

Influence Of Elastic Modulus on Bending Performance of OLED Screens

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Abstract. This research delves into the impact of the elastic modulus on the bending performance of OLED screens, a pivotal aspect in advancing flexible and wearable electronic devices. The study underscores the pivotal role of the elastic modulus in shaping stress distribution and deformation during bending, directly influencing the stability, durability, and user interaction of the screens. By scrutinizing the elastic modulus across various materials like substrates, organic luminescent layers, and packaging materials, the investigation identifies avenues to fine-tune the mechanical properties of OLED screens. Through a blend of experimental frameworks and simulation models, the paper offers a thorough analysis, accentuating the significance of material composition and structural design refinement. The findings advocate for strategic adjustments in the elastic modulus to bolster the mechanical robustness and prolong the operational lifespan of OLED screens, aligning with market demands for superior flexible display products. This research thus contributes significantly to the ongoing quest for advancements in flexible electronics, promising enhanced functionality and durability in future device iterations.

Keywords: Elastic modulus; OLED screen bending; material optimization; flexible electronics.

1. Introduction

Since the emergence of OLED technology at the end of the 20th century, it has swiftly gained prominence in the display industry owing to its exceptional performance. In contrast to traditional liquid crystal display technology, OLED screens have gradually emerged as the favored display option for mobile and wearable devices, attributed to their self-luminous properties, high contrast, rapid response times, and wide viewing angles [1,2]. As personal mobile devices like smartphones and smartwatches gain widespread popularity, the market demand for OLED screens continues to soar, leading to their widespread adoption in electronic products [3-5].

The rise of wearable devices and flexible electronics has ushered in heightened expectations for the bending performance of OLED screens. These novel devices often require thin, portable designs with robust mechanical flexibility to accommodate diverse environments [2]. Bending performance not only directly impacts product durability and reliability but also significantly influences user experience. For instance, in devices such as smartwatches and foldable phones, screen bending directly correlates with product lifespan and operational comfort [3,6].

Among the myriad performance metrics of OLED screens, the elastic modulus stands out as a crucial parameter. The elastic modulus, a fundamental concept in materials science, characterizes a material's ability to resist deformation under external forces. In the case of OLED screens, the elastic modulus directly influences stress distribution and deformation during bending, thereby affecting screen stability and longevity [3]. An optimal elastic modulus ensures that OLED screens maintain display integrity after repeated bending, thereby averting screen damage from stress concentration [5].

Thus, studying the impact of the elastic modulus on OLED screen bending performance holds significant importance in advancing flexible display technology. By refining the material composition and structural design of OLED screens, their adaptability and durability across various applications can be enhanced to meet the burgeoning demand for high-performance flexible displays [2]. With ongoing advancements in materials science and manufacturing processes, the bending performance

of OLED screens is poised for further enhancements, promising users a more immersive and convenient experience.

2. OLED Screen and Elastic Modulus

2.1. OLED Screen Base

OLED screens are a self-luminous display technology that operates based on the properties of organic materials emitting light when an electric current passes through them [3]. The structure of an OLED screen typically comprises multiple layers, arranged from top to bottom: a glass or plastic substrate, an anode, an organic luminescent layer, a cathode, and possibly a packaging layer [2,4]. Among these, the organic light-emitting layer serves as the core component of OLED, comprised of multiple organic films that generate red, green, and blue light when subjected to current, thereby achieving full-color display. Mainstream OLED screen types on the market encompass rigid OLED, flexible OLED, and foldable OLED. Rigid OLED screens find wide application in televisions and fixed display devices due to their stability and established manufacturing processes. Flexible OLEDs are utilized in wearable devices and some smartphones owing to their bendable characteristics. Foldable OLED represents a recent innovation, enabling devices to maintain display functionality after folding [2,5]. The light-emitting process of OLED is illustrated in Fig. 1 [5].

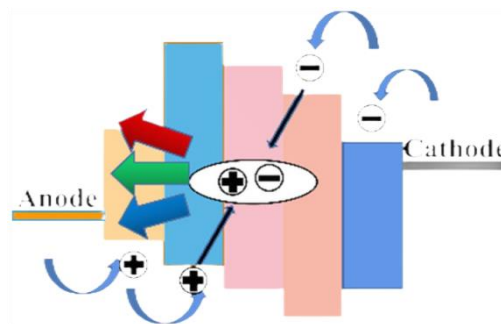


Fig. 1 Light-emitting process of OLED [2].

2.2. The Action of Elastic Modulus

In the manufacturing process of OLED screens, key materials involved include organic light-emitting materials, substrates (such as glass or plastic), anodes (such as indium tin oxide or metal films), and packaging materials [1,2]. The elastic modulus of these materials, which denotes their ability to resist deformation when subjected to force, significantly influences the bending properties of OLED screens. For instance, the elastic modulus of the substrate material determines the stability and durability of the screen when bent [2]. The elastic modulus of the organic luminescent layer directly impacts the display quality, as excessive stress may lead to reduced luminous efficiency or shortened lifespan [2]. Similarly, the elastic modulus of the packaging material relates to the waterproofing, dirt-proofing performance, and protection under mechanical stress [5,7].

The influence of the elastic modulus on the mechanical behavior of the bent screen is primarily manifested in the following aspects: Firstly, the elastic modulus of the substrate material determines the stress distribution of the screen during bending, thereby affecting its lifespan and reliability [7]. Secondly, the elastic modulus of the organic luminescent layer affects the display quality of the screen in its curved state. Finally, the elastic modulus of the packaging material ensures that the screen maintains good airtightness and mechanical strength after multiple bending cycles.

2.3. Case Study

In the realm of structural engineering, the emergence of flexible smartphones introduces distinct failure patterns not commonly observed in traditional mobile devices. A foldable phone typically incorporates a pliable cover glass and a display assembly that extends along the device's length and

bends around a pivot. As depicted in Fig. 2, this assembly represents the system's most crucial element, as it undergoes continuous bending with each fold of the device. Fig. 2 illustrates potential failure modes—such as creep, fatigue, buckling, and delamination—that may arise at various folding angles of the phone. The intensity of the bend and resulting stress distribution depend on the configuration of the display assembly layers and the device's bending radius. This paper introduces an experimental framework aimed at assessing various designs of foldable phones and examining their mechanical robustness.

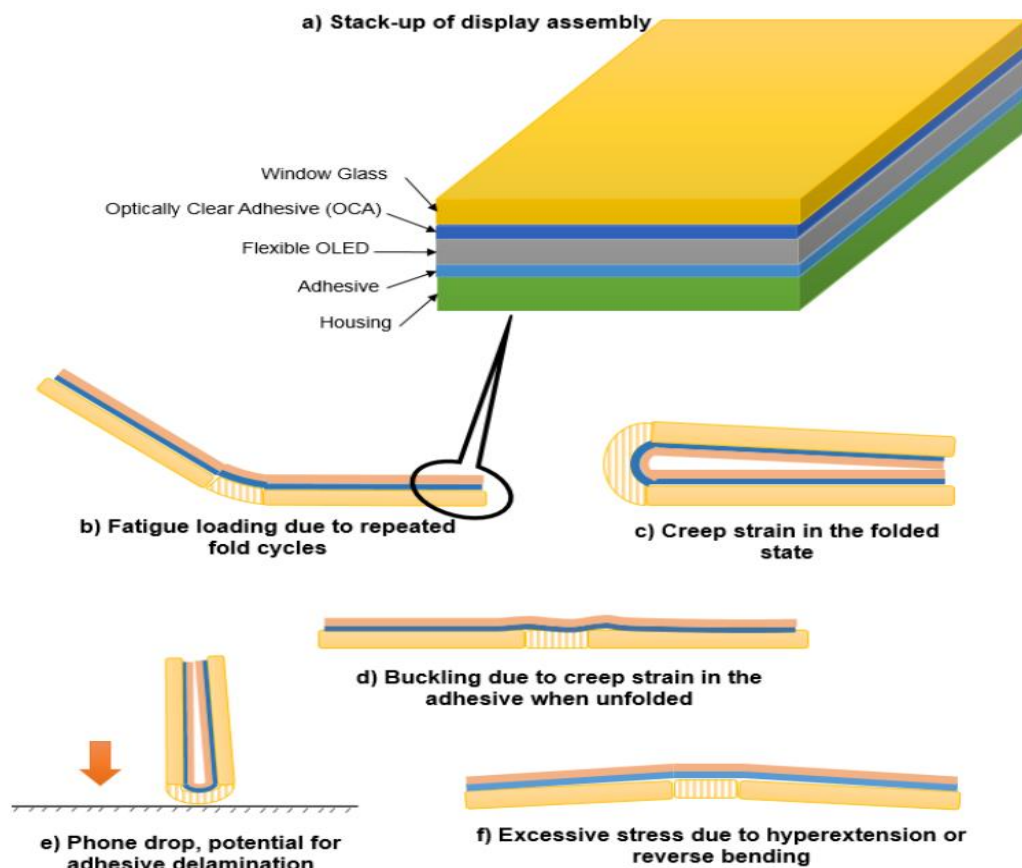


Fig. 2 Flexible OLED Display Assembly Stress Analysis (a) Stack-up of a typical display and cover glass assembly in a phone; (b)-(f) Potential failure modes in a foldable phone [7].

3. Research Status and Experimental Analysis

3.1. Literature Review

In literature, the investigation into flexible system deformation utilizes analytical, simulation, and experimental approaches. Scholars such as Harris et al. [8] and Rogers et al. [9] have examined the mechanical integrity of flexible mechanisms, identified failure modes and proposed design strategies. Shi et al. [10] discovered that employing a low modulus material in the middle layer of a composite beam stack can separate neutral axes, thereby reducing shear interaction and enabling significant shear deformations, with an analytical model predicting strain distribution.

Li et al. [11] and Lee et al. [12] also devised analytical methods for composite beam bending, recommending that brittle materials like glass be positioned near the neutral axis to minimize bending strain, emphasizing the significance of the length-to-thickness ratio for neutral axis splitting. These studies have implications for foldable smartphone displays, where layers of plastic and glass are joined using low-modulus adhesives.

Niu et al. [13] managed to decrease the critical bending radius of a flexible AMOLED display from 7mm to 4mm by adjusting layer thickness. Salmon et al. [14] investigated adhesive stiffness via finite element modeling, revealing that the display's performance hinges on the system-level response, with optically clear adhesives (OCA) playing a critical role. Cheng et al. [15] utilized the Taguchi design to reduce bending stress in OCA by 16% with a protective structure.

The research suggests employing a 3-point rolling configuration (Fig. 3) [7] to thoroughly examine the influence of elastic modulus on the bending performance of OLED screens. The Taguchi design method, as employed in M. M. Nath and G. Gupta's dissertation [7], is utilized to effectively minimize simulation runs.

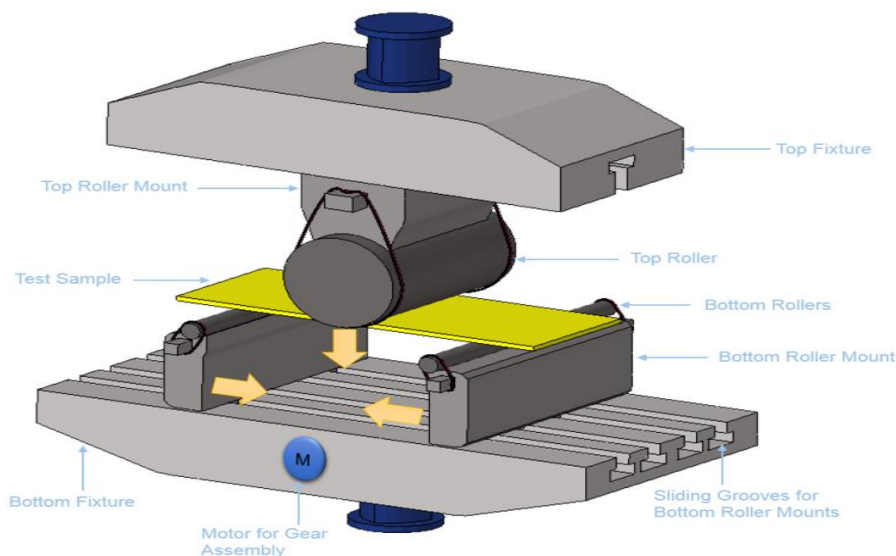


Fig. 3 CAD model of the proposed 3-Point rolling experimental setup for a foldable device [7].

3.2. Experimental Method

M. M. Nath and G. Gupta's experiment in 2018 [7] conducted a finite element analysis using an LS-DYNA implicit solver to evaluate the deformation and strains in a foldable phone during flexing. Their model comprised a cover glass, flexible display, and an optically clear adhesive (OCA) joining them, all attached to a rigid chassis for structural support. Excluding other real-world components, these key layers played pivotal roles, with the phone dimensions set at 80 mm × 50 mm × 1.8 mm.

The simulation assumed linear elastic behavior for materials, except for the OCA, for which a hyperelastic Ogden model was utilized based on uniaxial test data. 8-node brick elements were employed, ranging in size from 0.05 mm to 1.0 mm, with a maximum aspect ratio of 15 for accuracy.

In the 3-point rolling test simulation, three 3.5 mm diameter rollers replicated the fixture, undergoing synchronized bi-axial displacement [7]. Strain analysis revealed that both the cover glass and display experienced bending strains surpassing their failure thresholds (Fig. 4 and Table 1). To address this issue, they conducted design experiments to identify parameters that could reduce strain on these critical components [7].

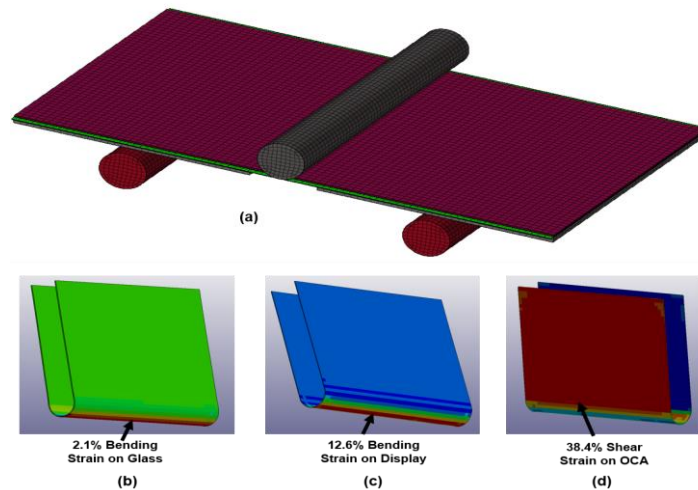


Fig. 4 (a) Simulation model for the 3-point rolling test, (b-d) Strain contour plots of the cover glass, display, and OCA [7].

Table 1. Dimensions and Properties of the Baseline Simulation Model [7]

Layer name	Material	Thickness(mm)	Young’s Modulus(MPa)	Poisson’s Ratio (ν)
Top Cover	Glass	0.3	70000	0.3
OCA	Liquid OCA	0.3	≈ 0.68 (Hyperelastic)	0.4955
Display	Plastic	0.2	2500	0.3
Housing	Rigid	1.0	2.1E+05	0.3

In this study, M. M. Nath and G. Gupta examined the bending behavior of a display system by varying four key design parameters: the thickness of the glass (GLS THK), the optically clear adhesive (OCA) (OCA THK), the display (DSP THK), and the material composition of the OCA (OCA MAT). While the properties of the cover glass and display materials remained constant, their thicknesses and the rigidity of the OCA were adjustable. To efficiently explore the impact of these variables, the Taguchi method for Design of Experiments (DOE) was applied to minimize the number of trials from 81 to a manageable number while identifying significant factors affecting the strain response.

Three levels for each parameter are outlined in Table 2, and Table 3 describes three hyperelastic material models for the OCA, with the Ogden model serving as the baseline, adjusted by factors of 0.1 and 10 to cover the typical range of OCA stiffness. The stress-strain curves for these models are depicted in Fig. 5. This approach aimed to optimize the design parameters for the desired mechanical performance of the display assembly [7].

Table 2. Levels of the Parameters for Taguchi Design of Experiments [7]

Levels	GLS_THK(mm)	OCA_THK(mm)	DSP_THK(mm)	OCA_MAT(MID)
1	0.10	0.10	0.10	1
2	0.20	0.20	0.15	2
3	0.30	0.30	0.20	3

Table 3. Material Constants for Ogden Material Models in LS-DYNA [7]

Material ID	μ_1	μ_2	μ_3	α_1	α_2	α_3
1(0.1x Baseline)	2.145	-0.01	-2.1E-10	7.3E-4	-4.9	-46.8
2(Baseline)	21.45	-0.13	-2.1E-09	7.3E-4	-4.9	-46.8
3(10x Baseline)	214.5	-1.36	-2.1E-08	7.3E-4	-4.9	-46.8

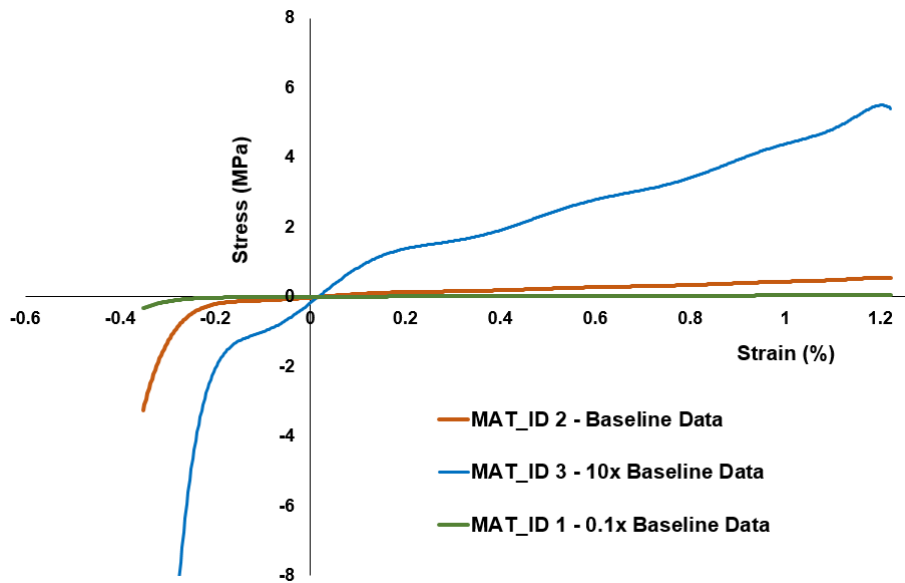


Fig. 5 Engineering Stress-Strain Data for the Three Hyperelastic material models used in the Taguchi Analysis [7].

3.3. Experimental Result

The DOE aims to identify optimal parameters for minimizing bending and shear strains on the cover glass, display, and Optically Clear Adhesive (OCA). Key findings reveal that reducing the thickness of the cover glass decreases tensile strain on both the cover glass and display, while thinner layers of cover glass, display, and OCA, along with a more flexible OCA, result in a reduction in bending strain of up to 30%. Moreover, shear strain in the OCA decreases with thicker display and OCA layers and higher OCA stiffness, leading to a 10% reduction. However, a delicate balance is necessary between OCA thickness and strain, as a thinner OCA reduces display strain but increases OCA strain. Two optimal design options are proposed, with Option 1 (GLS THK 0.1mm, OCA THK 0.1mm, DSP THK 0.2mm, OCA MAT MID 3) showing better performance in simulations, achieving significant strain reduction (up to 30-80%) compared to the baseline. The strain contour plot (Fig. 6) visually illustrates these improvements.

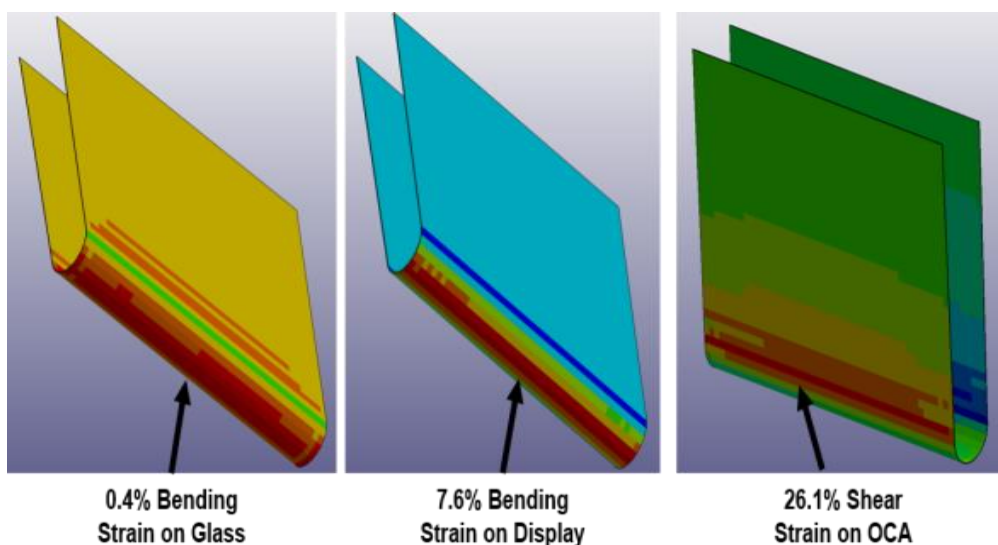


Fig. 6 Simulation result from the optimized run [7].

4. Suggestions and Prospects for Optimization

This paper proposes optimization suggestions and discusses prospects from four perspectives: material optimization, structural design, production processes, and future outlook.

Firstly, concerning material optimization, improving the bending performance of OLED screens involves utilizing materials with high elastic modulus and excellent flexibility. For instance, exploring and developing new types of flexible polymer substrates such as polyimide (PI) and polyether-ether-ketone (PEEK) is recommended, as they offer favorable bending properties while maintaining high mechanical strength [3-4]. Additionally, for OLED packaging materials, selecting optical transparent adhesives (OCA) characterized by low stress and high transparency is crucial to reduce stress concentration and minimize light loss during bending [3,4,16].

Secondly, in terms of optimizing structural design, enhancing the bending performance of OLED screens can be achieved by refining the structure of the OLED screen. Utilizing the neutral layer fracture principle to insert buffer layers between functional layers aids in dispersing concentrated forces [3-4]. Furthermore, through simulation analysis, various design schemes such as U-shaped bending and droplet bending are compared to evaluate their impact on stress distribution and deformation state, facilitating the selection of the optimal structural design [3,5]. Fig. 7 illustrates the schematic diagram of U-shaped bending and droplet bending [3], while Fig. 8 demonstrates the effect of bending methods on screen deformation [3].

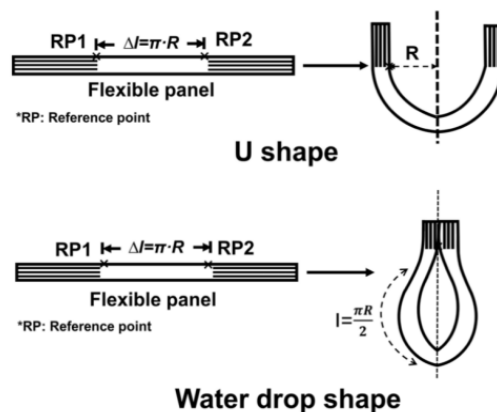


Fig. 7 Schematic diagram of U-shaped bending and drop-shaped bending [3].

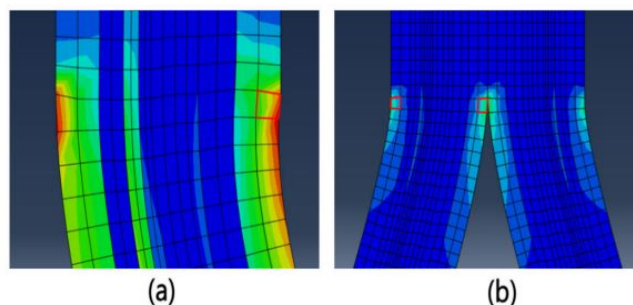


Fig. 8 Effect of the bending method on the deformation of the screen: (a) U-shape; (b) Water drop shape [3].

In industrial series production, existing processes may encounter limitations such as uniformity and adhesion issues when depositing organic materials on flexible substrates. It is recommended to develop new deposition technologies, such as inkjet printing and laser-induced transfer, to enhance material deposition uniformity and reduce production costs [1,2,17]. Additionally, exploring new packaging technologies like thin film packaging can improve the environmental resistance of OLED screens [1].

Moreover, OLED screen technology holds vast potential applications, spanning wearable devices, flexible displays, and smart car interiors. Future research directions may prioritize enhancing the mechanical stability of OLED screens, prolonging service life, and reducing costs [1,17]. Concurrently, challenges involve developing novel high-performance materials, optimizing production processes, and enhancing product reliability and durability. Through interdisciplinary collaboration, leveraging insights from fields like materials science, mechanical engineering, and electronic engineering, OLED screen technology can be propelled towards more innovative applications.

5. Conclusion

In conclusion, this paper presents a thorough analysis of the influence of elastic modulus on the bending performance of OLED screens, highlighting its significance in the realm of flexible and wearable electronic devices. The study emphasizes the critical role of optimizing material composition and structural design to enhance the adaptability and durability of OLED screens across various applications. Through meticulous examination of elastic modulus effects via experimental frameworks and simulation models, the research provides valuable insights for manufacturers and contributes to the evolution of flexible display technology. The findings suggest that strategic adjustments of the elastic modulus can lead to enhanced mechanical stability and prolonged service life of OLED screens, aligning with market demands for high-performance, flexible display products. Furthermore, the paper suggests future research directions, stressing the importance of exploring material combinations, assessing performance under extreme conditions, and ensuring long-term stability to fully exploit the potential of OLED screen technology.

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