Paper 85-1 has been designated as a Distinguished Paper at Display Week 2025. The full-length version of this paper appears in a Special Section of the *Journal of the Society for Information Display (JSID)* devoted to Display Week 2025 Distinguished Papers. This Special Section will be freely accessible until December 31, 2025 via:

https://sid.onlinelibrary.wiley.com/doi/full/10.1002/jsid.2074

Authors that wish to refer to this work are advised to cite the full-length version by referring to its DOI:

https://doi.org/10.1002/jsid.2074

First 200PPI Stretchable MicroLED Display with Serpentine-Shaped Bridge Designs

Jangyeol Yoon, Jinwoo Choi, GaNa Kim, KangYoung Lee, Gyujeong Lee,
Seongwon Kim, Jong-Ho Hong, Ji-Yong Park, Changhee Lee*
Display Research Center, Samsung Display Co., Ltd.,
1 Samsung-ro, Giheung-gu, Yongin-si, Gyeonggi-do, Korea

Abstract

In this paper, we have demonstrated the first result of 200PPI stretchable display by applying serpentine-shaped bridge design with a micro-Light Emitting Diode (micro-LED) base on the conventional display process, overcoming fundamental limitations of two existing development directions; pixel density and the stretchability. Methods like Kirigami remove portions of the substrate to implement structural stretchability, offering a high pixel resolution and maintaining image quality by using existing processes.

Author Keywords

Stretchable Display; Micro-LED; 11-inch Dynamic Display; Serpentine-shaped Bridge;

1. Introduction

With the development of AI-based interconnections among electronic devices, the real-time transfer/feed-back and synchronization of information between electronic devices have become key themes in 2025. Not only will these technologies provide accurate and intuitive real-time information, but the role of displays in offering efficient feedback is expected to become even more significant. Recently, displays are being developed with features such as low power consumption, shape-free design, and enhanced image quality simultaneously. Among these, shape-free design is rapidly evolving through display form factor innovations each year [1-4]. The innovation in display form factors is anticipated to enhance the delivery of diverse information and provide immediate feed-back. Basically the fundamental transformation is based on flexible display technology, and to achieve higher form factor innovation and variations, the development of stretchable displays is currently necessary. Dispite the remarkable acheivement in flexible displays have been including several improvements in flexibility, durability, and the curvature radii decrease, the local stress applied to each layer of the display which can exceed its mechanical limitation, leading to a decrease in durability during repeated deformations.

A stretchable display offers the advantage of creating surface shapes that are challenging for conventional flexible displays. For instance, achieving sphere-like or multi-curvature shapes is impossible with traditional flexible displays and requires the essential feature of stretching. Automotive interior displays have adopted an expanded form by accommodating the explosive increase in the display area, often extending beyond the conventional bar-type displays [5]. However, future car interiors are expected to adopt curved forms to accommodate various curvature designs, predicted by many designers to express multi curvatures rather than simple curves. Additionally, in the context of future wearable displays attached to the skin or worn, stretchable displays are considered excellent candidates because they are lightweight, resilient to external shocks, and meet the requirements of close adherence [6-9].

In recent years, there have been many attempts to address this by integrating micro-LED [10-11] instead of Organic Light Emitting Diode (OLED) [12-14]. Micro-LED features high brightness and a long-term life cycle, with a relatively low need for an additional encapsulation layer. It also has the advantage of a high expected life-span, and despite a lower pixel aperture ratio compared to OLED, it doesn't pose significant issues. Recent reports indicate that even with the application of micro-LED, stretchable displays is still not enough of the stretchability and pixel resolution required for commercialization [15]. Particularly, the trade-off relationship between these two factors necessitates additional efforts for fundamental technological innovation. Therefore, it is anticipated that the commercialization of stretchable displays will initially involve low-resolution products, followed by an evolution to high-resolution displays [16-17]. In that case of stretchable interconnects and electrode technologies have yet to achieve the high spatial resolution comparable to conventional displays, and their electrical conductivity is significantly lower than that of metal electrodes [18-19]. Moreover, the use of serpentine or wavy metal electrodes on thin substrates has hindered commercialization due to low spatial resolution and limited stretchability [16, 20].

This paper reports a state-of-the-art stretchable display with high spatial resolution upto 200PPI and stretchability comparable to conventional displays. By applying assymetric pixel/bridge design to optimize the pixel & bridge region with strain minimization compared to previous designs, micro-LEDs and TFTs can be integrated within each pixel without any degradation.

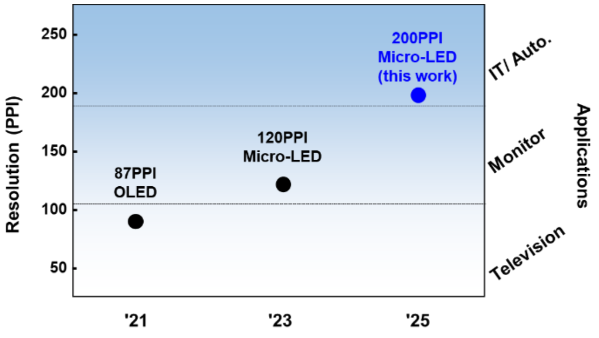

Figure 1. Recent Trend of Stretchable Display from SDC

Figure 1 presents a trend showing the resolution trends of stretchable displays developed by SDC from 2021 to 2025, along with the product lines applicable to each resolution. Recently, consumers' high demand for high resolution has raised the required resolution of most IT products from 4K to 6K. Moreover,

ISSN 0097-996X/25/5602-1162-$1.00 © 2025

the demand for high-resolution OLED monitors has been explosively increasing among gamers. To commercialize stretchable displays, a resolution of 200PPI, rather than the existing 100PPI, is expected to be necessary for application to these product lines. This research has been developed to a level applicable to most IT and automotive products, and thus, various form factor revolutions through stretchable displays can be expected in the future.

2. Result and Discussion

2.1. Display Structure and Fabrication Process

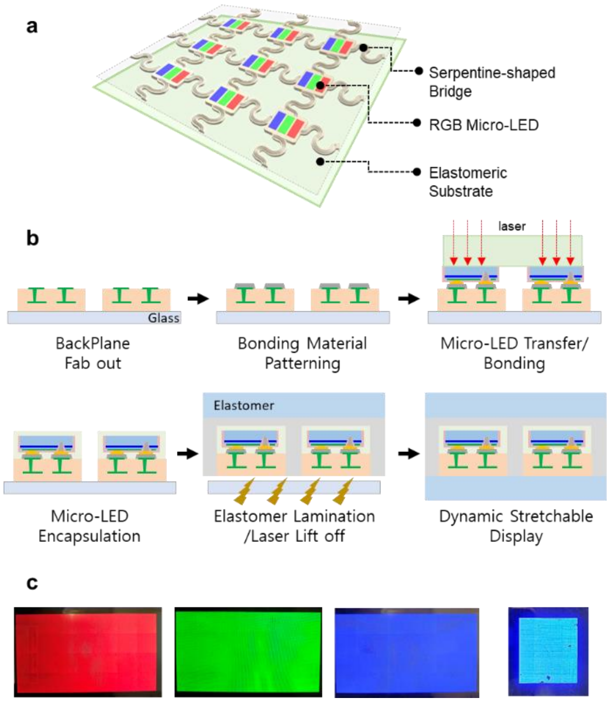

Figure 2. a. Schematic illustration of highly stretchable and the high pixel density micro-LED display with key technical features. **b.** Key fabrication process of stretchable micro-LED display. **c.** Optical microscope images of stretchable 120PPI RGB micro-LED displays (left), and 200PPI B-mono micro-LED display (right), respectively.

Figure 2a shows a representative schematic illustration of the highly stretchable serpentine-shaped display. The serpentine-shaped bridge is included in the stretchable region, and based on previous research, bridges tend to exhibit an increase in overall strain due to structural deformation as elongation increases. Micro-LED has the advantage of showing high brightness even with a smaller island area than OLED. Therefore, we can optimize the bridge design that enables high elongation ratio by minimizing the island area and maximizing the serpentine-shaped bridge area. In addition, we designed the serpentine-shaped bridge to be as narrow as possible while minimizing the pixel area of the stretchable display for high pixel resolution. For highly stretchable characteristics, elastomer with high elasticity and high recovery characteristics was laminated on the top and the bottom of the panel. Our newly developed elastomer substrate is an Elastic Polyurethane series, and is characterized by commercial-level transmittance (over 90%) and surface roughness (less than 0.15), while also having a high elastic recovery rate of over 90% under the 50% stretching conditions. As a result, it shows the advantage of minimizing changes in surface conditions - roughness, transparancy, yellow index, and haze - in repeated stretching-release evaluations of stretchable displays.

Figure 2b is the key fabrication steps for stretchable micro-LED display. Base on the fabricated stretchable panel, we transferred and the bonded the micro-LED on the pixel electrode. To compensate the large current acquirement of micro-LEDs, we optimized thin film transistors (TFTs) and circuits to maintain long range uniformity (LRU). Base on the conventional Low Temperature Poly-Silicone (LTPS) fabrication process, 200PPI pixel structure are designed for stretchable panel. It is noted that to avoid the breakdown of the metal electrode, there are no oxide layer in the bridge area. Because under the stretching, oxide layer can be easily broken to the external force to bring sequencial breakdown of metal electrode. Multi-stacked metal electrodes are patterned on the bridge. To minimize the maximum strain, a design with different gap margins between the inner and outer areas was applied, as strain concentrates within the serpentine-shaped curves during stretching. Furthermore, the overall shape of the bridge and the metal electrode were slightly designed differently to effectively decrease the strain applied to the metal electrode. This helped minimize tensile and compressive strain in the serpentine-shaped bridge area. The key design factor of serpentine bridge will be discussed later.

Stretchable panel is fully etched using Etching machine with shadow mask which is patterned to selectively etch the unnecessary region. Onto the metal electrode, thick bonding material is deposited which induced the eutectic bonding to Au-finished micro-LED electrode. Flip-chip type micro-LEDs (15 ㎛ x 25 ㎛) are aligned on the chip on carrier. Patterned bonding material is melted within 1 min selective laser assisted bonding process, which can focus each sub-pixel to protect remained bonding material. After the separate bonding of red, green, and blue micro-LEDs respectively, transparent negative-type photoresist is seletively patterned and cured to protect RGB micro-LEDs from the external impact which can also acts as an additional encapsulation layer. To effectively protect the stretchable display from the external impact, thick elastomeric substrate is laminated as a stretchable window. Base on our in-house strain-stress test, elastomer substrate showed almost no hysteresis and minimal variation in repeated evaluations. It suggests that the stretchable display can maintain a flat surface even after recovey, and we are currently developing it to have high stretchable characteristics at over 50% stretchability. Figure 2c show optical images of RGB micro-LEDs bonded onto an 11-inch stretchable panel. With a pixel resolution of 120PPI, it's evident that there's no stitch visibility during the LED bonding process. Reflecting the micro-LED optimized TFT design, it demonstrates uniform long-range uniformity. On the right, an optical microscope image of blue micro-LED on a 200PPI stretchable panel is shown. This also exhibits even illumination, and currently, the large-area bonding process is being optimized.

2.2. Optimal Pixel Design Derivation

To derive the optimal serpentine-shaped bridge for a stretchable display, we selected key design parameters, as discussed in previos result [21], and predicted the increase in pixel deisnty with the increase in elongation [22-23]. Based on the aforementioned conditions, considering parameters and the maximum strain on the bridge, a correlation can be derived follows as in (1);

$$\varepsilon_{max} = \frac{U_{app}}{4R\sin\left(\frac{\theta}{2}\right) + 2l\cos\left(\frac{\theta}{2}\right)} \qquad (1)$$

where, U_{app} is the applied tensile displacement, ε_{max} as the maximum strain on the metal electrode, l as the length of the straight-shaped bridge, R as the radius of the serpentine design, and θ as the angle of the curve, we selected optimal conditions to minimize strain. Figure 3a left present the local strain distribution results of our newly designed 200PPI pixel before and after more than 25% stretching in the two-dimensional direction.

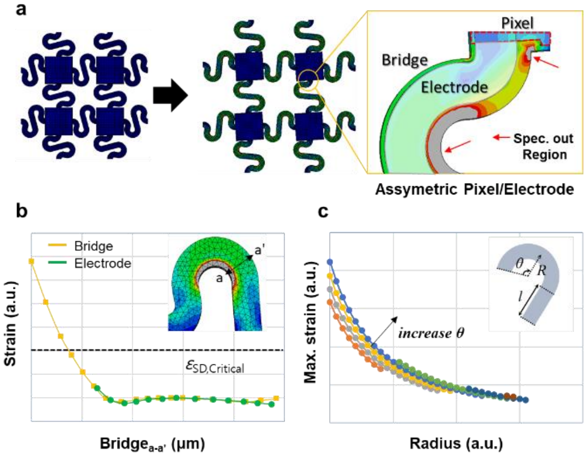

Figure 3. a. Simulation results of 200PPI stretchable display **b**. strain distribution in the a-a' direction of bridge and electrode, respectively. **c.** graph of Maximum strain-radius with difference angles of the curve.

Figure 3a right shows the regions where spec. out occurred when stretched by 25% or more in the simulation, indicated by red arrows. To ensure the durability of the display under stretching and releasing, we have developed an asymmetric pixel/bridge design that avoids spec. out in the pixel and bridge regions. In particular, serpentine structures tend to experience a rapid increase in tensile strain at the interface where the pixel and bridge meet as the resolution and stretchability increase. An asymmetric design that avoids these regions allows for the stable deformation of stretchable displays under biaxial stretching and is expected to become an even more important design factor as pixe resolution increases.

Figure 3b shows the strain distribution of the bridge and metal electrode in the inner and outer regions when the bridge is stretched. The proposed 200PPI stretchable design shows that the metal electrode (green line) is maintained below the critical strain. As resolution increases, the width of the bridge decreases, reducing the area available for safely placing metal electrodes within the bridge. Consequently, the multi-stacking process for metal electrodes is expected to become increasingly important. Figure 3c represents the distribution of maximum strain as a function of the angle of the curve for increasing radii of serpentine bridges. Through various design splits, we have confirmed that larger radii are beneficial for strain distribution, and the effect is maximized at a certain angle. This correlation will contribute to determining the optimal design parameters for changes in pixel pitch and resolution.

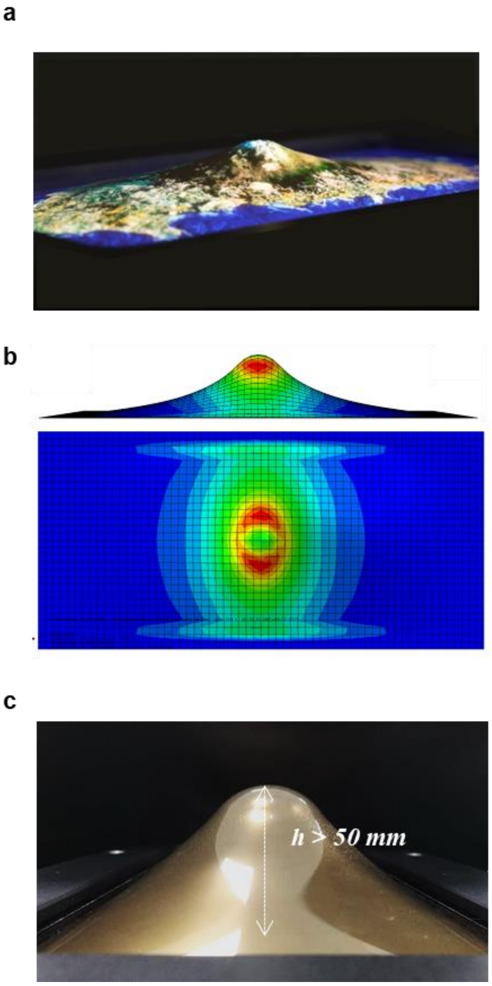

Figure 4. a. 11-inch Dynamic stretchable display with the concept image of Jeju-Island. **b.** local strain distribution of stretchable display. **c.** 200PPI dynamic stretchable panel with a protrusion of > 50 mm.

In Figure 4a, we demonstrated 11-inch dynamic display with the concept image of Jeju-island which manually stretched by using in-house stretchable testing machine. To effectively reduce the local strain affected by the friction coeffecient between the elastomer substrate and the stroke, we laminated a friction-relief layers below the stretchable panel which can distributed the tip-point stress of the elastomer substrate as shown in Figure 4b. Interestingly, as shown in the simulation results of protruding a stroke with a radius of 25 mm, the strain changes rapidly in the short-side direction of the stretchable display. This means that the larger the display size, the more deformation length can be created even if the stretchability is the same. Therefore, it is necessary to predict the strain distribution according to the deformation direction and to design and mechanically reinforce the display to effectively distribute the local strain. Figure 4c presents a biaxial stretching image of our newly developed 200PPI stretchable panel. The stretchable panel was stretched in the z-direction using in-house stretching system. The internal stroke is a hemispherical shape with a radius of 25 mm, and the panel was stretched without any damage even with a protrusion of over 50 mm. The pixel stretch ratio in this case was over 30%, confirming the high consistency of the high-resolution stretchable structure proposed through the simulation.

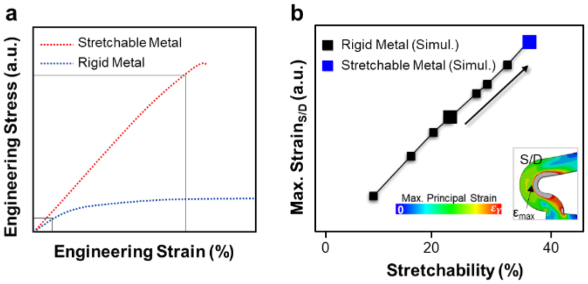

Figure 5. a. Strain-stress curves of stretchable metal electrode and rigid metal electrode, respectively. **b.** the increase of maximum stretchability of the proposed serpentine deisgn when the stretchable metal electrode applied.

Figure 5a demonstrates the strain-stress curve of the rigid metal and stretchable metal electrode we developed, respectively. The graph exhibits a high elastic strain capability, around 3%. The red lines can be slightly changed by varying the material and composition of the metal we fabricated, but demonstrating excellent elastic properties. Our newly modified stretchable electrodes exhibit a pattern resolution around a few micro-meter level and slightly lower electrical conductivity compared to conventional metal electrodes due to the stretchable characteristics of the material. Currently, we are developiong the performance of electrical conductivity by improving the process and high-resolution pattern density as well. The strain-stress curve in Figure 5b illustrates the proposed stretchable display structure's linear correlation with the increase in elongation rate, depicting the maximum strain applied to the bridge. Utilizing these conditions, we performed stretching in the two-dimensional direction. While expecting a maximum elongation of around 25% using the conventional metal electrode, we confirmed that with our developed stretchable metal electrode, stretching beyond 40% is estimated.

3. Conclusion

In this paper, we demonstrates the first results to overcome the pixel density upto 200PPI by applying advanced serpentine-shaped bridge design with a micro-LED base on the conventional display process. Methods like Kirigami with optimized assymetric pixel and bridge designs offering a high pixel resolution and maintaining image quality by using existing processes. Base on the fundamental study about the strain distribution of curved shaped, we can choose key design factors which can effectively distribute maximum strain. In addition, we also successfully transferred RGB micro-LED by using large-area transfer/bonding technique. Not only the structureal optimization but also with material innovations such as stretchable electrodes, EL, TFT, and substrates, future stretchable displays are expected to achieve diverse multi-curvature shapes, even allowing attachment to the skin like e-tattoos, surpassing the capabilities of traditional flexible displays.

References

1. Lamoureux, A. et al. "Dynamic kirigami structures for integrated solar tracking." *Nat. Commun*, **6**, 8092. (2015)
2. Zhang, Y. et al. Buckling in serpentine microstructures and applications in elastomer-supported ultra-stretchable electronics with high areal coverage. *Soft Matter*, **9**, 8062-8070 (2013)
3. Kim, D.-H. et al. "Complementary metal oxide silicon integrated circuits incorporating monolithically integrated stretchable wavy interconnects." *Appl. Phys. Lett*., **93** (4), 044102 (2008)
4. Ko, H.C. et al. "Curvilinear Electronics Formed Using Silicon Membrane Circuits and Elastomeric Transfer Elements." *Small*, **5**, 2703-2709 (2009)
5. Miyakawa M. et al. "Highly Stretchable Liquid Metal-based Deformable Micro-LED Displays" *SID Symposium Digest of* Technical *Papers* **55**, 2 (2024)
6. Kim, D. W. et al. Interface design for stretchable electronic devices." *Adv. Sci*. **8**, 2004170 (2021)
7. Kim, D. W. et al. "Highly deformable transparent Au film electrodes and their uses in deformable displays." *ACS Appl. Mater. Interfaces* **12**, 41969–41980 (2020)
8. Rossiter, J. "Lighting up soft robotics." *Nat. Mater*. **19**, 134–135 (2020)
9. Zhuang, Q. et al. "Liquid-metal-superlyophilic and conductivity-strain-enhancing scaffold for permeable super elastic conductors." *Adv. Funct. Mater*. **31**, 210558 (2021)
10. Liu, Z. et al. "Micro-light-emitting diodes with quantum dots in display technology". *Light: Sci. Appl*. **9**, 1–23 (2020)
11. Huang, Y. et al. "Mini-LED, Micro-LED and OLED displays: present status and future perspectives." *Light: Sci. Appl*. **9**, 1–16 (2020)
12. Hong J.-H. et al. "9.1-inch Stretchable AMOLED Display based on LTPS technology" *SID Symposium Digest of Technical Papers* **25**, 194 (2017)
13. Kim S. et al. "Three Dimensionally Stretchable AMOLED Display for Freeform Displays" *SID Symposium Digest of Technical Papers* **50**, 1194-1197 (2019)
14. Yoon, J. et al. "Technical Advances in Stretchable Displays for High *Pixel* Density and High Stretchability" *SID Symposium Digest of* Technical *Papers* **1**, 514-516 (2022)
15. Lim M.-S. et al, "Evaluation Method and Results for Measuring Stretchability of Two-Dimensional Stretchable Displays" *SID Symposium Digest of Technical Papers* **55**, 4 (2024)
16. Choi, M. et al. "Stretchable active matrix inorganic light-emitting diode display enabled by overlay-aligned roll-transfer printing." *Adv. Funct. Mater*. **27**, 1606005 (2017)
17. Lim, M. S. et al. "Two-*dimensionally* stretchable organic light-emitting diode with elastic pillar arrays for stress relief" *Nano. Lett*. **20**, 1526–1535 (2020)
18. Veerapandian, S. et al, "Hydrogen-doped viscoplastic liquid metal microparticles for stretchable printed metal lines" *Nat. Mater*., **20** (4), 533-540 (2021)
19. Liang, J. et al, "Elastomeric polymer light-emitting devices and displays" *Nat. Photonics*, **7**, 817-824 (2013)

20. Lim, M. S. et al. “Two-dimensionally stretchable organic light-emitting diode with elastic pillar arrays for stress relief” *Nano. Lett.* **20**, 1526–1535 (2020)
21. Yoon, J. Y. et al. “Highly Stretchable Display with Serpentine-shaped Design and Intrinsically Stretchable Materials” *SID Symposium Digest of Technical Papers* **1**, 1327-1330 (2024)
22. Widlund, T. et al. "Stretchability and compliance of freestanding serpentine-shaped ribbons" *International Journal of Solid and Structures* **51**, 4026-4037 (2014)
23. Fan. Z. et al. "A finite deformation model of planar serpentine interconnects for stretchable electronics" *International Journal of Solid and Structures* **91**, 46-54 (2016)