3D Approaches to Stretchable Displays with High Geometrical Fill Factor

Seunghyup Yoo[*,], Donggyun Lee[*], and Su-Bon Kim[*]**

[*]School of Electrical Engineering, KAIST, Daejeon, Republic of Korea
[**]Graduate School of Semiconductor Technology, KAIST, Daejeon, Republic of Korea

Abstract

This talk will describe recent results obtained with ultrathin OLEDs transferred to 3-dimensional objects, aiming to create high-density stretchable OLEDs and/or pixel-compensation schemes to address the inevitable reduction in pixel density in stretchable displays.

Author Keywords

OLED; ultrathin; stretchable; geometrical fill factor.

1. Introduction

One of the most popular approaches to stretchable displays is to use an array of rigid islands connected to one another with serpentine interconnectors [1,2]. When a system gets stretched, rigid islands provide mechanically stable platform for active devices while serpentine interconnectors, often containing bus electrodes, are getting extended without failure in their integrity or performance degradation. This approach is particularly useful as active device components can be made with the same conventional materials used for rigid devices with high performance and reliability. Otherwise, one would need intrinsically stretchable materials, which are often difficult to have a similar level of performance. Given with such advantages, however, the rigid island approach has a severe drawback of a so-called limited geometrical fill factor (FF), or the ratio of the active area to the whole device area [**Figure 1(a)**]. This limitation results from the two-dimensional nature of the rigid-island, approach where a substantial area has to be dedicated to the serpentine interconnectors to secure a certain level of stretchability. The degree of the maximum strain that can be applied to stretchable displays scales with the dimension of the serpentine interconnectors, making things worse when designing stretchable displays that can withstand a high degree of strain [3,4].

In this respect, this talk explores three-dimensional architectures that can overcome the inherent limitation of 2D rigid-island configurations. Two representative structures are introduced: firstly, an ultrathin OLED is combined onto an array of rigid rectangular blocks attached to a stretched elastomer. Upon strain being released, a part of the ultrathin OLED gets folded in between adjacent rectangular blocks, serving as a hidden active area (HAA) that reveals itself again when gets stretched, enabling high FF for both pre-stretched and post-stretched states [3]. Secondly, 3D popup approaches are introduced wherein every other rigid islands are free-standing while the others are fixed to an elastomer [4]. The free-standing rigid islands pop up via buckling process that occurs when compressed while return to a planar state when stretched. In this way, stretchable OLED displays with high initial FF are realized with a native matrix geometry kept. Design criteria for both of the cases will be introduced, and actual experimental results will be described to demonstrate their advantages with respect to conventional two-dimensional rigid island approaches [3,4].

2. Hidden active area approach

Figure 1 (b) depicts the photograph of a high-FF stretchable OLED based on a hidden active area (HAA) in its initial state, along with its key working principle. Ultrathin OLEDs are made in a configuration in which parylene (1 μm)/Al_2O_3 (60 nm) dyads are employed as a substrate and a superstrate, respectively, while providing adequate encapsulation to protect OLEDs from ambient air. The symmetrical, sandwiched structure inherent to this approach protects active layers of the OLEDs from experiencing too high strain when being bent at a small radius of curvature [3,5].

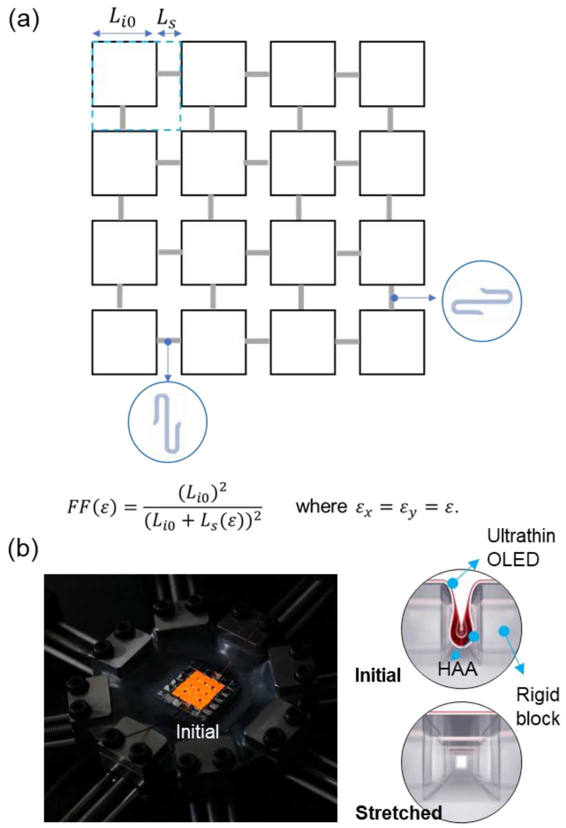

Figure 1. (a) Definition of FF in a stretchable display base on a conventional 2D rigid island array and a serpentine interconnector. (b) (left) The photograph of a high-FF stretchable OLED based on a hidden active area (HAA) in its initial state. The OLED is mounted on a quad-axial stage for uniform expansion along both x and y directions. (right) The HAA configurations in its initial and stretched states. (Some images were reproduced from Lee, D. et al., Nat. Commun. 15, 4349 (2024), under CC BY-NC-ND 4.0 (http://creativecommons.org/licenses/by-nc-nd/4.0/).

The ultrathin OLEDs are patterned via reactive ion etching with O_2 plasma to have an array of holes with the spatial period of 2.9 mm in a 2D square lattice, as shown in **Figure 2**. These holes help smooth transition from the stretched to the unstretched state by avoiding formation of undesired irregular creasing. These holes are virtually invisible in the initial, unstretched state as shown in Fig. 1(b), although they start to show their presence once the device is stretched. This is bound to yield a reduced FF in a stretched state, but they are designed to be small enough to maintain the high FF close to 80-90% and minimize visual artefacts [3].

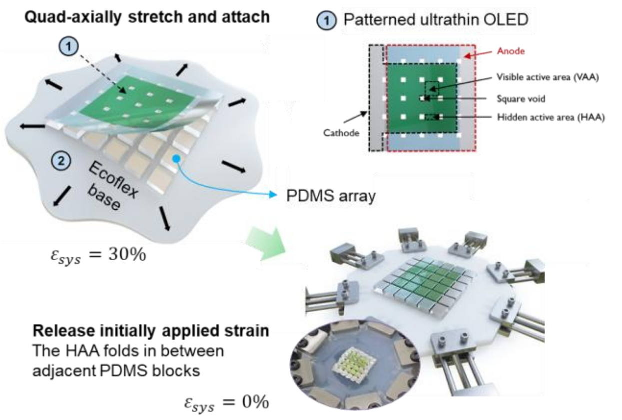

Figure 2. Overview of integration process. An ultrathin OLED is attached onto the rigid PDMS array held on an elastomer base that is quad-axially stretched to yield the system strain ($\boldsymbol{\varepsilon_{sys}}$) of 30%. Once the ultrathin OLED is attached flat, the system strain is released, and the part of the ultrathin OLED referred to as 'hidden active area (HAA)' folds in between adjacent PDMS blocks. (Some images were reproduced from Lee, D. et al., Nat. Commun. 15, 4349 (2024), under CC BY-NC-ND 4.0.

3D rigid island blocks are prepared from hard PDMS and transferred onto a soft elastomer like Ecoflex^{TM}. The ratio of the thickness of rigid PDMS blocks to that of the Ecoflex base was chosen to be ca. 0.8, which turned out to ensure deformation of rigid islands to be minimal when the base is stretched. Once both the ultrathin OLED and the PDMS block array on the Ecoflex base are prepared, they are combined together by attaching An ultrathin OLED onto the rigid PDMS array held on an elastomer base that is quad-axially stretched to yield the system strain ($\boldsymbol{\varepsilon_{sys}}$) of 30%. Once the ultrathin OLED is attached flat, the system strain is released, and the part of the ultrathin OLED referred to as 'hidden active area (HAA)' in Fig. 2 folds in between adjacent PDMS blocks. Finite-element mechanical simulation indicates that strain concentration could occur at the points at the edge of the PDMS block as the ultrathin OLEDs are folded with respect to those sharp edges. The level of strain concentration at the edge becomes more severe when the thickness of the parylene layer increases. The 1 μm thick parylene layer was chosen to make sure the strain applied to all the layers involved remain lower than the respective crack onset strain values.

As shown in Figure 3(a), the fabricated stretchable OLEDs exhibit reliable operation under dynamic stretch-release cycles between ε_{sys}=0 and ε_{sys}=30%. It is also shown that the proposed stretchable OLEDs work well in a dynamic situation over a non-Gaussian curved object, which was demonstrated with an expanding balloon as well as a moving elbow [Fig. 3(b)].

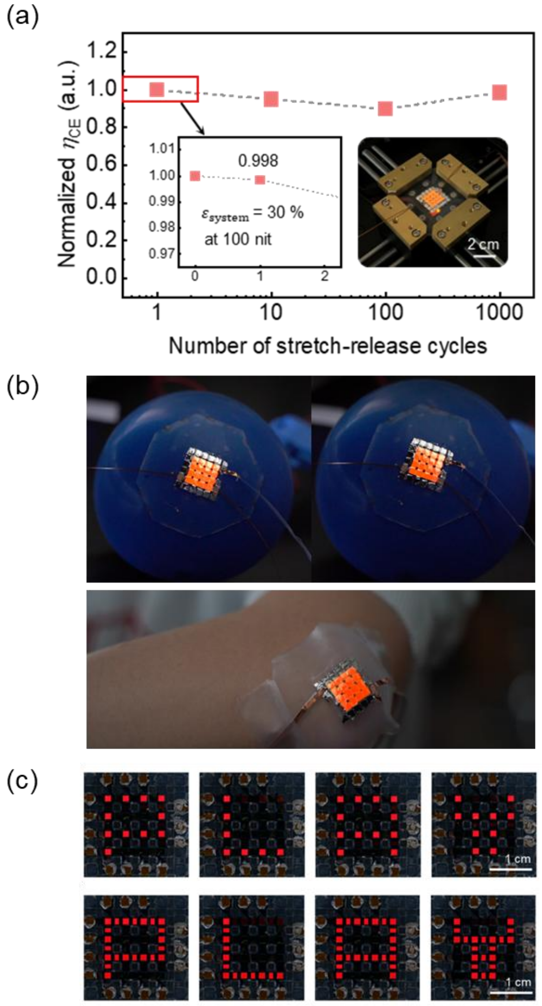

Figure 3. Experimental results of the proposed stretchable OLEDs. (a) Performance evolution of the stretchable OLED under dynamic stretch-release cycles between $\boldsymbol{\varepsilon_{sys}}$=0 and $\boldsymbol{\varepsilon_{sys}}$=30%. (b) Demonstration of the operation over moving curved objects. (c) Passive matrix demonstration illustrating the benefit of resolution compensation enabled upon selective addressing of HAA. (Upper: HAA off; Lower: HAA on.) (Some images were reproduced from Lee, D. et al., Nat. Commun. 15, 4349 (2024), under CC BY-NC-ND 4.0.

In conventional 2D rigid island approaches, resolution is severely degraded when stretched because the pixel-to-pixel distance increases. In the proposed scheme, the HAA can be used as a hidden pixel that compensates stretching-induced resolution loss, overcoming the limitation of the conventional 2D scheme. As illustrated in Fig. 3(c) with the passive matrix configuration, HAAs can be turned on or off with selective electrical addressing and enables resolution compensation when the system gets stretched, illustrating the ample benefits of the proposed HAA-based approach [3].

3. Height-alternant rigid island approach

While the HAA-based approach does solve the problem of the limited fill factor, the presence of square void arrays makes it difficult to route bus electrodes when forming passive-matrix displays. This in turn reduces FF that can be achieved with the proposed system. In this regard, it would be beneficial to realize a configuration that has a native compatibility while still maintaining relatively high FF. One solution could be to start with conventional rigid-island approach and allow it to accommodate 3D motion to a degree that is just right to fulfill the high FF requirements. This can be done by letting every other rigid islands pop up or down according to the applied strain. In this scheme, the free-standing islands are connected to adjacent islands, which are fixed to an elastomeric base, via serpentine electrodes that does not only get stretched but also function like a hinge. As shown in **Figure 4(a)** and 4(b), this approach can make the apparent FF remain high and allow the maximum applicable strain ($\boldsymbol{\varepsilon_{max}}$) to be increased as well [4].

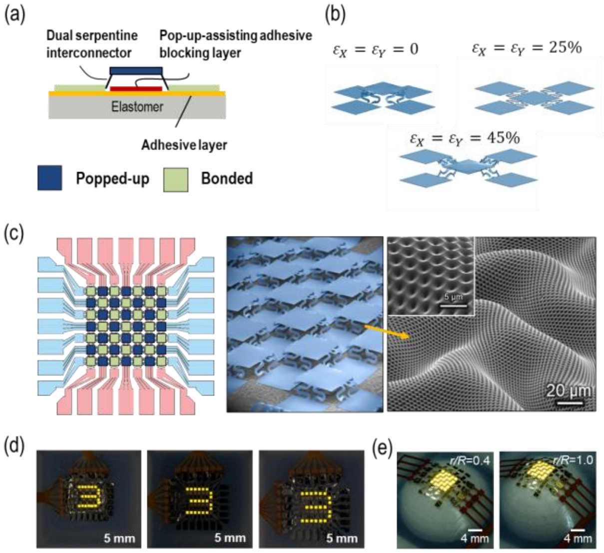

Figure 4. (a) Schematic overview of the height-alternant rigid island approach. Key components include bonded islands, popped-up (freestanding) islands, base elastomer, dual serpentine electrodes, adhesive layer, and pop-up assisting blocking layer (PA-ABL). (b) Configuration of adjacent islands for several strain combinations: 0% corresponds to the initial state, with the freestanding islands fully popped up. (c) Top-view matrix layout (left) and SEM image of the popped-up freestanding islands (middle) and the texture of the PA-ABL. (d) Passive-matrix operation under biaxial strain of 0, 25%, and 45%. (e) Operation demonstration over curved objects. (Some images were reproduced from Kim, S. et al., Nat. Commun. 15, 7802 (2024), under CC BY-NC-ND 4.0.

As can be seen in Fig. 4(c) and 4(d), the layout for matrix configuration is straightforward, essentially the same as that of 2D rigid OLED displays. This allows FF to remain almost the identical between one-cell and matrix configurations. Key engineering that needs to be done to realize this idea was to make the PA-ABL with minimal interaction with the freestanding islands. A flat PDMS, for example, could prevent the freestanding islands from directly facing the adhesive layer; however, the attractive interaction with the freestanding islands was still significant, and they were not able to pop up as intended when compressed. To overcome this problem, we came up with an array of microscopic concave structures as shown in Fig. 4(c). This 'dimpled' PA-ABL allows the freestanding island not only to avoid direct contact with adhesive layer but also to have a very low attractive interaction with PA-ABL so that they pop up or down as designed, with 100% yield, according to the applied strain [4]. Fabricated stretchable OLEDs worked well under PM operation up to 45% system strain and over curved objects with a tight radius of curvature. The proposed approach is highly useful as it adopts polyimides as substrates, which are widely used in active-matrix OLED production.

4. Conclusions

3D approaches that combine ultrathin OLEDs were demonstrated as methodologies that can be promising to solve the problem of low geometrical fill factors inherent to conventional 2D rigid island approaches. Among potential 3D approaches, we introduced those based on a hidden active area and those based on a mechanically guided assembly that incorporates a novel spatially selective adhesion control and an optimal dual serpentine architecture. The proposed methods facilitate a predictable and reliable 2D-to-3D transition, enabling stretchable OLEDs that exhibit a high spatial density. While the proposed methods were demonstrated with OLEDs, they can be extended to other emerging light-emitting technologies as well.

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