Kirigami-Inspired 3D Organic Light-Emitting Diode (OLED) Lighting Concepts

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As the technical performance and reliability of white organic light-emitting diodes (OLEDs) begin to mature, broader adoption in the lighting market will increasingly rely on exploiting the unique aesthetic opportunities that OLEDs afford. Here, kirigami-based concepts that enable ultraflexible thin film OLEDs to be cut, folded, and "popped up" into a variety of 3D shapes ranging from globes to candle flame mimics are used. It is demonstrated that large area (>15 cm²) OLEDs fabricated and encapsulated on sub-50 μ m thick polyimide films can be cut and folded into 3D with negligible impact on their efficiency and electrical characteristics. These results point to an alternate paradigm for OLED lighting that moves beyond traditional 2D panels toward 3D designs that deliver unique and creative new opportunities for lighting.

White organic light-emitting diodes (OLEDs) are being pursued as a future solid-state lighting technology. Recent milestones in white OLED efficiency ($\eta > 90 \text{ lm W}^{-1}$) and operational lifetime (LT₇₀ > 50 000 h) have paved the way for early stage commercialization,^[1,2] shifting the focus of technical development toward reducing manufacturing cost, improving yield, and creating a unique OLED aesthetic appeal that drives demand in compliment to established inorganic LED products.^[3–5] A dazzling variety of OLED lighting and luminaire concepts have been demonstrated to address this last challenge;^[6] however, to a large extent, the paradigm for OLED lighting is still rooted in a 2D flat or curved panel form factor.^[7,8]

Here, we explore the opportunity to create 3D OLEDs using concepts borrowed from kirigami, the Japanese art of paper cutting and folding.^[9] Building on kirigami-inspired work in a range of other fields,^[10–13] we demonstrate a series of large-area OLEDs fabricated on clear polyimide thin films that are subsequently cut, folded, and "popped up" into a variety of different shapes

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ranging from globes to candle flame mimics. We show that the efficiency and electrical characteristics of each device are largely maintained in the transition to three dimensions, thereby enabling more light to be generated within the footprint of a given flat panel due to the added 3D OLED active area. Our results offer a path to leverage the flexibility of OLEDs for innovation in lighting design and point toward a more general opportunity to derive new functionality from thin film organic electronic devices folded into three dimensions.

Figure 1a illustrates the basic concept of using predefined cut and fold (along the solid and dashed lines, respectively) pat-

terns to transform a planar thin film OLED into a 3D device. Figure 1b extends this idea to a globe lamp design based on three similar pop-up patterns that are subsequently assembled into the shape of a rugby ball. Figure 1c shows a more intricate Kirigami cut and fold pattern intended to evoke a candle flame when assembled. In this case, a series of rhombus-like contours (black solid lines) are cut in the 2D layout, curled in opposite directions, and then adhered at their corners to mimic the wisp of the flame.

Paper-like flexibility is a natural requirement for Kirigamibased OLEDs. It is achieved here by fabricating devices on a 25 or 45 μ m thick clear polyimide film substrate, which is spin-cast onto a 100 mm glass carrier wafer as shown in **Figure 2**. The metal and organic layers in the OLED stack are subsequently deposited via thermal evaporation through a series of shadow masks and then the devices are encapsulated with a 5 or 30 μ m thick film of ultraviolet-curable adhesive. The resulting thin film devices are scribed with the Kirigami cut pattern, delaminated from the carrier wafer, and then folded into their final 3D structure.

Figure 3 shows the pop-up globe lamp design from Figure 1b implemented with a green bilayer N,N'-di(1-naphthyl)-N,N'-diphenyl-(1,1'-biphenyl)-4,4'-diamine (NPD)/tris-(8-hydroxyquinoline)aluminum (Alq₃) OLED stack and a semitransparent 15 nm thick Au anode using three shadow mask levels as detailed in the Supporting Information. The photograph in Figure 3a shows one of the three globe lamp component OLEDs lighted at 5 V bias after delamination from the carrier wafer; the completed 3D globe lamp is shown from different angles in Figure 3b,c as well as Video S1 in the Supporting Information. Because the globe lamp is too large for our integrating sphere, we use a home-built integrating "cube" constructed from six 15.6 × 15.6 cm² commercial Si photovoltaic cells to measure the lamp efficiency. The photovoltaic cube,

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2D structure

(a) Kirigami approach

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3D structure

Figure 1. a) General concept of a flexible thin film OLED that is cut, folded, and popped up into three dimensions. b) Globe lamp consisting of three OLED films that are cut as shown in the left-hand image and then popped up and assembled in a trefoil fashion as shown in the right-hand image. c) Candle flame design based on a single OLED film in which the corners of scored concentric squares (top left image) are alternately rolled up forwards and backwards and adhered to one another (subsequent three images).

shown in Figure 3d with the top removed, produces an accurate and reliable measurement of the total light output from the globe lamp irrespective of its orientation (see the Supporting Information for details).

Figure 3e displays the current density–voltage–luminance (J-V-L) characteristics of the 3D globe lamp together with those of a flat component panel on and off the carrier wafer. The 3D globe lamp exhibits an increase in the shunt current at low bias (<2 V), though this is mainly a reflection of the sub-



Figure 2. Outline of the OLED fabrication process. A clear polyimide (CP1) film is spin-coated and cured on a glass carrier wafer prior to evaporation of the OLED layer stack through a series of shadow masks. The completed device is encapsulated with a thin layer of ultraviolet-curable adhesive and then scored in the desired Kirigami cut pattern prior to delaminating from the carrier wafer.

stantial shunt current variation between the three constituent panels (since the assembly is dominated by the worst) rather than leakage paths that are intrinsic to the Kirigami cut and flex process. At higher bias, the current density and luminance of the globe lamp are slightly lower than the planar references, leading to a ~10% relative drop in external quantum efficiency (EQE) as shown in Figure 3f.

Figure 4 presents the candle flame Kirigami structure from Figure 1c implemented with a fluorescent orange OLED containing a 4-(dicyanomethylene)-2-methyl-6-(4dimethylaminostyryl)-4H-pyran (DCM)-doped Alq3 emissive layer. In its planar configuration on the carrier wafer (see Figure 4a), the OLED active area is divided among a series of concentric squares that are cut and rolled from the corners in opposite directions to create the 3D candle flame structure shown in Figure 4b and also from different angles in Video S2 in the Supporting Information. In this device, the bending radii range from 2.5 mm for the smallest square to 7.5 mm for the largest square; significantly smaller radii (≈1 mm) are possible without adversely affecting the OLED operation. Figure 4c shows that the current density of the OLED remains unchanged in transitioning from the carrier wafer to 3D except for the low bias leakage current, which decreases, presumably due to isolation from the scribing. The slight decrease in luminance of the 3D device reflected by the EQE in Figure 4d is due, at least in part, to the hindrance in extracting light from the inward-rolled portions of the candle flame (i.e., the left-hand side of the device pictured in Figure 4b).

While the examples above demonstrate the feasibility of macroscale kirigami OLEDs, similar concepts may also be possible at the microscale by exploiting mechanically guided assembly



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Figure 3. a) One panel of the globe lamp after delamination from the carrier wafer. b,c) The photographs show the completed 3D globe lamp from different angles. The OLED is illuminated at a voltage of 5 V in all of these images. d) Picture of the unilluminated globe lamp within the photovoltaic integrating cube used to measure its efficiency. e) Current density–voltage–luminance characteristics measured for a single globe lamp panel on the carrier wafer (black line), the same panel after delamination from the carrier wafer (red line), and the fully assembled globe lamp (blue line). f) External quantum efficiency calculated for each of the cases shown in (e).

approaches.^[14–16] In the context of lighting, this could lead to high aspect ratio, 3D mesh-like OLEDs that yield more active device area within a given lateral footprint, thereby enabling a higher panel luminance to be achieved at a given device current density. More broadly, thin film organic devices such as transistors, photodetectors, and even entire circuits could be processed conventionally on planar substrates and then transformed into 3D to achieve new functionality.^[17,18]

In summary, we have applied a kirigami-based approach to demonstrate various 3D OLED concepts that are cut, folded, and popped up from traditional planar thin film devices with little to no degradation in their efficiency or electrical characteristics. These results expand the creative possibilities available for OLED lighting to include a wide range of artistic kirigamiand origami-inspired designs that can be fabricated using standard planar processes and then cut, folded, and assembled into 3D by consumers themselves.

Experimental Section

Fabrication: Devices were fabricated on clear polyimide films supported by a 100 mm glass carrier wafer. The wafers were initially treated with chlorotrimethylsilane for 5 min to facilitate delamination of the polyimide film following OLED growth. A resin consisting of 33 or 38 wt% clear polyimide powder (NeXolve) dissolved in diglyme (Sigma Aldrich) was then spin-coated on the wafer at 1000 rpm for 50 s and postbaked at 100°C for 80 min to yield ~25 or 45 μ m

thick films, respectively. The wafer was subsequently loaded into a vacuum thermal evaporator, where a 15 nm thick semitransparent Au anode followed by a 3 nm thick MoO₃ hole injection layer was deposited through a shadow mask. The globe lamp organic stack was a 60 nm NPD/60 nm Alq₃ bilayer whereas the candle flame consisted of a 40 nm thick NPD hole transport layer, a 10 nm thick 3 wt% DCMdoped Alq₃ emissive layer, and a 40 nm thick Alq₃ electron transport layer. Both devices used a LiF (0.7 nm)/Al (100 nm) cathode. The globe lamp stack was encapsulated by spin-coating and ultraviolet curing a $\approx 5 \ \mu m$ thick layer of Norland optical adhesive (NOA72), followed by lamination of a 70 µm thick polyester film for mechanical stability. The candle flame device was encapsulated with a 30 µm thick layer of Norland optical adhesive (NOA 63), and then a 100 nm thick layer of Teflon AF 1600 (Chemours) was evaporated on top to serve as an adhesion-reduction layer. The devices were scribed with a razor blade and then peeled off the carrier wafer prior to assembling their final 3D structure.

Characterization: The current density-voltage-luminance characteristics of the OLEDs, both on the carrier wafer and assembled in 3D, were measured inside a custom integrating cube using a Keysight B2912A sourcemeter. The integrating cube was comprised of six Si solar cells (Bosch, M 3BB – C4 1200, 15.6 × 15.6 cm² area) with near-unity external quantum efficiency across the visible spectrum. Further details on the performance and calibration of the cube are provided in the Supporting Information.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.





Figure 4. a) Photograph of the candle flame OLED illuminated at 5 V while still on the carrier wafer. b) Photographs showing the assembled 3D device prior to illumination (left image) and illuminated at 5 V in both ambient light (middle image) and darkness (right image). c) Current density-voltage-luminance characteristics measured for the candle flame device flat on the glass substrate (black line), peeled off the substrate (red line), and fully assembled in 3D (blue line). d) The corresponding external quantum efficiency calculated in each case is shown.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

3D, flexible electronics, kirigami, lighting, organic light-emitting diodes (OLEDs)

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- [1] S. Jang, Y. Lee, M. Park, SID Symp. Dig. Tech. Pap. 2015, 46, 661.
- [2] J. Spindler, M. Kondakova, M. Boroson, J. Hamer, V. Gohri, M. Büchel, M. Ruske, E. Meulancamp, *SID Symp. Dig. Tech. Pap.* 2016, 47, 294.
- [3] J. Brodrick, DOE SSL Program R&D Plan, U.S. Department of Energy, Washington, DC, USA 2016.
- [4] J. P. Spindler, J. W. Hamer, M. E. Kondakova, in Handbook of Advanced Lighting Technology, Vol. 1 (Eds: R. Karlicek, C. Sun, G. Zissis, R. Ma), Springer International Publishing, Cham, Switzerland 2017.
- [5] N. J. Miller, F. A. Leon, OLED Lighting Products: Capabilities, Challenges, Potential, Pacific Northwest National Laboratory, Richland, WA, USA 2016.

- [6] M. Hack, M. S. Weaver, J. J. Brown, SID Symp. Dig. Tech. Pap. 2017, 48, 187.
- [7] M. Koden, OLED Displays and Lighting, John Wiley & Sons, Chichester, UK 2017.
- [8] H. Pang, P. Mandlik, P. A. Levermore, J. Silvernail, R. Ma, J. J. Brown, in *Proc. of SPIE* (Eds: F. So, C. Adachi), Vol. 8476, SPIE, Bellingham, USA 2012.
- [9] F. Temko, Kirigami: The Creative Art of Paper Cutting, Platt & Munk, New York, NY, USA 1962.
- [10] A. Lamoureux, K. Lee, M. Shlian, S. R. Forrest, M. Shtein, *Nat. Commun.* 2015, 6, 8092.
- [11] M. A. Dias, M. P. McCarron, P. Hanakata, D. Rayneau-Kirkhope, D. Campbell, H. Park, D. P. Holmes, Soft Matter 2017, 13, 9087.
- [12] R. M. Neville, F. Scarpa, A. Pirrera, Sci. Rep. 2016, 6, 31067.
- [13] A. Rafsanjani, K. Bertoldi, Phys. Rev. Lett. 2017, 118, 084301.
- [14] Z. Yan, F. Zhang, J. Wang, F. Liu, X. Guo, K. Nan, Q. Lin, M. Gao, D. Xiao, Y. Shi, Y. Qiu, H. Luan, J. H. Kim, Y. Wang, H. Luo, M. Han, Y. Huang, Y. Zhang, J. A. Rogers, *Adv. Funct. Mater.* **2016**, *26*, 2629.
- [15] S. Xu, Z. Yan, K. Jang, W. Huang, H. Fu, J. Kim, Z. Wei, M. Flavin, J. McCracken, R. Wang, A. Badea, Y. Liu, D. Xiao, G. Zhou, J. Lee, H. U. Chung, H. Cheng, W. Ren, A. Banks, X. Li, U. Paik, R. G. Nuzzol, Y. Huang, Y. Zhang, J. A. Rogers, *Science* **2015**, *347*, 154.
- [16] Y. Zhang, F. Zhang, Z. Yan, Q. Ma, X. Li, Y. Huang, J. A. Rogers, Nat. Rev. Mater. 2017, 2, 17019.
- [17] X. Xu, M. Davanco, X. Qi, S. R. Forrest, Org. Electron. 2008, 9, 1122.
- [18] H. C. Ko, M. P. Stoykovich, J. Song, V. Malyarchuk, W. M. Choi, C. Yu, J. B. Geddes III, J. Xiao, S. Wang, Y. Huang, J. A. Rogers, *Nature* **2008**, 454, 748.