Emission Area Patterning of Organic Light-Emitting Diodes (OLEDs) via Printed Dielectrics

Donggeon Han, Yasser Khan, Karthik Gopalan, Adrien Pierre, and Ana C. Arias*

Solution-processibility is one of the distinguished traits of organic light-emitting diodes (OLEDs) compared to existing solid-state LED technologies. It allows new opportunities which can simplify the fabrication and potentially reduce the cost of manufacturing process. Emission area patterning is one of the crucial fabrication steps and it usually involves subtractive methods, such as photolithography or etching. Here, printing techniques are used to pattern the emission area of blade-coated OLED layers. The print qualities of a number of printing schemes are characterized and compared. Spray coating and screen printing are used to deposit dielectrics with desired patterns on the OLED layers. At luminance of 1000 cd m⁻² the OLEDs patterned using spray-coated and screen-printed dielectric show current density of 8.2 and 10.1 mA cm⁻², external quantum efficiency (EQE) of 2.1% and 2.1%, and luminous efficacy of 5.5 and 6.3 lm W⁻¹, respectively. The OLED characteristics and features of each printing scheme in depositing the dielectric layer are discussed. The printing methods are further applied to demonstrate displays with complex shapes and a seven-segment display.

1. Introduction

Organic light-emitting diodes (OLEDs) technology has advanced significantly over the past few decades,[1–6] Although OLEDs have now developed to an extent where they are successfully incorporated in commercial products, there still are unexploited traits of OLEDs which could allow new applications. OLEDs are capable of being flexible or stretchable, which enables them to conform well to human skin.[7,8] In wearable electronics or sensors, conformal electronics can directly influence the design of the wearable system and the quality of the collected signals.[9,10] In addition, OLEDs can be made using printing schemes which can significantly simplify the manufacturing process and reduce the cost.[11–13] Recently, OLEDs printed on flexible substrates via blade coating were used as components of a sensor that monitors pulse and blood oxygenation, where the solution-processed printed OLEDs showed sufficient light flux output.[14]

One of the crucial steps in the fabrication of OLEDs is the emission area (EA) definition. The EA is usually defined by subtractive processes which involve either photolithography or etching. One typical way of defining the EA is by determining it with the overlapping region of the patterned bottom and the top electrode (Figure 1a–b). This type of EA patterning will be referred to as “overlap patterning,” and (OP) in short, in this report. Indium-tin-oxide (ITO) is frequently used for the bottom electrode (Figure 1ai), and is generally patterned by etching (Figure 1aii), while the metal electrode is patterned by shadow mask (Figure 1aiii). The resulting OLED structure is shown in Figure 1b. The shape of the EA achievable with this method is limited and it often requires careful etching and alignment processes. For instance, when the desired shape is a circle, the manufacturer will often end up with an incomplete circle, as shown in the red dashed region of the bottom figure in Figure 1b.

One can also pattern the EA using a dielectric layer with openings (Figure 1c–d). This type of EA patterning will be referred to as “dielectric patterning,” and (DP) in short, in this report. For this scheme, the bottom electrode does not need to be patterned (Figure 1ci). After OLED layers are deposited (Figure 1cii), a dielectric layer with desired pattern(s) (Figure 1ciii) and top electrode completely covering the EA (Figure 1civ) are deposited. The complete structure for this scheme is shown in Figure 1d. Note that the dielectric layer can be deposited prior to the OLED layers to pattern the EA (Figure S1, Supporting Information). Compared to the scheme in Figure 1a–b, where the degree of freedom in design is limited by the overlap between the two electrodes and their alignment, it is easy to achieve the desired patterns using DP, especially when the patterns are detailed or complex.

Both OP and DP have been commonly used to define the EA of OLEDs. For the EAs of OLED stack constructed via conventional methods of film patterning, such as shadow mask and laser processes, either OP or DP are used depending on the manufacturer’s preference.[15–17] DP is normally used for inkjet printed OLEDs, where hydrophobic patterned banks or wells are formed prior to ink deposition to effectively confine the deposited ink.[15,18,19] The hydrophobic banks are formed via subtractive methods, which requires high baking temperature and etching processes that are undesirable for the OLED materials and adds complexity to the fabrication process. Dry contact printing, also known as transfer printing method has been used in the fabrication of OLEDs using OP and by transferring the
organic layer with desired patterns directly onto unpatterned electrodes.\[20–24\] The fabrication of a template used in stamp molding usually requires subtractive methods, the donor films are either vacuum-deposited or spin-coated, and the compatibility of this method with large area roll-to-roll production is still in question. Demonstration on patterning methods that does not rely on complex conventional methods and at the same time are compatible with large area and large volume manufacturing is still elusive.

In this paper, we use spray coating or screen printing to perform DP for EA definition of OLEDs. Both deposition methods are compatible with low-cost roll-to-roll mass production. The step shown in Figure 1ciii is demonstrated with either spray coating or screen printing. The DP is performed on blade-coated OLED layers and the pattern in the dielectric layer defines the EA of the OLEDs. The printing techniques are compared in terms of their printing capabilities and ability to maintain the desired shapes. OLEDs with circular EAs are fabricated using both OP and DP, where for DP devices, spray coating and screen printing are used to print the dielectric layer. The characteristics of the devices are compared and discussed. Then we demonstrate examples of application using DP, which requires more steps and is complex when realized by OP; an OLED with an EA displaying the word “Cal” with spray coating, and a seven-segment display patterned with screen printing, the latter of which is operated by external control electronics.

2. Results and Discussions

2.1. Printing Patterned Dielectric

First, spray coating and screen printing are tested in terms of the quality of the printed dielectric. The spray coating process flow is shown in Figure 2a. In order to create a patterned dielectric using spray coating, a mask is needed. Conventional stencil mask tend to float above the target and make an incomplete contact with the substrate. In solution processing, a good contact between the mask and substrate is needed to ensure good pattern definition. Polydimethylsiloxane (PDMS) has been shown to provide firm contact directly with organic layers without damage.\[21,22,25,26\] PDMS prevents unwanted ink reflow after deposition, and leaves no residue when it is removed. On the substrate (Figure 2ai), a PDMS structure with a desired shape made by a 3D printed mold is gently placed on top (Figure 2aii). The dielectric solution is spray-coated (Figure 2aiii) and the PDMS is carefully removed (Figure 2aiv), which results in a dielectric layer with an opening that has the shape of the PDMS structure. In this study, (ciii) process step is performed using different printing techniques. In (b) and (d), the EA is indicated with red dashed lines.

![Figure 1. Illustration of procedures and structures that are used to make OLEDs. Process flow a) and structure b) of OLEDs with EA defined by an overlapping region of the bottom and the top electrodes. This method of patterning will be termed overlap patterning method (OP). Process steps in (a): i) substrate with bottom electrode, ii) bottom electrode etched, iii) OLED layers deposited, and iv) top electrode with circular pattern deposited. Process flow c) and structure d) of OLEDs with EA defined by a patterned dielectric layer. This method of patterning will be termed dielectric patterning (DP). Process steps in (c): i) bottom electrode, ii) OLED layers, iii) dielectric with circular pattern, and iv) top electrode deposited. In this study, (ciii) process step is performed using different printing techniques. In (b) and (d), the EA is indicated with red dashed lines.](image-url)
through the screen (Figure 2bv), printing the dielectric layer with patterned openings (Figure 2bvi).

2.2. Ink and Print Quality Assessment

For spray coating, the ink used should be low in viscosity so that it will go through the spray nozzle without clogging it, but also viscous enough to maintain its intended shape after the spray. For screen printing, the ink should be shear thinning, where the viscosity of the ink decreases for increasing shear rate. As a result of the different ink requirements for each printing process, different materials are used for the two methods: PVDF-trf (PVDF) for spray coating and Blue dielectric (BD) for screen printing, both of which are printable.

Figure 3a shows the viscosity versus shear rate of the inks. The recipe of each ink is described in the experimental section. PVDF10% has a viscosity of around 200 cp (Figure S2, Supporting Information), which frequently clogs the spray nozzle due to high viscosity, and is not characterized. The viscosities of PVDF2% and PVDF1% are around 2 and 1 cp and are sprayable without any problem. 2.5 mL of these inks are sprayed on a polyethylene naphthalate (PEN) substrate with a square shaped PDMS placed on top. After spraying, the PDMS is removed which leaves a square shaped opening in the deposited dielectric layer. Micrographs in Figure 3b,c show spray-coated dielectric layer with square openings, focused on one of the four corners. With PVDF2%, the edges are not clearly defined, leaving residues at undesired places after PDMS removal (Figure 3b). This is due to the sticky nature of the ink used. When the ink is further diluted to PVDF1%, it is possible to obtain clean edges and the desired shape can be achieved (Figure 3c). Figure 3d,e shows the edges of the screen-printed BD layers. With BD33% in Figure 3d, it can be seen that the deposited ink failed to maintain its original form after printing. With BD100%,
which has the highest viscosity, it shows well-defined edges (Figure 3e). The full characterization using four inks (BD100%, BD77%, BD50%, and BD33%) is shown in Figures S2 and S3 (Supporting Information). Boundaries of BD77%, BD50%, and BD33% are all distorted or unclear, which becomes worse when the ink is more diluted. This is a result of ink reflow after printing. Stencil printing with the same inks are also performed. The methods are identical to the work done by Khan et al., where stencil printing was used to deposit Nickel Oxide thermistors.[30]

The quality of the deposited films are shown in the top row of Figure S3 (Supporting Information). With stencil printing, it is innately difficult to print layers with openings, since the print area needs to be void and the pattern should be free-standing, not connected to the frame of the mask. This limits the use of stencil printing in EA patterning, requiring an additional patterning through the electrodes in order to fully pattern the EA. For this reason, stencil printing is used here to simply compare the print quality with other printing techniques. A square shaped structure is printed instead of a layer with a square shaped opening. As can be seen in the top row of Figure S3 (Supporting Information), the edges are poorly defined for all four inks. Note that the print quality itself can be improved by using an automated stencil printer along with inks that are more suitable for the purpose.[31] As a result, PVDF1% via spray coating and BD100% via screen printing are chosen for depositing the dielectric layer. Thickness profile of each layer, characterized at the boundary indicated by the yellow line, is also shown in the inset figure at the top left corners of each micrograph. For layers spray-coated with PVDF2% and PVDF1%, the thicknesses are around 4 and 1 µm, respectively. Screen-printed BD33% and BD100% have thicknesses of around 3 and 10 µm. The thicknesses and the profiles of other inks are also shown in Figure S3 (Supporting Information). The thicknesses of the deposited layers are of interest since they have direct influence on the step coverage of the top electrode which is deposited on top of them. This will be explained in detail later in the future text.

2.3. OLED Fabrication with Printed Dielectric

OLEDs are fabricated using both OP and DP. For DP, spray coating and screen printing are used with the previously selected inks. OLEDs with EAs defined by OP are termed OP-OLED, and the ones defined by DP is termed DP-OLEDs. DP is performed either by spray coating or screen printing, and are referred to as Sp-OLED and Sc-OLED, respectively. For OP-OLEDs, pre-patterned ITO on a flexible PEN substrates are used. Solution-processable OLED layers, which consist of PEDOT:PSS/TFB/F8BT:TFB, are blade-coated on the substrates in a subsequent manner using the method described previously.[14] Then, a bilayer top electrode, calcium (10 nm) and aluminum (100 nm), is deposited. For Sp- and Sc-OLEDs, nonpatterned ITO is used. The same OLED layers are blade-coated and the dielectric layers are deposited either by spray coating or screen printing. The same bilayer top electrode is deposited to finish the OLED structure.

For Sp-OLEDs it is important to take caution when placing the PDMS on top of the OLED stack. When PDMS is pressed with too much force, the OLED stack easily collapses. Figure S4 (Supporting Information) shows example of Sp-OLED with...
a damaged EA from excessive force. In order to place PDMS without damaging the OLED stack, the PDMS should be gently placed at the desired location and let it adhere to the substrate itself. Also, before spraying, one should make sure that there is no air gaps underneath the PDMS.

As mentioned earlier, when DP is used for EA patterning of OLEDs, step coverage of the top electrode can become an issue. The profile in Figure 3e shows a thickness of around 10 µm, which is almost 100 times thicker than the thickness of the top electrode. A picture of Sc-OLED with thin aluminum (100 nm) operating at 4 V is shown in Figure S5a (Supporting Information). The emission is not uniform, where the boundary is brighter than the other portions of the EA. This nonuniformity indicates that the conductance of the top electrode has discrepancies. This is solved when thicker thickness of aluminum (300 nm) is deposited and the picture of this Sc-OLED operating at 4 V is shown in Figure S5b (Supporting Information). When compared to Figure S5a (Supporting Information), the improvement in the emission uniformity as well as the brightness is evident.

In order to check if the quality of the step-coverage can be observed, the devices are put under the microscope and images taken at the boundaries of the OLED EAs with different light settings are shown in Figure 4. In Figure 4a,d, the location of the EA boundaries for Sc-OLEDs with thin (100 nm) and thick (300 nm) aluminum can be confirmed, respectively. When the light is shone from below, Sc-OLED with thin aluminum in Figure 4b exhibits light leakage along the perimeter of the OLED EA, where there is a step difference in height. When the bottom light is blocked, the thin line of leakage light disappears (Figure 4c), suggesting that there exist a crevice or relatively thinner aluminum region at the border of the printed dielectric in devices with thin aluminum. For Sc-OLED with thick aluminum, this leakage light cannot be observed (Figure 4e).

2.4. OLED Characteristics

Pictures of OP-, Sp-, and Sc-OLEDs are shown in Figure 5a–c. As mentioned before, it is difficult to make an OP-OLED with a circular EA. OP-OLED shown in Figure 5a shows emission of an incomplete circle with a small protruding rectangle. Sp- and Sc-OLEDs (Figure 5b,c) on the other hand, demonstrate perfect circular EAs. The current-density–voltage (J–V), voltage–luminance (V–L), external quantum efficiency–J (EQE–J), and luminous efficacy–J characteristics of the three OLEDs are presented in Figure 5d–g. Improvement of device performance for Sc-OLED with thicker top electrode compared to the ones with thin electrode can be confirmed by comparing the J–V–L plot of the thin electrode device in Figure S6 (Supporting Information) to the thick electrode ones in Figure 5d,e. The amount of current as well as the luminance increased; at 7 V, the values of current density and luminance are 113 mA cm$^{-2}$ and 8670 cd m$^{-2}$, compared to 25 mA cm$^{-2}$ and 3439 cd m$^{-2}$ (Table 1). The characteristics of Sp- and Sc-OLEDs do not deviate much from OP-OLED, although the EQE and luminous efficacy are slightly lower in the low J regions. At a luminance of 1000 cd m$^{-2}$,
OP-, Sp-, and Sc-OLEDs show operating voltages of 3.1, 3.8, and 4.0 V current densities of 7.1, 8.2, and 10.1 mA cm$^{-2}$, EQEs of 3.2%, 2.1%, and 2.1%, and luminous efficacies of 11.6, 5.5 and 6.3 lm W$^{-1}$, respectively (Table 2). This deviation may come from the fact that the blade-coated layers of the Sp- and the Sc-OLEDs are exposed to ambient air for the DP process. Also, the EAs of the DP-OLEDs come in direct contact with the PDMS figure for Sp-OLEDs and the screen for Sc-OLEDs during the DP process, which can contaminate the EAs.[32] Nevertheless, the OLEDs exhibit uniform emission and show stable performance throughout the characterization.

2.5. Application

One great advantage of Sp-OLEDs is that it can pattern a delicate shape with relatively less complexity. Figure S7 (Supporting Information) show pictures of the procedures associated with the fabrication of a Cal logo OLED. The procedure is identical to Figure 2a. A Cal logo mold is 3D printed and used to form the PDMS shape (Figure S7a, Supporting Information and Figure 2aii). The PDMS shape is gently placed on the blade-coated OLED layers (Figure S7b, Supporting Information and Figure 2aiii) and the dielectric ink is sprayed. When the PDMS is removed, the deposited dielectric layer is left with a Cal logo shaped aperture. The top electrode is then deposited to finish the OLED structure. The bottom view of the Cal OLED in the off-state is shown in Figure S7c (Supporting Information), and the device in operation at 7 V is shown in Figure 6a. Due to the sticky nature of the PVDF inks discussed previously, the Cal logo PDMS did not peel off properly at small spacings between the letters “Ca” and the underline below them, which led to a partially undefined logo. The boundaries of the Cal logo is clearly visible in Figure S7d (Supporting Information), where the device is operated at low brightness (4 V), meaning that the initial patterning was successful. It is clear that delicate patterning of EA is possible with spray-coated DP. With appropriate material selection, spray coating can be a cheap and effective way to pattern the EA, providing a fast turnaround time for OLEDs with various patterns.

With screen-printing, it is simple and quick to print layers with desired patterns once the screen is ready, which makes

<p>| Table 2. Summary of operating voltage, current density, EQE, and luminous efficacy of OP-, Sp-, and Sc-OLEDs at luminance of 1000 cd m$^{-2}$. The values are averaged over three devices. The value after ± represents standard deviation. |</p>
<table>
<thead>
<tr>
<th>V [V]</th>
<th>J [mA cm$^{-2}$]</th>
<th>EQE [%]</th>
<th>LE [lm W$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>OP-OLED</td>
<td>3.1 ± 0.2</td>
<td>7.1 ± 1.3</td>
<td>3.2 ± 0.4</td>
</tr>
<tr>
<td>Sp-OLED</td>
<td>3.8 ± 0.1</td>
<td>8.2 ± 1.6</td>
<td>2.1 ± 0.3</td>
</tr>
<tr>
<td>Sc-OLED</td>
<td>4.0 ± 0.2</td>
<td>10.1 ± 0.3</td>
<td>2.1 ± 0.1</td>
</tr>
</tbody>
</table>
it compatible with mass-production. As an example of application, Sc-OLEDs are used to make seven-segment display. In addition to the dielectric layer printing steps described in Figure 2b, Ag traces are screen-printed which enables individual addressing of each segment. The Ag traces are printed subsequently to the dielectric printing. The completed display is thin, light-weight and flexible as shown in Figure 6b. Figure 6c shows a top view of the display. Figure 6d is a picture of the display interface with a driving board. The printed Ag traces make it possible to directly connect the display to a flexible flat cable (FFC) connector, which allows the board to drive the display. The display can be programmed to display desired segments. Figure 6e shows such example, where the display is displaying “CA,” “20,” and “18.” Movie clips of the printed display demonstrating stable operation and various signals are provided in the Supplementary Information.

3. Conclusion

In summary, OLED EA patterning is realized by printing dielectric layers with openings which is either done by spray coating or screen printing. There are the two primary methods of patterning the emission area of the OLEDs; i) overlapping region of the bottom and the top electrodes (OP), and ii) through a dielectric layer with openings (DP). We performed DP, with spray coating or screen printing, to deposit dielectric layers with openings. For spray coating, deposition method of using PDMS structure as a mask to create an opening with a desired shape is presented. Different dielectric inks are tested for each deposition method with varying concentrations. For fine prints, it was important for all printing methods to use inks that have appropriate viscosity values and characteristics. Using the optimized inks with respective deposition methods, OLEDs are fabricated and characterized. OP-OLED, Sp-OLED, and Sc-OLED all showed stable and reasonable performance. For Sc-OLEDs, there was an issue regarding the poor step coverage of the top electrode due to a steep step height. The step-coverage is improved by making the top electrode thicker, which also improves emission uniformity and the performance of the OLED. The improvement of step-coverage is also identified by comparison through an optical microscope and the performances. As examples of demonstration, Cal logo Sp-OLED and seven-segment display Sc-OLED are successfully shown. These results suggest that the dielectric layer patterning methods presented in this paper can be readily applied to OLEDs. Specifically, the spray coating patterning technique can be an effective way to pattern OLEDs with a fast turnaround time. Screen printing, on the other hand, is more convenient when multiple openings or pixels are required, and is more compatible with mass-production. We believe that the methods, the results and the demonstrations presented here can contribute and promote novel application of printing schemes to light-emitting technologies.

4. Experimental Section

OLED Structure: poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) (Clevios AI4083, Heraeus) was used as a hole transport layer, poly(9,9-dioctylfluorene-co-N-(4-butylphenyl)-diphenylamine) (TFB) was used as an electron blocking layer, and a blend of poly[(9,9-dioctylfluorene-2,7-diyl)-alt-(2,1,3-benzothiadiazole-4,8-diyl)] (F8BT) mixed with TFB with weight ratio of 9:1 was used as an emission layer. The layers mentioned above were all blade-coated. Then bilayer of calcium and aluminum was thermally evaporated. The resulting structure is ITO/PEDOT:PSS (70 nm)/TFB (<10 nm)/TFB:F8BT (100 nm)/Ca/Al.

Thickness Measurement: Substrates were firmly mounted on a glass/Gel-Pak carrier. A Dektak profiler (Veeco 6M) was used to measure the film thickness and profile.

Preparation of Inks: For spray-coated dielectric, P(VDF-TrFE-CFE) (PVDF, PIEZOTECH ARKEMA) was purchased as paste. PVDF was dissolved in 2-butanone (Sigma-Aldrich) with weight ratio of 1:9 (PVDF10%), 1:49 (PVDF2%), and 1:99 (PVDF1%). For screen-printed dielectric, translucent blue solvent resistant high performance dielectric ink (Creative Materials Inc.) was purchased as paste. 118-08A was mixed with a B119-44 (Creative materials Inc.) with weight ratio of 50:1 prior to application (BD100%). The ink was diluted with Propylene glycol monomethyl ether acetate (pGMEA, Sigma Aldrich) with volume ratio of 1:0.3 (BD77%), 1:1 (BD50%), and 1:2 (BD33%) for screen-printed Ag traces, solvent-resistant electrically conductive ink (Creative Materials Inc.) was purchased as paste. 118-09A was mixed with B119-44 with weight ratio of 100:1.5 prior to application.

Printing Methods: For blade coating, a doctor blade (Zehntner ZUA 2000.60) was used to coat PEDOT:PSS, TFB, and F8BT:TFB. Linear
Actuators (Servo City) were set up inside and outside a glovebox, height of which were adjusted to coat on the substrate placed on a hotplate.

For spray coating, a spray coater (Air Brush Model 105, Badger) driven by nitrogen pressure was used to deposit the dielectric layer. No substrate heating was employed during ink deposition. The deposited film was annealed at 100 °C in air for 5 min.

For stencil printing, a 50 μm thick polyethylene terephthalate (PET) was laser-cut to have a square shaped aperture of 2 mm × 2 mm. The ink was deposited by manually sliding a glass slide.

For screen printing, an industrial-grade screen printer (ASYS, ASP 01M) was used to deposit the dielectric layer and the Ag traces. No substrate heating was employed during ink deposition. Both the dielectric and Ag were annealed at 100 °C in air for 5 min.

**Device Encapsulation:** A drop of UV curable epoxy was placed on top of an active pixel and pressed gently with a precut plastic film (MELINEX ST504). The sample was placed under UV radiation with a UV lamp (DR-301C, Melody Susie).

**Control Electronics for the Seven-Segment Display**

For stencil printing, a 50 μm thick PET was used to deposit the dielectric layer and the Ag traces. Most conventional desktop 3D printers would be suitable for deposition modeling (FDM) 3D printer with polylactic acid (PLA) filament. Most conventional desktop 3D printers would be suitable for this application. Each mold was modeled in Autodesk Fusion 360 and sliced with Cura. Printing was conducted with a hot end temperature of 200 °C with a slow travel speed to minimize warping.

**Device Characterization**—The fabricated devices were measured using Keithley 2601 and Keithley 2400 to characterize for J−V and take photodiode readings, respectively. Emission spectra and total flux were measured using Keithley 2601 and a spectrometer (SP-75, Orphotonix) equipped with an integrating sphere.

**3D Printed Mold:** The mold was printed using a custom built fused deposition modeling (FDM) 3D printer with polylactic acid (PLA) filament. Most conventional desktop 3D printers would be suitable for this application. Each mold was modeled in Autodesk Fusion 360 and sliced with Cura. Printing was conducted with a hot end temperature of 200 °C with a slow travel speed to minimize warping.

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**Control Electronics for the Seven-Segment Display** The seven-segment display was used in a common anode configuration, where the pixels were controlled using Darlington Transistor Arrays (Texas Instruments ULN2803A) and an Arduino Mega. The hardware and the software for the display driver are provided under open source license at [https://github.com/yasser-khan/oled_array_driver](https://github.com/yasser-khan/oled_array_driver).

**Supporting Information**

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

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**Conflict of Interest**

The authors declare no conflict of interest.

**Keywords**

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Supporting Information

**Figure S1.** Dielectric layer can be deposited prior to other layers to define the EA of the OLEDs.

**Figure S2.** Ink viscosity vs shear rate of all the ink used for spray coating and screen printing.
Figure S3. (Top two rows) Optical micrographs showing printed dielectric layers using stencil printing and screen printing. The red lines in each of the micrograph represent the intended shape. (Bottom row) Profiles of the printed dielectric layers.

Figure S4. Examples of Sp-OLEDs with collapsed OLED stack. The damage in the EA can be visibly seen.
**Figure S5.** Sc-OLEDs operating at 4 V. a) Sc-OLED with thin Aluminum top electrode shows dim and non-uniform emission. b) Sc-OLED with thick Aluminum is relatively brighter and more uniform.

**Figure S6.** Characteristics of Sc-OLED with thin Aluminum. Current density vs voltage ($J - V$) and voltage vs luminance ($V - L$).
**Figure S7.** Pictures associated with Sp-OLED. a) Cal logo PDMS structure made with 3D printed mold. b) PDMS structure placed on the blade-coated stacks. c) Sp-OLED with Cal logo shaped emission area. d) Cal logo Sp-OLED operating at 4 V.