Tacky-Free Stretchable Cover Window with Anti-Scratch Property

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Abstract

This study presents the development of a 12-inch, 100-ppi active-matrix micro-LED stretchable display that demonstrates up to 45% area stretchability and stable performance over 10,000 stretching cycles at 20% uniaxial tensile strain. To achieve stretchability, the display employs a polydimethylsiloxane (PDMS)-based stretchable substrate. However, the tacky nature of PDMS poses a significant drawback, making it challenging to effectively protect the thin and flexible panel from external environmental factors.

To overcome this limitation, we developed a novel cover window with over 20% elongation capability and non-tacky properties. This material enhances surface scratch resistance and provides robust protection against external impacts and stresses. The technological advancements presented in this study are expected to contribute significantly to improving the productization potential of next-generation stretchable display.

Author Keywords

Flexible Display and e-Paper / Flexible Display Components and Materials Including Substrates, Films, Adhesives, Encapsulation and Barriers.

1. Introduction

The flexible display market has experienced rapid growth following the introduction of foldable mobile electronic devices. Simultaneously, advancements in flexible technology and innovative device designs have driven progress toward multi-flexible, rollable, and stretchable devices. These trends have significantly accelerated the growth of the flexible electronics and device industry.

Recent innovations in electronic devices have also fueled the growth of human-interface wearable devices and Internet of Things (IoT) technologies. As a result, hardware development has increasingly shifted toward soft devices that can easily deform under external forces. Interest in and demand for flexible devices, including in the commercial display markets such as healthcare, sports, and various types of consumer electronics, have surged. In response, significant efforts have been devoted to designing new form factors that enhance shape freedom, such as foldable and rollable displays.

Among these advancements, stretchable displays have emerged as a globally popular research topic and a next-generation technology poised to succeed flexible devices. Several display companies have introduced stretchable display as a key future technology in recent years, emphasizing their ability to maintain original performance even under significant strain. [1-4]

Compared to conventional flexible displays, stretchable displays offer much higher elasticity and freedom of deformation. These unique mechanical properties make stretchable displays particularly suitable for applications involving soft and curved surfaces, such as human skin or clothing. Researchers have studied stretchable electronic devices for decades, focusing particularly on sensors and simple displays for human-centric applications. [5,6]

Most stretchable technologies address stretchable reliability as a key indicator, but from a productization perspective, the cover window of a stretchable display has the challenging task of not only having stretchable reliability, but also having a certain level of surface durability. In this study, we developed a cover window that protects stretchable panels with excellent stress resistance. PDMS, widely used in research related to stretchable devices, provides excellent elasticity and environmental stability, but has the disadvantages of being sticky and difficult to coat with other materials. To overcome these issues, we introduced polyurethane-based elastomer, resulting in a tacky-free surface and superior surface durability.

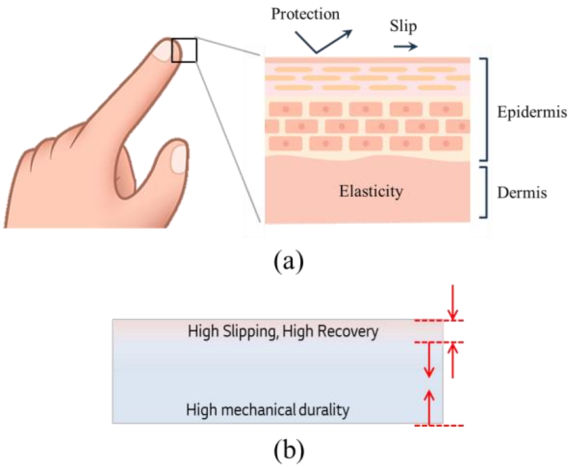

Figure 1. (a) Application of biomimetic design inspired by the functional structure of human skin, where the epidermis provides protection and slip properties, while the dermis ensures elastic. (b) Illustration of cover window layer structure, consisting of an upper high-slip layer and a lower high-mechanical-durability layer.

2. Methods

The cover window for stretchable displays requires a flexible, film-based material since conventional glass or rigid materials cannot be utilized. One of the most used soft materials is polydimethyl-siloxane (PDMS), which exhibits high stretchability. However, PDMS suffers from tacky surface properties and low durability, making it susceptible to scratches and abrasion.

To overcome these limitations, this study proposes a biomimetic multilayer structure inspired by human skin, which balances protection and elasticity. The upper layer was designed with a smooth surface and high slip properties, effectively reducing friction resistance to provide a smooth tactile experience even during touch interactions. Meanwhile, the lower layer exhibits high flexibility, allowing for unrestricted movement, as well as superior stretchability and recovery properties, ensuring mechanical stability under repeated deformation.

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2.1 Structural Design and Material Selection

2.1.1 Upper Layer

The upper layer was designed to enhance surface durability by incorporating slip and recovery properties, while also providing controlled friction resistance to maintain a smooth tactile experience.

A nano cross-linker was introduced to strengthen the intermolecular bonding between the main polymer chains, reinforcing the overall structural integrity. This modification not only improved the cohesion of the polymer network but also imparted slip characteristics, significantly enhancing scratch resistance and surface robustness against external abrasions.

2.1.2 Lower Layer

The lower layer was engineered to provide high stretchability and recovery properties, ensuring mechanical stability and elastic resilience under external loads.

A soft polymer-based composition, such as PDMS, was utilized as the base material. The material properties were further optimized by adjusting the ratio of low glass transition temperature (T_g) components and hard/soft segments, allowing for tailored modulus and minimized hysteresis, ultimately maximizing its mechanical performance.

2.2 Physical Property Evaluation

2.2.1 Tacky Evaluation Method

To assess the tacky properties of the fabricated cover window, the specimen was placed on a stage, and a spherical probe (5 mm in diameter) was brought into contact with the surface under a 500 g load. After maintaining contact for 10 seconds, the force was gradually increased in the opposite direction until the probe detached from the surface.

The peel-off force at the point of maximum adhesion was analyzed using a spherical probe method, and the adhesion strength was evaluated based on JKR theory. [7] The relationship governing this phenomenon is expressed as follows :

$$F_{pull-off} = \frac{3}{2}\pi R W_{adh} \tag{1}$$

where $F_{pull-off}$ is the maximum detachment force, R is the probe radius, and W_{adh} represents the work of adhesion per unit area. Using this equation, the unit-area adhesion energy W_{adh} was calculated and compared among different materials, allowing for the design optimization to minimize adhesion energy.

2.2.2 Scratch Resistance Evaluation Method

The scratch resistance of the cover window was evaluated following ASTM D8380-21 standards. The specimen was placed on a stage, subjected to a constant load, and moved reciprocally over a 100 mm stroke. The number of cycles required for visible surface scratching was recorded.

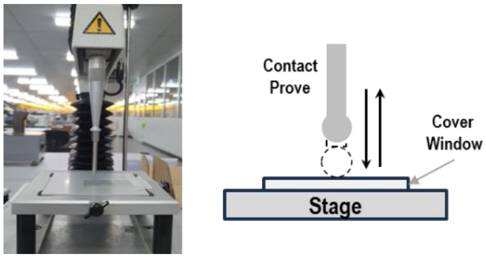

Figure 2. Schematic illustration and experimental setup for tacky property analysis

Figure 3. Evaluation of applied pressure on a stretchable panel to determine the reference load for scratch resistance testing.

Since stretchable cover windows inherently possess a soft and fragile surface, conventional scratch resistance evaluations may not accurately reflect real-world conditions. To establish a practical test standard, the applied force of 300g was determined based on measurements of a stretchable panel placed on a scale and pressed with finger and palm (Figure 3). The material was rubbed using Steel Wool #0000, a fine-grade abrasive material, to assess its resistance to micro-scratches.

Based on these measurements, the scratch resistance of the cover window material was evaluated and compared to conventional materials to assess its durability and practical applications.

2.2.3. Hysteresis Evaluation Method

The hysteresis behavior was analyzed based on the load-strain curve. A 100 mm-wide specimen was clamped and stretched to a 30% strain level, where it was held for 60 seconds before being returned to its initial zero-strain state. The tensile speed was set to 300 mm/s, and the loading and unloading energy loss was calculated from the resulting force-strain curve. [8]

$$W_{hyst} = \int_{loading} F d\epsilon - \int_{unloading} F d\epsilon \tag{2}$$

$$\eta_{hyst} = \frac{W_{hyst}}{W_{total}} \times 100\% \tag{3}$$

The hysteresis energy loss W_{hyst} was determined by integrating the enclosed area between the loading and unloading curves, representing the energy dissipated during deformation.

Additionally, the hysteresis ratio η_{hyst} was calculated relative to the total deformation energy, allowing for a quantitative compare-son of energy loss across different material compositions.

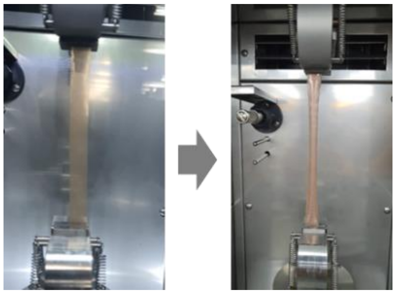

Figure 4. Images of the cover window specimen before and after 30% tensile deformation using a universal testing machine (UTM).

Table 1. Evaluation of modulus characteristics of materials formed with various combinations.

Material	Modulus (MPa)	Material	Modulus (MPa)
PDMS	0.7		
A-1	15	B-1	13.9
A-2	5.6	B-2	6.7
A-3	5.5	B-3	5.3
A-4	3.8	B-4	5.8

3. Result & Discussion

3.1 Physical Property Evaluation

Conventional PDMS-based materials, known for their high stretchability and recovery, typically exhibit an elastic modulus in the range of 0.7-1 MPa. While PDMS offers excellent recoverability, its low modulus results in insufficient durability, making it unsuitable for cover window applications.

In this study, an optimized combination of upper and lower layers was designed to achieve both mechanical durability and recovery characteristics through a multilayer structure. The lower layer was fabricated by adjusting the hard/soft segment ratio while maintaining the same backbone structure, resulting in an elastic modulus range of 3.8-15 MPa (Table 1, Group A). This modification allowed for enhanced mechanical stability while preserving flexibility and stretchability.

Subsequently, various upper layer compositions were applied to construct the final double-layer structure (Table 1, Group B). The upper layer was designed to improve surface durability, slip properties, and resistance to external abrasion, complementing the mechanical performance of the lower layer.

Mechanical property evaluations of the fabricated double-layer structures confirmed that the B-4 composition exhibited the most favorable mechanical properties for application as a cover window material.

3.2 Tacky and Contact Angle Analysis

The adhesive properties of the B-4 cover window material were compared with those of conventional PDMS. Using the tacky evaluation method described earlier, the work of adhesion per unit area was measured. The results showed that PDMS exhibited an adhesion energy of 1259 mJ/m², whereas B-4 demonstrated a significantly reduced adhesion energy of approximately 20.8 mJ/m², representing a 98.4% decrease in adhesion energy.

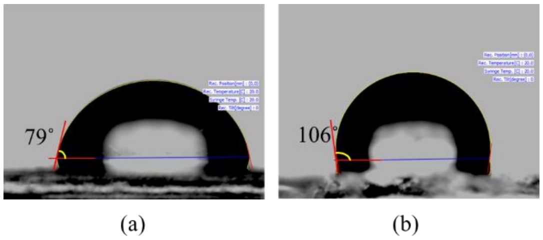

Figure 6. The water contact angle was determined to be approximately (a) PDMS: 79° (b) B-4: 106°

Additionally, to evaluate the slip characteristics of the surface, the water contact angle was measured. The results indicated that PDMS had a contact angle of 79°, while B-4 exhibited an increased contact angle of 106°, confirming an enhancement in surface hydrophobicity (Figure 6).

These findings suggest that the B-4 material exhibits reduced surface friction and improved slip properties compared to PDMS, making it a promising candidate for cover window applications.

3.3 Hardness and Hysteresis Analysis

To evaluate surface durability, a hardness analysis was conducted to compare the scratch resistance of PDMS and B-4 materials. The results indicated that PDMS developed surface scratches within 10 cycles of repeated friction (Figure 7a). In contrast, B-4 exhibited no visible scratches even after 300 cycles, with only minor scratches appearing beyond this point (Figure 7b). These findings confirm that the upper layer of B-4 provides significantly improved durability compared to conventional PDMS.

Furthermore, the hysteresis properties of each sample were evaluated to determine energy loss ratio. The experimental results revealed that PDMS exhibited a 44% energy loss, whereas B-4 demonstrated only a 5% energy loss, indicating a substantial reduction in mechanical deformation and enhanced elastic recovery. This suggests that the B-4 material maintains structural integrity under repeated tensile deformation while minimizing energy dissipation.

Therefore, the proposed B-4 material successfully enhances surface durability and mechanical stability compared to PDMS, confirming its potential applicability as a stretchable cover window material.

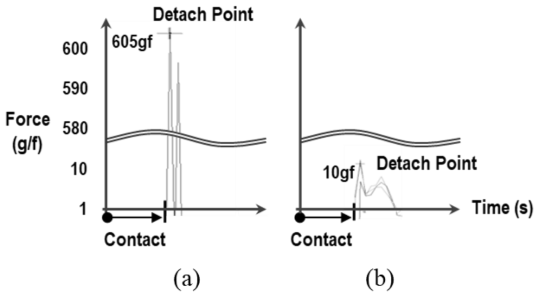

Figure 5. The tackiness was assessed after the surface treatment, with the average value recorded at approximately (a) PDMS: 605 gf , (b) B-4: 10 gf

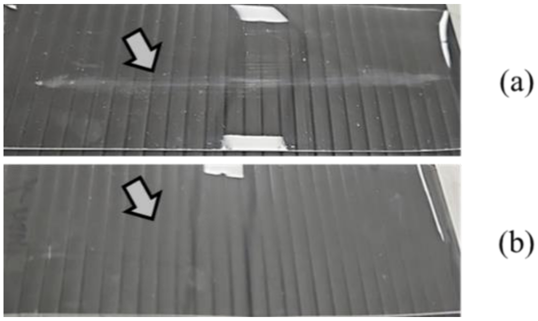

Figure 7. Surface comparison after scratch resistance evaluation: (a) PDMS – scratches observed after 10 cycles, (b) B-4 – no visible scratches observed after 300 cycles

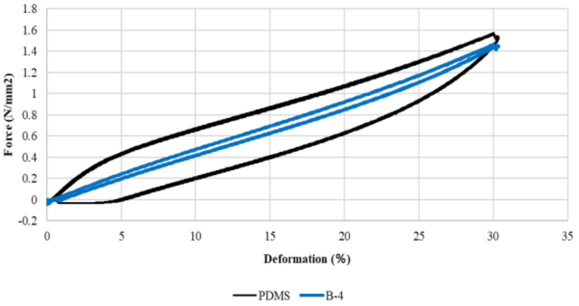

Figure 8. The hysteresis was evaluated to be approximately 1.6% following 5 consecutive cycles of 30% elongation and recovery conducted under room-temperature condition.

4. Conclusion & Limitations

The developed cover window achieved slip properties comparable to conventional cover window materials while exhibiting excellent scratch resistance and stable mechanical properties. These characteristics ensure reliability under extreme deformation and external conditions, demonstrating the material's practical applicability to next-generation technologies, such as wearable displays.

However, despite the significant improvements in durability and surface properties, the proposed cover window still has certain limitations. While the current design maintains mechanical stability and surface protection under moderate loads (~300 g), its resistance to higher impact forces and severe abrasive conditions remains a challenge. Further research is required to enhance its robustness against stronger mechanical stresses and to explore alternative material formulations that could offer greater scratch and impact resistance while maintaining flexibility.

These findings suggest that while the proposed material is a promising candidate for stretchable display applications, additional comprehensive studies on its long-term durability and real-world performance are essential for its widespread adoption.

To further evaluated its practical feasibility, the cover window was successfully integrated into wearable displays, which were showcased during the 2025 S/S Seoul Fashion Week. One of the highlights of the exhibition was Figure 9, which captured the wearable display in a dynamic, real-world application. The photograph illustrates the device seamlessly incorporated into a flexible, fashion-forward garment, demonstrating the cover window's ability to maintain both performance and aesthetic integrity under continuous deformation.

This demonstration underscored the material's potential in bridging technology and fashion, enabling the creation of innovative wearable designs. The displays, presented in various interactive settings, attracted significant attention from industry experts, designers, and consumers. The exhibition emphasized the practicality and versatility of the developed cover window, further solidifying its position as a cornerstone technology for next-generation flexible electronics.

Figure 9. The hysteresis was evaluated to be approximately 1.6% following 5 consecutive cycles of 30% elongation and recovery conducted under room-temperature condition.

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