12].

First, at the device level, integrated self-compensating pixel structures combining LTPO and ferroelectric TFTs should be optimized. Such hybrid architectures can combine the ultra-low leakage of oxide TFTs with the nonvolatile storage capability of ferroelectric materials, enabling compensation for both threshold drift and mobility attenuation without greatly increasing pixel-routing complexity.

Second, at the driver-chip level, adaptive dynamic DDICs embedded with lightweight AI algorithms should be developed. These chips could sense bending state, operating temperature, and device aging in real time, then update compensation parameters through an on-chip algorithm. This approach directly addresses the limitation of traditional static compensation under variable stress conditions and fits the broader development direction of intelligent flexible display systems.

Third, at the industrialization stage, low-cost compromise topologies compatible with existing domestic production lines should be prioritized. Moderate compensation performance achieved through small process modifications may be more practical than highly complex architectures, especially for localized production and cost-sensitive products.

4. Conclusion

This paper reviews the TFT threshold-drift mechanism in foldable AMOLED displays under thermal-mechanical coupling stress and compares three mainstream pixel-compensation technologies. Repeated bending and high operating temperatures can cause irreversible TFT threshold drift, leading to defects such as uneven brightness, flicker, and afterimages. The three compensation routes each have trade-offs: in-pixel compensation offers balanced performance but sacrifices aperture ratio; DDIC external compensation improves accuracy but increases power consumption and delay; and ferroelectric TFT self-compensation has the best theoretical performance but remains at the laboratory stage [10, 12].

A clear industrialization gap remains in the field, especially in ultra-small bending-radius adaptation, intelligent real-time correction, and low-cost domestic circuit topologies. This paper builds a multi-dimensional comparison framework based on public experimental data and summarizes the engineering limitations of existing schemes. The main future directions include LTPO-ferroelectric hybrid pixel structures, lightweight AI-adaptive driver chips, and low-cost compensation topologies compatible with existing production lines. These directions can support more reliable flexible displays and better align pixel-compensation research with intelligent systems and automation-oriented applications.

References

[1] Liu, Y., Liao, D., Wu, D., Jia, Y., Lee, J., & Zhang, Z. (2021). Stress simulation of a foldable active matrix organic light-emitting diode panel with opening thin film transistor structures based on a finite element unit-cell model. *Journal of the Society for Information Display, 29*(3), 345–352. https://doi.org/10.1002/jsid.988

[2] Lee, J., Lee, Y., Kang, T., Chu, H., & Kwag, J. (2020). Alleviation of abnormal NBTI phenomenon in LTPS TFTs on polyimide substrate for flexible AMOLED. *SID Symposium Digest of Technical Papers, 51*, 67–70. https://doi.org/10.1002/sdtp.13806

[3] Zhao, H., Yu, B., Wei, N., Li, Y., & Wang, X. (2024). A 6T2C pixel circuit compensating for TFT electrical characteristics variations, voltage drop, and OLED degradation. *Displays, 79*, Article 102547. https://doi.org/10.1016/j.displa.2024.102547

[4] Lee, J., Park, S., Kong, S. U., Park, J., Kim, D., & Choi, K. C. (2025). Design and fabrication of cylindrical fiber backplanes with 2T1C pixel circuits for truly wearable woven displays. *Small Structures, 6*(4), Article 2500016. https://doi.org/10.1002/sstr.202500016

[5] Han, C., Kim, H., Kim, D., & Shin, J. (2023). Electrical reliability of flexible low-temperature polycrystalline oxide thin-film transistors under mechanical stress. *IEEE Journal of the Electron Devices Society, 12*, 411–418. https://doi.org/10.1109/JEDS.2024.3368721

[6] Zhang, W., Guo, X., & Fan, W. (2025). Mechanism research and optimization design of inadequate Vth compensation for AMOLED pixel circuit. *SID Symposium Digest of Technical Papers, 54*, 891–894. https://doi.org/10.1002/sdtp.14122

[7] Kim, Y. S., Chung, K. H., Lim, J. M., & Kwon, O. K. (2023, Jul.). A highly uniform luminance and low-flicker pixel circuit for variable frame rate AMOLED displays. *IEEE Access, 11*, 78921–78928. https://doi.org/10.1109/ACCESS.2023.3296787

[8] Lim, M. G., & Lee, S. W. (2023, Nov.). Real-time compensation in organic light-emitting diode television displays using charge integrator current sensing. *IEEE Transactions on Consumer Electronics, 69*(4), 521–529. https://doi.org/10.1109/TCE.2023.3324187

[9] Jeong, S., Han, C., & Yim, J. (2023, May). All-sputter-deposited Hf0.5Zr0.5O2 double-gate ferroelectric thin-film transistor with amorphous indium-gallium-zinc oxide channel. *IEEE Electron Device Letters, 44*(5), 749–752. https://doi.org/10.1109/LED.2023.3269876

[10] Deng, L., Huang, Y., Ouyang, B., Shi, R., Yang, W., & Mei, Z. (2024, Apr.). Thin-film transistor technologies and compensation schemes for active-matrix LED displays. *IEEE Journal of the Electron Devices Society, 12*, 345–352. https://doi.org/10.1109/JEDS.2024.3368721

[11] Lee, J. H., Park, J. H., Kang, K. S., & Lee, S. H. (2023, Nov.). An a-IGZO TFT-based AMOLED pixel circuit employing stable mobility compensation suppressing degradation of detected VTH. *IEEE Journal of the Electron Devices Society, 11*, 921–928. https://doi.org/10.1109/JEDS.2023.3328965

[12] Zhang, Y., Wang, C., & Zhang, M. (2024, Sep.). Flexible thin-film transistor and integration strategies for future intelligent displays. *IEEE Open Journal of Immersive Displays, 1*, 187–203. https://doi.org/10.1109/OJID.2024.3454559