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Highly Recoverable and Robust Rollable AMOLED Display with Smart Elastomer Materials

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Abstract

A new highly recoverable and robust rollable AMOLED display with a novel double stacked module structure consisting of two smart elastomer layers with high modulus and low modulus, was suggested and significantly improved pen drop height from 2cm to 9.5cm with additional special treatment for elastomer layer removing an electro-static damage on panel image, coming from increase of gate voltage of 1.2V due to repeated friction between top layer and bottom layer during cyclic rolling. The top protective layer of elastomer enormously reduced strain of panel and shear strain of PSA and therefore, lessened deformation height of rollable display at the edge up to 4mm after rolling radius of 15mm and rolling cycles of 200,000. The top protective layer of elastomer with tensile hardening property was able to remarkably increase energy damping effect for pen drop test and led to rise of pen drop height. The unique rolling strain distribution was systematically analyzed using strain gauge sensor and simulation tool and validated by experimental results. This novel double stacked structure also showed outstanding environmental reliability results as well.

Author Keywords

AMOLED; Rollable Display; Robustness

1. Introduction

Nowadays, rollable display has been drawing a lot of attention as one of the best candidates for future display to realize ultimately expandable property by virtue of outstanding portability. There are, however, several required important features for the development, which might include high flexibility, excellent recoverability, and terrific robustness in panel and module structure. In addition to these essential properties, rollable display has to show remarkable sustainability under diverse test conditions. Most of display companies have been trying to get sufficient reliability both in environmental and mechanical test conditions. But, it has never been an easy task to fulfill high robustness, sufficient flexibility, excellent recoverability, and outstanding reliability simultaneously with regards to products of foldable and rollable display. [1,2,3,4,5,6] We suggested new impressive approaches to considerably enhance recoverability, robustness, and anti-static reliability of rollable display.

2. Results and Discussion

In rollable display, pressure sensitive adhesive (PSA) located between layer with high modulus usually experiences large shear strain due to very low modulus of pressure sensitive adhesive (PSA) which is applied in order to reduce strain of layer with high modulus and therefore, minimize total strain of module structure. This heavily increases shear strain of pressure sensitive adhesive (PSA) at the edge of rollable display which is much higher than shear strain at the edge of foldable display

since rollable display undergoes accumulative strain all over panel and therefore, has large shear strain at the end of panel during rolling process, unlike foldable display that suffers localized strain in folding area. We used a simple stacked structure where PSA was located between dummy panel (PI) and protective film (PI) and each of two protective films was placed over and under dummy panel respectively. For rolling radius and folding radius of 10mm, PSA in rollable display had big shear strain of 1000%~1500% but PSA in foldable display had much lower shear strain of less than 400% in Figure 1.

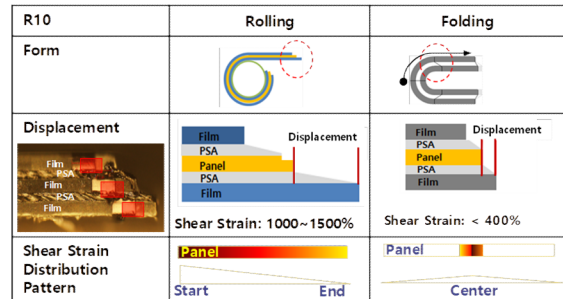


Figure 1. Shear strain distribution of PSA in both rolling and folding state with simple stacked structure at rolling and folding radius of 10mm.

Pressure sensitive adhesive (PSA) has inborn property of creep under a constant stress condition which causes permanent non-reversible deformation of display after static and dynamic rolling in Figure 2. [7]

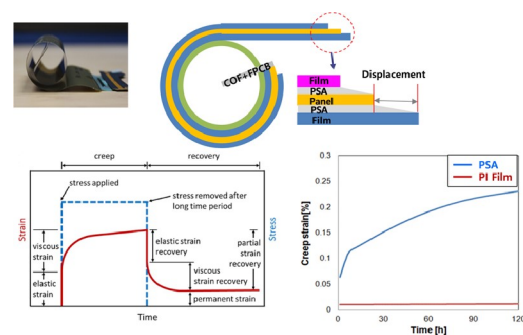


Figure 2. Permanent deformation at the edge of display after rolling due to creep property.

Therefore, it is very tough to fully restore rollable display to initial flat state after static rolling and cyclic rolling condition. To improve recovery performance of rollable display, highly restorable films such as elastomer including thermoplastic polyurethane (TPU), polydimethylsiloxane (PDMS) and so on,

might be very desirable in Figure 3. The simple module structure with polyimide (PI) as dummy panel instead of real panel, employing several elastomers and polyimide as protective layer, was introduced at top side and bottom side of module structure in order to compare recovery property of each film. Elastomers demonstrated remarkable recoverability after rolled test of 10 hours at rolling radius of 5mm and therefore, reduced deformation height from 51mm (polyimide) to 19mm (coating PU), 9mm (TPU), and 3mm (PDMS) due to excellent resilient properties of these elastomes in Figure 3.

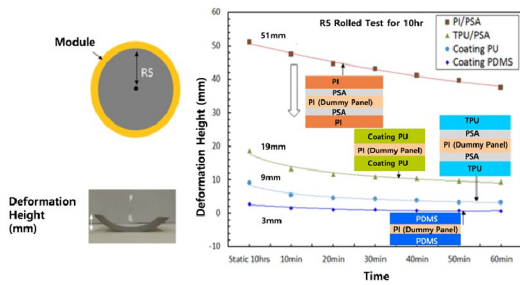


Figure 3. Recovery test results of simple stacked using different materials after rolled state at rolling radius of 5mm for 10 hours.

Elastomer also showed much better recovery performance than polyimide after rolling cycles of 5,000 for polyimide and rolling cycles of 200,000 for elastomer at rolling radius of 15mm, respectively. Elastomer reduced deformation height at the edge of display from 35mm to 4mm even if rolling cycles was increased from 5,000 to 200,000 in Figure 4.

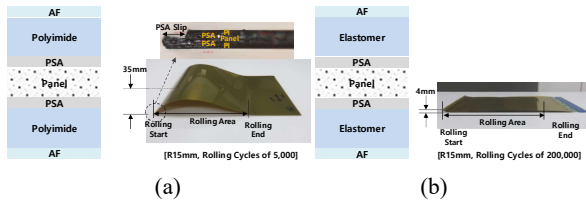


Figure 4. Recovery test results for two different stacked structures after rolling cycles of (a) 5000 for polyimide and (b) rolling cycles of 200,000 for elastomer at rolling radius of 15mm.

Simple stacked structure consisting of three polyimide layers and two PSA layers was used in order to analyze shear strain distribution of PSA during rolled state. To estimate shear strain of PSA after rolling and rolled test, initial positions of PSA and PI were marked using laser beam and displacements of initially laser-marked positions of PSA were measured using microscope after rolled test. Both simulation result obtained by ABAQUS and experimental result indicated similar shear strain distribution of PSA after rolled state for 24 hours at rolling radius of 10mm and indicated that shear strain of PSA was growing toward the end of panel and module in Figure 5 (a). Both simulation result obtained from ABAQUS and experimental result presented that larger deformation height occurred at rolling start position than rolling end position after rolled state for 1hour at rolling radius of 5mm because larger shear strain occurred at rolling start position coming from smaller rolling radius at rolling start position in Figure 5 (b).

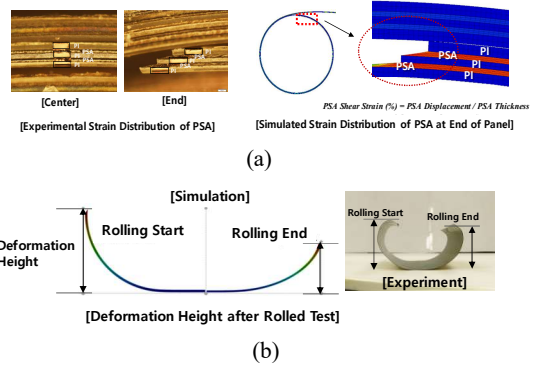
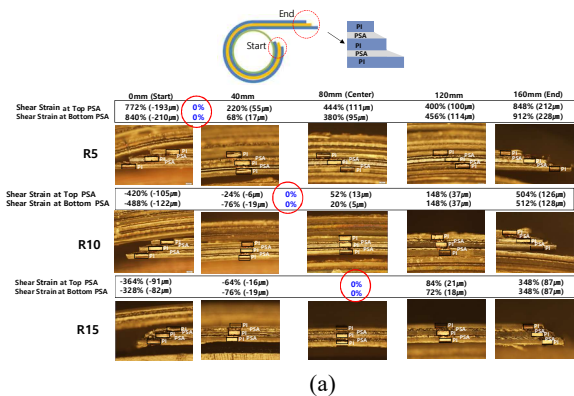


Figure 5. (a) Shear strain distribution of PSA results at rolled state obtained by experiment and simulation and (b) results of deformation height obtained by experiment and simulation after rolled stress at rolling radius of 5mm for 1 hour.

As rolling radius decreased, the position of maximum shear strain was shifted from the center of display toward the position of rolling start due to the unique strain distribution of rolling in Figure 6 (a) where experimental test was carried out at the condition of rolled state for 24 hours at rolling radius of 5mm, 10mm, and 15mm. During rolling process, decoupling of strain in PSA layers to enable multiple neutral planes (NPs) usually took place at both ends of panel and module in Figure 6 (b). The maximum shear strain of PSA exists near the center of display, since displacement of PSA is almost zero at the center when rolling radius is large and displacement of PSA becomes dominant at the end of display in Figure 6 (a) and (b). There is one neutral plane at the center of display and possibility of creating multiple neutral planes (NPs) rises toward the end of display, because shear stain of PSA grows toward the end of display in Figure 6 (b). Strains of PI layer at several positions of top and bottom layers of this module structure were measured using strain sensor and these results of strains on PI layer was very similar to simulation result obtained by simulation tool (ABAQUS) in Figure 6 (c). Simulation results of PI strain were in good accordance with experimental results of PI strain obtained by strain sensor.



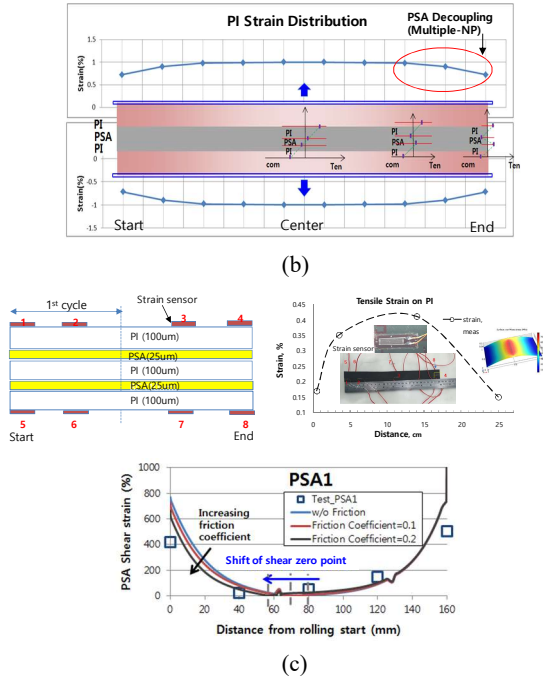


Figure 6. (a) Shear strain of PSA measured using microscope, (b) strain distribution of PI based on simulation tool (ABAQUS), and (c) strain measured of PI using strain sensor (□) and simulation tool (ABAQUS) at rolled state for 24 hours at rolling radius of 10mm.

Regarding rolling strain distribution, rollable display had a combined strain of rolling strain of each layer (polyimide (PI) layer) and PSA shear strain in Figure 7 (a). Figure 7 (a) presented a unique rollable strain distribution of PI as a top protective layer based on the sum of rolling strain of PI and shear strain of PSA, and indicated that the position of neutral plane did not located the center but was displaced away from the center due to the added rolling strain.

As rolling radius decreased from 15mm to 5mm, the position of maximum strain of PI on the top of module structure was shifted from the center of display toward the position of rolling start in Figure 7 (b), since rolling strain was inversely proportional to rolling radius.

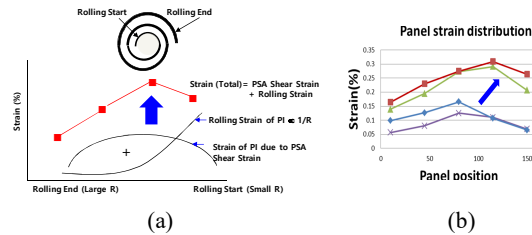


Figure 7. Rolling strain of PI placed on the top of simple module structure during rolling process: (a) rolling strain concept of PI, and (b) rolling strain of PI measured by strain gauge.

This explanation about a unique rolling strain distribution was also confirmed by experimental result in Figure 8, which showed that the position where display damages like crack or

thin film encapsulation (TFE) delamination happened due to growth of accumulated strain, was shifted from the center of display to the position of rolling start of display as rolling radius became smaller. These damages such as crack, buckling, and delamination took place first at the position of the maximum strain inside display.

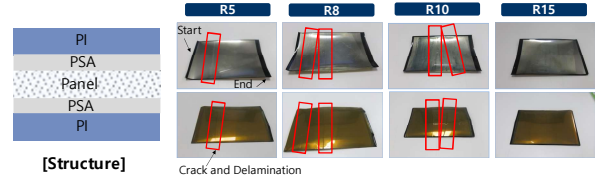


Figure 8. Position of crack or delamination during rolling process with different rolling radius.

Polyimide (PI) layer on the top of simple module structure was replaced with elastomer layer, shear strain of PSA at the end of panel, significantly declined from 420~512% to 36%~104% due to low modulus and high flexibility of elastomer in Figure 9. Therefore, elastomer material can be strongly considered when rollable display with small rolling radius is necessary.

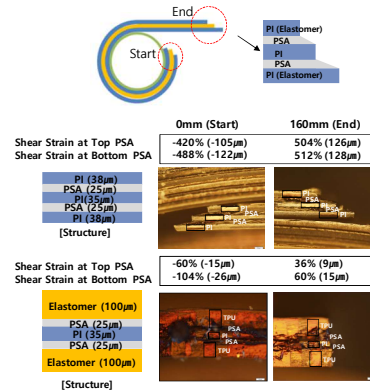


Figure 9. Strain of PI and TPU on the top of module structure after rolled state for 24 hours at rolling radius of 10mm.

Cyclic rolling usually causes panel damage due to electro-static discharge accumulated by repetitive contact between the top and bottom layer of module structure as shown in Figure 10 (a). The electric field triggered by this electro-static discharge is at least higher than 10^7 V/m, which amounts to rise of gate voltage of 1.2V in Figure 10 (a). Anti-static treatment with sheet resistance (R_s) less than $10^8 \Omega/\square$ on the top and bottom layer film was able to get rid of the electro-static damage of panel in Figure 10 (b).

Rollable display must be robust to external impact such as pen drop and ball drop. Pen drop height is the maximum height where panel does not show any panel damage such as dark pixel and bright pixel. In order to enhance pen drop height, a new robust stacked structure including two layers with different modulus, was suggested in Figure 11, where layer with high modulus had to be placed as close to panel as possible to prevent delamination or buckling problem during cyclic rolling, since positioning layer with high modulus as close to panel as possible (neutral plane (NP) is normally located inside panel) is able to lessen large stress (σ) of layer with high modulus by diminishing distance (L) between layer with high modulus and

neutral plane (NP) during rolling and L is in proportion to strain (ϵ) of layer with high modulus as shown in equation (1) and equation (2), where r is rolling radius. This new structure consisted of two separate layer (two separate functions), which located elastomer layer at the top layer of module to effectively absorb external impact energy and placing hard layer with high modulus just above and below panel to reduce strain of hard layer as much as possible in a collision with a falling ball. This novel structure showed an outstanding increase in pen drop height from 2cm to 9.5cm in Figure 11 (a). As modulus of hard layer increased, pen drop height rised due to lower strain of panel. However, growth of modulus of hard layer also deteriorates flexibility of rollable display. There is a trade-off between robustness and rollability. When stain of panel exceeds a critical strain in a collision with falling ball, dark pixel or bright pixel occurs in Figure 11 (b).

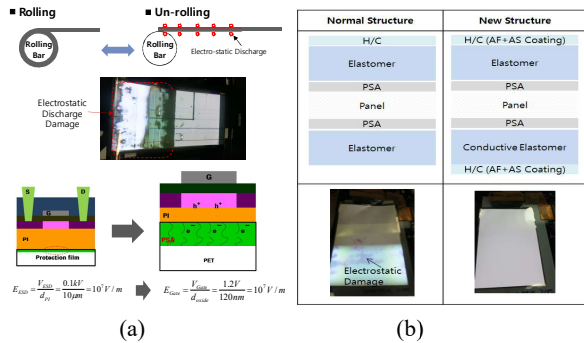


Figure 10. (a) Panel damage and electric field induced by electro-static discharge and (b) electrostatic damage and anti-static treatment effect.

	Normal	High Robust Structure-I	High Robust Structure-II
Structure	H/C Elastomer PSA Panel PSA Elastomer	H/C (AF+AS Coating) Elastomer PSA High Modulus Layer (Medium Value) PSA Panel PSA High Modulus Layer PSA Conductive Elastomer H/C (AF+AS Coating)	H/C (AF+AS Coating) Elastomer PSA High Modulus Layer (High Value) PSA Panel PSA High Modulus Layer PSA Conductive Elastomer H/C (AF+AS Coating)
Pen Drop Height (cm)	2cm	6.5cm	9.5cm

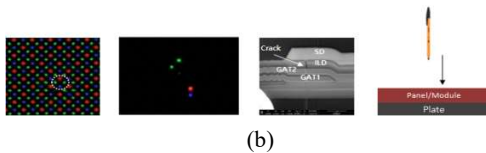


Figure 11. (a) Robust stacked structure and (b) image of bright pixel and crack due to pen drop impact.

$$\sigma = E\epsilon \quad (1)$$

$$\epsilon \sim \frac{L}{r} \quad (2)$$

As thickness of elastomer protective film and polyimide protective film increased from 50um to 300um, pen drop height for elastomer protective film increased exponentially but pen drop height for polyimide mounted linearly in Figure 12.

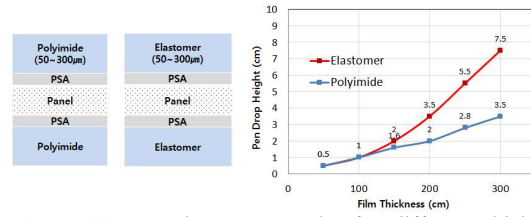


Figure 12. Pen drop test results for different thickness of polyimide and elastomer.

Elastomer is formed as a unit structure of hard segment and soft segment in Figure 13 (b). For elastomer protective film, Young's modulus abruptly rised at some tensile rate as tensile rate continued to increase in Figure 13 (a). The reason for sharp increase of Young's modulus is supposed to come from tensile thickening effect of elastomer (similar to shear thickening effect in viscoelastic material in Figure 13 (c)), which might be caused by enhancing alignment of hard segment parts of elastomer as tensile rate increases. [8,9]

For PI and pol poly-ethylene terephalate (PET) materials, however, Young's modulus gradually declined as tensile rate increases, which is typical phenomenon for plastic materials, called as tensile thinning (similar to shear thinning in viscoelastic materials) in Figure 13 (a). Shear thickening effect indicates that viscosity increases due to increased alignment inside viscoelastic material as shear rate goes up and shear thinning means that viscosity decreases as shear rate rises in viscoelastic material.

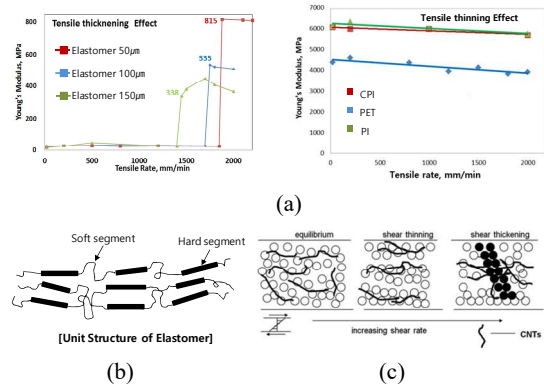


Figure 13. (a) Tensile modulus vs. tensile rate for elastomers with different thickness, CPI (colorless PI), PET, and PI, (b) typical unit structure of elastomer, and (c) shear thickening phenomenon at viscoelastic materials.

When ball (or pen) falls on panel, elastomer can first reduce external impact energy by absorbing external impact energy and pen presses energy damping layer into a certain depth (d), called as a penetratin depth in equation (3) and (4), and transfers a remaining impact energy due to penetraion depth (d) and contact time (dt) toward high modulus layer in Figure 14. The hard layer with high modulus plays a role of ramping down level of panel bending caused by transferred impact energy and therefore, avoiding crack of panel by maintaining strain of panel

below critical strain where crack of panel occurs. This extremely robust and highly recoverable rollable AMOLED display was also very stable after outward rolling cycles of 20,000 at rolling radius of 5mm and after 240 hours at high temperature and high humidity condition of 85°C/85% RH, and low temperature condition of -40°C, respectively without any noticeable deterioration of image quality.

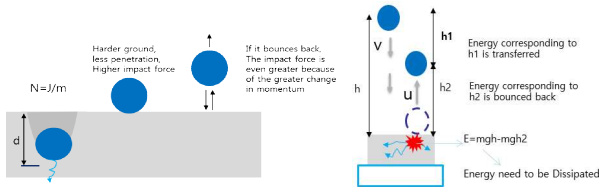


Figure 14. Energy damping process for ball drop test.

$$F = \frac{mgh}{d} \tag{3}$$

$$F = m \frac{dv}{dt} = m \frac{(v-(-u))}{dt} \tag{4}$$

We also demonstrated a proto-type 12.4-inch automotive rollable display for CID (Center Information Display) with rolling radius of 5mm. The unique advantage of rollable display can extremely expand the display screen by just rolling out from small space in Figure 15.



Figure 15. Panel image after environmental test such as rolling cycles of 200,000 at 25°C, 85°C/85% for 240 hours, and -40°C for 240 hours, respectively.

3. Conclusion

Highly reversible and robust stacked structure for rollable display using smart elastomer material was suggested based on systematic analysis of simulation and experiment. This new structure enormously improved recoverability and robustness of rollable display with two separate layers consisting of two separated functions. Layer with low modulus played a role of improving external impact energy damping and layer of high modulus played a role of lessening strain of panel. This novel stacked structure considerably increased pen drop height from 2cm to 9.5cm and eliminated electro-static damage on panel during cyclic rolling by applying anti-static treatment to elastomer. This 12.4-inch novel rollable AMOLED display did not show any noticeable deterioration of image quality after diverse environmental reliability test at rolling radius of 5mm.

4. References

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