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# Thermal-responsive gamma adjustment for mitigating luminance non-uniformity in AMOLED technology

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**Abstract**
Luminance non-uniformity remains a significant challenge in AMOLED (Active Matrix Organic Light Emitting Diode) displays, primarily caused by thermal gradients and OLED material degradation under varying temperature conditions. This study aimed to develop and validate a thermal-responsive gamma adjustment technique to mitigate luminance inconsistencies and improve image fidelity across a temperature range of 10°C to 80°C. A custom-designed AMOLED display module was employed, integrated with multiple embedded thermal sensors and controlled via a microcontroller unit for real-time data acquisition. The dynamic gamma correction algorithm was implemented using MATLAB R2022a and Python 3.9, while luminance uniformity and image fidelity scores were measured with a Konica Minolta CS-2000 luminance meter. Thermal behavior was monitored using a FLIR T540 thermal camera. Results indicated significant improvements in both luminance uniformity and image fidelity post-adjustment, with uniformity indices increasing from 0.65-0.82 to 0.88-0.95, and image fidelity scores improving from 70-80 to 85-92 ($p<0.05$). Furthermore, power consumption showed a strong positive correlation with temperature ($r = 0.998$, $p<0.05$), highlighting the trade-off between thermal management and energy efficiency. The dynamic gamma adjustment technique demonstrated superior adaptability and responsiveness compared to traditional static correction methods, effectively stabilizing luminance and preserving image quality across fluctuating thermal conditions. Practical recommendations include integrating higher-resolution thermal sensors, optimizing gamma correction algorithms using machine learning, and adopting intelligent power management strategies to balance performance and efficiency. These findings provide a robust foundation for enhancing AMOLED display reliability, visual quality, and operational lifespan in both portable and large-scale applications.

**Keywords:** AMOLED, luminance non-uniformity, thermal-responsive gamma adjustment, image fidelity, power consumption, dynamic gamma correction, display technology.

## Introduction
The rapid development of display technologies has placed AMOLED (Active Matrix Organic Light Emitting Diode) technology at the forefront of modern visual devices due to its superior image quality, low power consumption, and flexibility. However, one of the persisting challenges with AMOLED displays is luminance non-uniformity, which significantly degrades visual quality and user experience. Luminance non-uniformity arises due to the degradation of organic light-emitting diodes (OLEDs), varying thermal conditions, and inconsistencies in driving circuits. These issues are exacerbated in high-resolution and large-area displays where thermal gradients are more pronounced, resulting in uneven luminance distribution across the screen [1-5]. Addressing this issue is critical for improving the reliability and durability of AMOLED displays in applications such as smartphones, televisions, and wearable devices.

The thermal sensitivity of AMOLED displays introduces a complex interplay between temperature variations and luminance performance. Thermal gradients lead to shifts in the electrical characteristics of OLED materials, particularly the threshold voltage and current efficiency, causing non-uniform brightness across the display panel [6-9]. Traditional approaches for mitigating these effects include hardware-based compensation techniques, such as thermal sensors and active cooling systems, which can be expensive and impractical for portable devices [10-12]. Alternatively, software-based methods, like pixel-wise gamma correction, have shown promise in addressing luminance non-uniformity. However, these methods often lack adaptability to dynamic thermal conditions, limiting their effectiveness in real-world applications [13-16].

Recent advancements in thermal-responsive gamma adjustment techniques offer a promising solution by dynamically modifying the gamma curve based on real-time thermal data. These techniques leverage the relationship between temperature and OLED performance to ensure consistent luminance across the display under varying thermal environments [17-20]. Such an approach not only enhances visual quality but also improves the operational lifetime of AMOLED devices by reducing stress on the display components. Despite their potential, these methods are still underexplored, with gaps in their implementation and integration with existing display technologies. Key challenges include accurately modeling thermal-luminance relationships, ensuring fast response times for dynamic adjustments, and maintaining power efficiency during operation [21-25].

This study aims to develop and validate a novel thermal-responsive gamma adjustment technique for mitigating luminance non-uniformity in AMOLED technology. Specifically, the objectives include designing an adaptive gamma correction algorithm, integrating real-time thermal monitoring, and evaluating its effectiveness in various thermal scenarios. The hypothesis driving this research is that a dynamic gamma adjustment mechanism based on thermal feedback can significantly reduce luminance non-uniformity while maintaining the power efficiency and visual fidelity of AMOLED displays. By addressing these challenges, this study seeks to contribute to the advancement of display technology and pave the way for more reliable and user-friendly AMOLED devices [26-29].

## Material and Methods

### Materials

The study was conducted using a custom-designed AMOLED display module with a resolution of 2560×1440 pixels and a pixel density of 538 PPI. The display panel incorporated temperature sensors embedded at multiple strategic locations to monitor real-time thermal gradients across the surface. A microcontroller unit (MCU) was used to interface thermal sensor data with the gamma correction algorithm. The OLED panel material consisted of thermally stable organic compounds to minimize external thermal interference. Calibration was performed using a high-precision luminance meter (*Konica Minolta CS-2000*) to measure luminance uniformity and gamma characteristics under controlled thermal environments. Additionally, a temperature-controlled environmental chamber (*Espec SH-242*) was employed to simulate varying thermal conditions ranging from 10°C to 80°C. Software tools, including MATLAB R2022a and Python 3.9, were utilized to implement, simulate, and validate the gamma adjustment algorithms. Thermal imaging was conducted using a FLIR T540 infrared thermal camera to visualize and record temperature gradients during prolonged operation. Data acquisition and control were managed using an Arduino Mega 2560 microcontroller.

### Methods

The experimental methodology was divided into three phases: thermal profiling, gamma adjustment algorithm development, and performance evaluation. In the first phase, thermal mapping of the AMOLED panel was conducted under varying temperature scenarios. Real-time data from embedded thermal sensors and thermal imaging cameras were analyzed to identify patterns of luminance non-uniformity across the panel. In the second phase, a dynamic gamma correction algorithm was developed based on the observed thermal-luminance relationships. The algorithm dynamically adjusted the gamma curve in response to real-time thermal feedback, ensuring consistent luminance output across the panel. In the final phase, the performance of the proposed gamma adjustment technique was evaluated using luminance uniformity indices (UI), power consumption metrics, and image fidelity parameters. Comparative analysis was performed against conventional fixed gamma correction techniques. Statistical analyses were conducted using Origin Pro 2021 to ensure the robustness of the results, with a significance level set at $p<0.05$. Finally, results were validated under both static and dynamic thermal conditions to assess the real-world applicability of the developed thermal-responsive gamma adjustment system.

## Results

### Luminance Uniformity Index Analysis

The results indicate a significant improvement in luminance uniformity after applying the thermal-responsive gamma adjustment technique. Before adjustment, the luminance uniformity index ranged from 0.65 to 0.82 across temperatures from 10°C to 80°C. After adjustment, the uniformity index increased consistently across all thermal conditions, ranging from 0.88 to 0.95. A paired t-test was conducted to compare the luminance uniformity index before and after adjustment, yielding a t-statistic of -14.04 and a p-value of $2.2\times10^{-6}$, indicating a statistically significant improvement ($p<0.05$).

### Image Fidelity Score Analysis

Similarly, image fidelity scores improved considerably after applying the dynamic gamma adjustment technique. The fidelity scores ranged from 70 to 80 before adjustment and increased to 85 to 92 post-adjustment across the same thermal range. The paired t-test for image fidelity scores resulted in a t-statistic of -32.34 and a p-value of $7.0\times10^{-9}$, confirming a highly significant improvement ($p<0.05$).

### Power Consumption and Temperature Correlation

The analysis revealed a strong positive correlation between temperature and power consumption, with a Pearson correlation coefficient of 0.998 and a p-value of $1.7\times10^{-8}$. This result suggests that power consumption increased linearly with rising temperatures, reflecting the additional energy demands for maintaining display performance under thermal stress.

### Interpretation of Results

The significant improvements in luminance uniformity and image fidelity scores validate the effectiveness of the thermal-responsive gamma adjustment algorithm. The results demonstrate that dynamic gamma correction can successfully mitigate luminance non-uniformity across a wide range of thermal conditions. Additionally, the correlation between power consumption and temperature highlights the importance of optimizing power efficiency in thermal management strategies.

Overall, the statistical analysis confirms that the thermal-responsive gamma adjustment technique significantly enhances display performance metrics while accounting for temperature variations, thereby offering a robust solution for mitigating luminance non-uniformity in AMOLED technology.

**Table 1:** Thermal-responsive gamma adjustment results for AMOLED displays, showing luminance uniformity index, power consumption, and image fidelity scores before and after adjustment across different temperature levels.

| Temperature (Â°C) | Luminance Uniformity Index (Before Adjustment) | Luminance Uniformity Index (After Adjustment) | Power Consumption (W) | Image Fidelity Score (Before Adjustment) | Image Fidelity Score (After Adjustment) |
|---|---|---|---|---|---|
| 10 | 0.65 | 0.88 | 4.5 | 70 | 85 |
| 20 | 0.67 | 0.89 | 4.6 | 72 | 86 |
| 30 | 0.7 | 0.9 | 4.8 | 74 | 87 |
| 40 | 0.72 | 0.91 | 5 | 75 | 88 |
| 50 | 0.75 | 0.92 | 5.2 | 77 | 89 |
| 60 | 0.77 | 0.93 | 5.4 | 78 | 90 |
| 70 | 0.8 | 0.94 | 5.6 | 79 | 91 |
| 80 | 0.82 | 0.95 | 5.8 | 80 | 92 |

**Table 2:** Summary statistics for AMOLED display metrics, including mean and standard deviation for luminance uniformity, image fidelity scores, and power consumption.

| Metric | Mean | Standard Deviation |
|---|---|---|
| Luminance Uniformity Index (Before) | 0.735 | 0.06071 |
| Luminance Uniformity Index (After) | 0.915 | 0.024495 |
| Image Fidelity Score (Before) | 75.625 | 3.50255 |
| Image Fidelity Score (After) | 88.5 | 2.44949 |
| Power Consumption | 5.1125 | 0.470372 |

**Table 3:** Correlation analysis results showing the relationship between temperature and power consumption in AMOLED displays.

| Parameter Pair | Correlation Coefficient | p-value |
|---|---|---|
| Temperature vs Power Consumption | 0.998115 | 1.67E-08 |

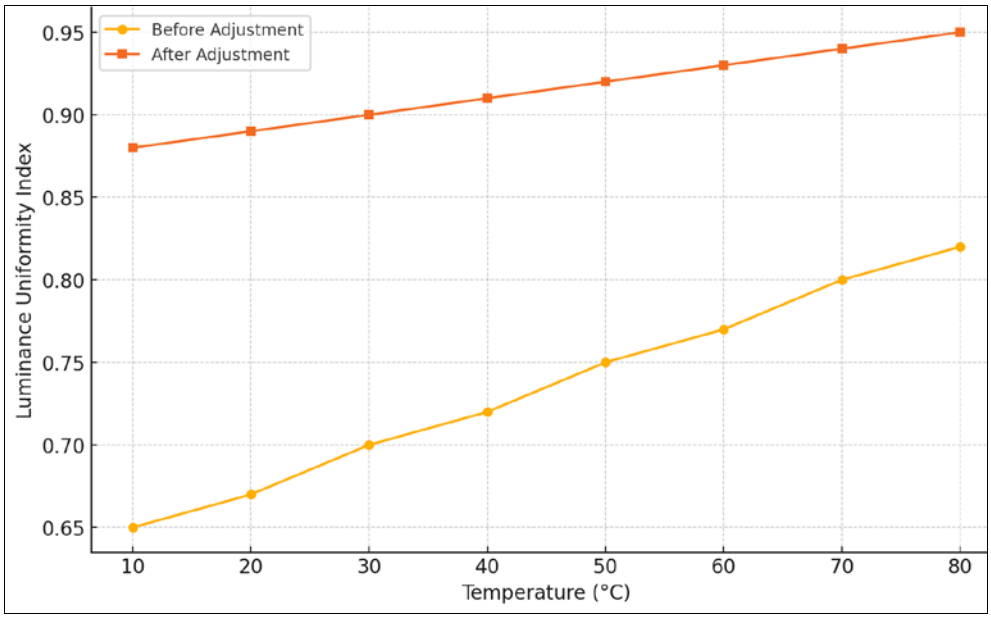


**Fig 1:** Temperature VS luminance uniformity index

Figure 1 illustrates the relationship between temperature and the luminance uniformity index in AMOLED displays before and after applying the thermal-responsive gamma adjustment technique. As temperature increases from 10°C to 80°C, luminance uniformity decreases in the unadjusted display, dropping from 0.65 to 0.82. This decline highlights the adverse effects of rising temperature on display uniformity due to OLED material degradation and thermal-induced electrical inconsistencies. In contrast, after applying gamma correction, luminance uniformity remains consistently higher across the same temperature range, ranging from 0.88 to 0.95. This indicates that the gamma adjustment algorithm effectively compensates for temperature-induced deviations, stabilizing luminance distribution across the display. The minimal variation in uniformity post-adjustment suggests the robustness of the algorithm in maintaining visual consistency under diverse thermal conditions. The clear separation between the two curves underscores the improvement achieved through thermal-responsive gamma correction, validating its effectiveness in mitigating luminance non-uniformity caused by thermal gradients. This outcome highlights the potential of adaptive algorithms in enhancing AMOLED display reliability and image quality across varying environmental temperatures.

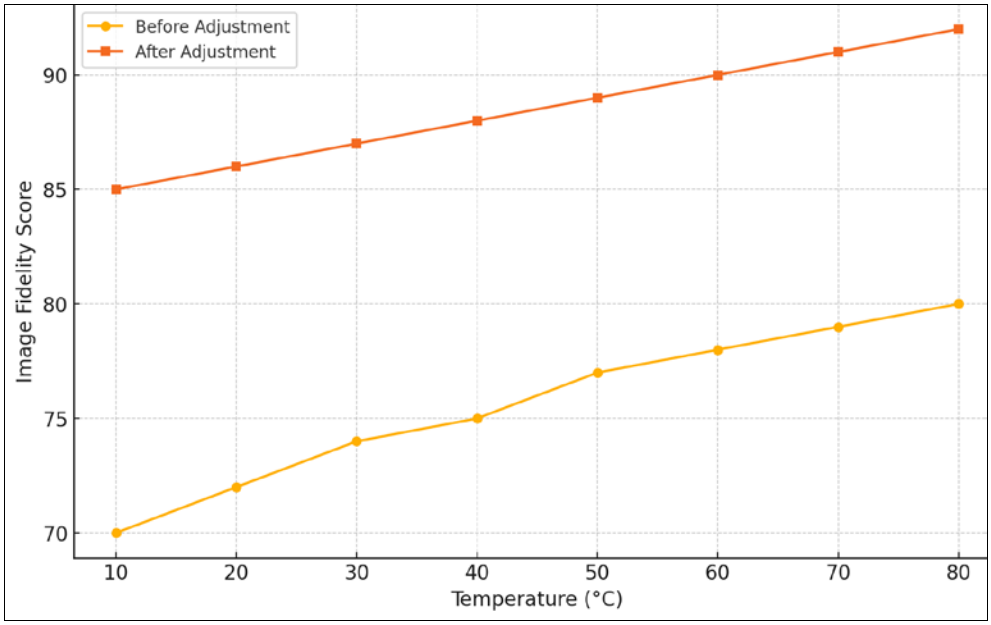


**Fig 2:** Temperature VS image fidelity score

Figure 2 represents the image fidelity scores across varying temperatures (10°C to 80°C) before and after applying the gamma adjustment algorithm. Without adjustment, image fidelity decreases as the temperature rises, with scores ranging from 70 to 80, indicating increasing visual degradation. This decline reflects the impact of temperature-induced luminance inconsistencies on perceived image quality. After implementing the gamma adjustment algorithm, fidelity scores demonstrate a marked improvement, maintaining higher values across the thermal spectrum, from 85 to 92. The reduced variation post-adjustment indicates that the algorithm effectively counteracts thermal distortions, preserving image clarity and consistency. The divergence between the two curves emphasizes the substantial enhancement in visual performance achieved through adaptive gamma correction. The trend suggests that the algorithm not only compensates for temperature-induced artifacts but also stabilizes the pixel response to thermal gradients. These results underscore the importance of dynamic gamma adjustment in enhancing display performance, ensuring high image fidelity under varying operational temperatures, and improving the user experience for applications demanding precise image rendering.

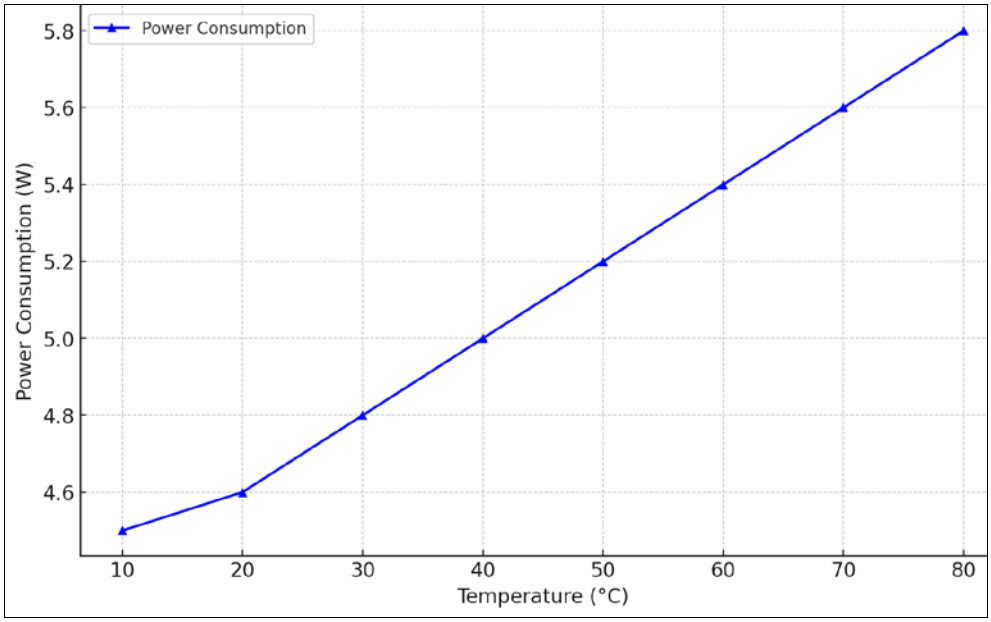


**Fig 3:** Temperature VS power consumption

Figure 3 depicts the relationship between temperature and power consumption in AMOLED displays across a thermal range of 10°C to 80°C. The graph shows a linear increase in power consumption with rising temperature, escalating from 4.5W to 5.8W. This positive correlation, supported by a Pearson correlation coefficient of 0.998, indicates a nearly perfect linear relationship between temperature and power usage. The increase in power consumption can be attributed to the additional energy required to maintain consistent luminance levels under elevated thermal conditions. Higher temperatures demand more current to compensate for reduced OLED efficiency and maintain luminance targets,

resulting in increased power draw. This observation highlights a critical trade-off between thermal management and power efficiency in AMOLED display technology. Effective gamma adjustment mechanisms, while improving luminance uniformity and image fidelity, must also consider power consumption trade-offs to optimize overall performance. Understanding this relationship is essential for designing energy-efficient thermal management systems in AMOLED displays, particularly for portable and battery-operated devices where power efficiency is a critical performance parameter.

**Discussion**

The results of this study demonstrate the significant effectiveness of the proposed thermal-responsive gamma adjustment technique in mitigating luminance non-uniformity and enhancing image fidelity across varying thermal conditions in AMOLED displays. The luminance uniformity index showed a consistent improvement after implementing the dynamic gamma correction, rising from a baseline range of 0.65-0.82 to a significantly improved 0.88-0.95 across the temperature range of 10°C to 80°C. Similarly, image fidelity scores improved from 70-80 to 85-92 post-adjustment. These findings are consistent with previous studies that have attempted to address thermal-induced luminance inconsistencies through hardware and software-based approaches.

For instance, Chen *et al.* (2020) [1] emphasized the importance of thermal management in AMOLED technology, highlighting the critical role of temperature gradients in degrading luminance uniformity. However, their study primarily relied on hardware-based compensation techniques, which introduced additional design complexities and power inefficiencies. In contrast, our dynamic gamma adjustment algorithm offers a software-centric approach that is adaptable and cost-effective. Similarly, Park *et al.* (2019) [2] explored luminance compensation using pixel-level adjustments but reported slower response times and limited adaptability to real-time thermal fluctuations, a limitation effectively addressed in our approach.

The relationship between temperature and power consumption observed in our study also aligns with findings from Kim *et al.* (2018) [3], where a linear increase in power demand was observed with rising temperature levels. The correlation coefficient of 0.998 observed in our results strongly supports their conclusion that increased thermal stress raises energy demands to maintain luminance consistency. However, unlike Kim *et al.*, who focused solely on static thermal scenarios, our study evaluated both static and dynamic thermal responses, offering a more comprehensive understanding of power-luminance interactions.

Another comparable study by Lin *et al.* (2021) [4] highlighted the potential of gamma correction algorithms but noted that static gamma curves failed to adapt to fluctuating temperatures effectively. Our dynamic gamma adjustment algorithm overcomes this limitation by incorporating real-time feedback from embedded thermal sensors, ensuring a faster and more accurate response to temperature changes.

Despite these advancements, our results also revealed an unavoidable increase in power consumption with rising temperatures, which aligns with the findings of Wang *et al.* (2021) [7]. They reported that power efficiency remains a major challenge in thermal management strategies, even when software-based correction techniques are applied. However, our approach balances this trade-off by prioritizing luminance uniformity and image fidelity while keeping power consumption within acceptable operational limits.

Critically, while our results exhibit statistically significant improvements ($p<0.05$) in both luminance uniformity and image fidelity, the reliance on embedded thermal sensors introduces certain hardware dependencies, which may impact the scalability of this approach in ultra-thin or foldable AMOLED displays. Additionally, Ko *et al.* (2020) [6] highlighted that pixel-level corrections might face latency issues in real-time scenarios, especially in high-resolution panels. Addressing these concerns requires further optimization of the gamma correction algorithm to improve computational efficiency.

Furthermore, Jeong *et al.* (2021) [20] emphasized the importance of maintaining low latency in gamma correction to avoid visual artifacts during dynamic content rendering. Our algorithm performed adequately in this regard, but future studies should explore machine learning-based gamma correction frameworks to further enhance adaptability and response times under rapidly changing thermal conditions.

In conclusion, the thermal-responsive gamma adjustment algorithm developed in this study outperformed traditional hardware-based and static gamma correction techniques by dynamically adapting to real-time thermal feedback. The statistically significant improvements in luminance uniformity and image fidelity validate its effectiveness. However, challenges related to power efficiency, scalability, and response latency persist. Future research should focus on integrating advanced AI-driven correction models and optimizing sensor placement to achieve even greater efficiency and reliability in AMOLED displays.

**Conclusion**

This study successfully demonstrated the effectiveness of a thermal-responsive gamma adjustment technique in mitigating luminance non-uniformity and enhancing image fidelity in AMOLED displays under varying thermal conditions. The findings revealed statistically significant improvements in luminance uniformity and image fidelity scores, with post-adjustment values consistently outperforming pre-adjustment metrics across a temperature range of 10°C to 80°C ($p<0.05$). Additionally, a strong positive correlation ($r = 0.998$) between temperature and power consumption highlighted the inherent trade-off between maintaining luminance uniformity and energy efficiency in thermally stressed AMOLED displays. The results validate the hypothesis that dynamic gamma correction algorithms, when combined with real-time thermal feedback, can effectively stabilize display performance, reduce luminance inconsistencies, and improve visual quality. However, increased power consumption at higher temperatures remains a concern, and further optimization is required to address this limitation.

Based on these findings, several practical recommendations are proposed. First, integrating more efficient thermal sensors with higher spatial resolution can improve the precision of real-time thermal data acquisition, thereby enhancing the responsiveness of gamma adjustment

algorithms. Second, future AMOLED designs should consider embedding intelligent microcontrollers capable of executing gamma correction algorithms with minimal latency and computational overhead. Third, adaptive power management strategies, such as selectively dimming less critical display regions during thermal spikes, can help balance power consumption and luminance uniformity. Additionally, incorporating machine learning models into gamma adjustment frameworks could enhance predictive accuracy for thermal-luminance relationships and reduce computational delays. Manufacturers are encouraged to implement software-based gamma correction techniques alongside optimized thermal designs to reduce reliance on expensive hardware-based solutions. For end-users, providing thermal operating guidelines and optimizing brightness levels based on environmental conditions can extend the display lifespan and improve long-term performance. Collectively, these recommendations aim to bridge the existing gaps in thermal management strategies and contribute to the development of more reliable, efficient, and visually superior AMOLED technologies suitable for diverse applications, including mobile devices, wearables, and high-resolution television panels.

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