Printed Anodes and Internal Extraction Layers on Flexible Glass to Create Cost Effective and High Efficacy Bendable OLED Lighting Panels

Final Technical Report

DOE Office of Science Grant DE-SC0018880
Recipient: OLEDWorks LLC, Rochester, NY
Principal Investigator: Jeffrey Spindler
Project Period: July 2, 2018 to April 1, 2019

Contents

I. SUMMARY 3
II. BACKGROUND 3
PROOF OF CONCEPT OBJECTIVES 4
III. EXPERIMENTATION AND RESULTS 5
Substrate preparation 5
Development of internal light extraction 7
Development of silver nanowire electrode 12
Development of stacked white OLED structure 17
IV. CONCLUSIONS 20
V. RECOMMENDATIONS 20
VI. ACKNOWLEDGEMENTS 21

I. SUMMARY

In this project, OLEDWorks developed a high efficacy and cost-effective flexible OLED lighting system which could reduce the cost of OLED light by introducing a combination of printable and scalable scattering type internal light extraction (ILE) and transparent conductive silver nanowire technologies that are compatible with roll-to-roll (R2R) processing methods. High efficacy was achieved by co-optimization of the internal light extraction, silver nanowire and ITO anodes, and stacked white OLED structure to reduce unwanted absorption, increase the outcoupling efficiency, and lower the OLED voltage. At the end of Phase I of this project a power efficacy of 90 lm/W was demonstrated in a flexible OLED lighting device based on ultrathin bendable glass.

The goal was to demonstrate an OLED efficacy of 100 lm/W using higher performance internal light extraction combined with lower absorption transparent conductive anode layers and state-of-the-art stacked white OLED architectures. The materials and components used for the thin glass substrate, internal light extraction, and transparent conductor are compatible with low cost manufacturing methods such as direct printing and R2R manufacturing. The 100 lm/W goal would exceed the 2018 DOE target of 90 lm/W and approach the 2020 target of 110 lm/W[1].

In the end, we successfully demonstrated bendable OLED devices with an efficacy of 92 lm/W. Without much additional work, the milestone of 100 lm/W is certainly within reach, and with further work on light extraction and white OLED materials, we believe 120 lm/W or higher is achievable within the next few years.

II. BACKGROUND

OLED lighting is predicted to contribute significantly to the US energy savings that will result from the implementation of Solid-State Lighting (SSL). LED lighting adoption is predicted to result in a 75% reduction in lighting sector energy consumption by 2035,[2] and OLED lighting adoption is predicted to reach approximately 5% of the lighting market by 2020, growing at 20% CAGR.[3] A recent DOE analysis showed that using OLEDs instead of traditional designs in commercial corridors could bring energy savings of 73%, which translates into 163 TBtu per year, saving businesses $1.7 billion in 2020. However, the OLED lighting market has grown more slowly than anticipated and in general the SSL market penetration is less than it could be. This project addressed three main factors that will potentially lead to higher volumes and more widespread adoption of OLED lighting:

1) Higher performance – OLED efficacy has improved greatly, but the performance gap between LEDs and OLEDs has limited the OLED market. This project demonstrated an OLED efficacy of 90 lm/W using higher performance scattering type internal light extraction combined with lower absorption transparent conductive anode layers and new stacked OLED architectures.

2) Lower cost – Despite great progress in reducing the cost of OLED lighting in recent years, much more progress is required to reduce the perceived high first-cost of OLED lighting and to achieve the 2025 cost target of $\$100/m^2$. The internal light extraction and transparent

[1] DOE SSL Program, “2017 Suggested Research Topics Supplement: Technology and Market Context,” edited by James Brodrick, Ph.D.

[2] “Energy Savings Forecast of Solid-State Lighting in General Illumination Applications,” Sep. 2016, Prepared for DOE by Navigant Consulting Inc.

[3] N. Bardsley, "Defining the SSL Market Potential for OLEDs," in *OLED World Summit*, San Francisco, CA, 2013.

conductor technology developed in this work have never been used in a commercial OLED lighting panel, but they are compatible with additive printing or other cost-effective patterning methods which will lead to higher throughput manufacturing and greater material utilization than existing approaches if they can be combined and commercialized, significantly lowering the cost of OLED lighting products.

3) Conformable/flexible form factor – OLEDs are already thin and lightweight, and combining these features with flexibility and higher efficacy will open many new market opportunities. Flexibility is predicted to be a critical Unique Selling Point (USP) for distinguishing OLED lighting from LED lighting. As opposed to rigid glass OLEDs, flexible OLEDs can be produced using roll-to-roll (R2R) manufacturing methods which can lead to lower manufacturing costs through increased productivity and higher throughput. R2R processing for OLEDs has been estimated to reduce the cost of producing OLEDs by 30%, in addition to the above savings.[4] The 90 lm/W efficacy achieved on bendable glass substrates is well above the 60 lm/W efficacy of current commercial bendable OLED lighting panels based on plastic (LGDisplay) and thin glass (OLEDWorks).

If successful, this work could lead to commercialization of the world's highest performance and most cost-effective flexible or bendable OLED lighting products and the world's first flexible or bendable OLED lighting products to use internal light extraction and printed anodes.

PROOF OF CONCEPT OBJECTIVES

This project developed cost-effective technology that can be integrated into a high efficacy, bendable OLED lighting panel. During Phase I, the Technical Objectives (TO) were:

1) Produce functional white OLED samples with the baseline OLED architecture; printable IEL formulation and ITO anodes achieving an efficacy of 90 lm/W.
2) Produce functional white OLED samples with the baseline OLED architecture, printable IEL and silver nanowire anode achieving an efficacy of 90 lm/W.
3) Produce a high efficacy bendable white OLED on thin glass with an optimized OLED architecture, printable IEL and silver nanowire anode achieving an efficacy >100 lm/W (at ~3,000 K, <0.004 Duv and 3,000 cd/m^2).
4) Collect data on costs and throughputs (TAC times) needed to estimate the capital, BOM, maintenance, and labor costs of a production operation in anticipation of a Phase II Application.

While we did achieve 92 lm/W efficacy with printable ILE and ITO anode, we did not achieve the final target of 100 lm/W with either ITO or silver nanowire anodes. With the demonstration of an all-phosphorescent white structure, we successfully demonstrated the components required to achieve 100-120 lm/W but did not have time to combine all the components within the short timeframe of this Phase I project.

[4] Dipak Chowdhury – Corning, "Integrated Substrate to Enable Conformable OLED Lighting", OLEDs World Summit – 2016, Sept. 22, 2016, page 7.

III. EXPERIMENTATION AND RESULTS

Substrate preparation

Today, flexible plastic OLED lighting panels are available at high prices, but all are quite susceptible to damage and premature defect formation due to water ingress. In 2015 OLEDWorks and Corning Inc., began a Joint Development project to develop bendable glass OLED panels based on Willow™ glass. By using a thin glass substrate rather than barrier-coated plastic, the goal was to produce panels that had very long lifetime with respect to moisture ingress, over the existing plastic panels in the marketplace. Significant benefits of the thin bendable glass substrate include:

1. Perfect barrier properties to water and other external contaminants
2. An extremely low roughness surface known to be important for manufacturing of highly reliable OLED lighting panels
3. Compatibility with high temperature sputtering of indium tin oxide (ITO) known to produce the highest quality ITO with respect to low optical absorption, low surface roughness and high electrical conductivity

For the bendable substrate we used 0.2mm thick Corning Willow™ glass, as shown in Figure 1. This avoided the bonding and de-bonding processes that are required when using 0.1mm thick Willow glass, as it is too flexible to handle without a rigid carrier glass. The 0.2mm glass is rigid enough to allow processing of the thin glass with all the same equipment and processes that would normally be used for rigid glass. We also prepared similar OLEDs on standard 0.7mm thick sodalime glass for comparison.

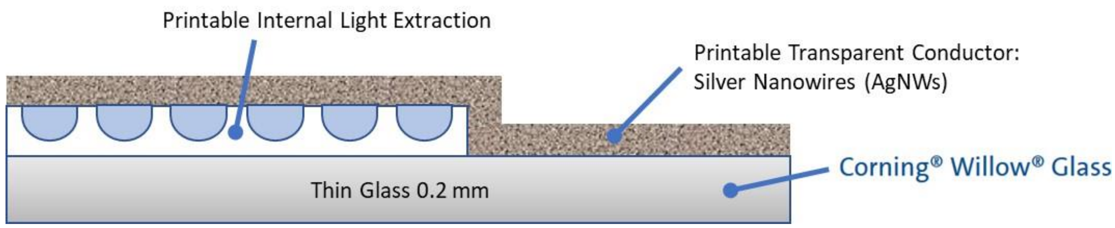


Figure 1. Structure of bendable substrate with printed ILE and anode

We originally planned to investigate barrier coated plastic films in addition to thin glass. Although we had done preliminary work with a Japanese supplier of barrier coated films, we were not able to obtain films for this project due to IP issues they encountered with their technology. Supply of OLED quality (WVTR<10-6) barrier films from U.S. companies such as Vitriflex were also not available during this project timeframe, therefore we continued to focus on thin glass substrates.

A supply of 0.2mm Willow™ glass substrates was obtained from Corning. The substrate size was 63.3mm x 63.3mm (approximately 2.5”) which is a standard development size substrate used by OLEDWorks. Blank substrates were sent to Pixelligent, University of Michigan, and North Carolina State University for application of their printable light extraction materials. Corning also supplied substrates coated with their own proprietary printable scattering type light extraction material. A “Dual Pixel” OLED substrate design was developed to allow for ILE and non-ILE pixels to be fabricated on the same substrate. The OLED pixels have an area of 1.5cm^2 in this design. The internal extraction layer (IEL) was printed according to the drawing shown in Figure 2. Also shown is a photograph of a printed ILE sample.

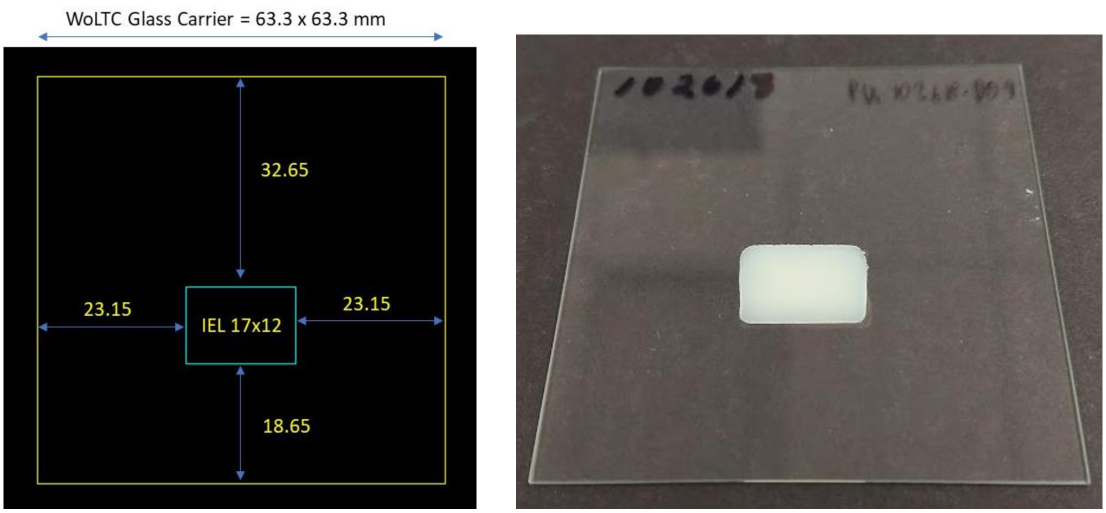


Figure 2. Dual pixel ILE design (left) and printed ILE pattern (right)

The transparent conductor (TC) was then applied to the samples. In the case of ITO, a shadowmask was used to pattern the ITO during the sputtering process. A simple mask design was created that allowed for 3 separate ITO electrical leads – one for the cathode contact, and 2 for the anode contacts to the 2 different OLEDs. The shadowmask (left) and an ITO substrate (right) are pictured in Figure 3 below. The ITO and ILE patterns are visible on the glass substrate to the right.

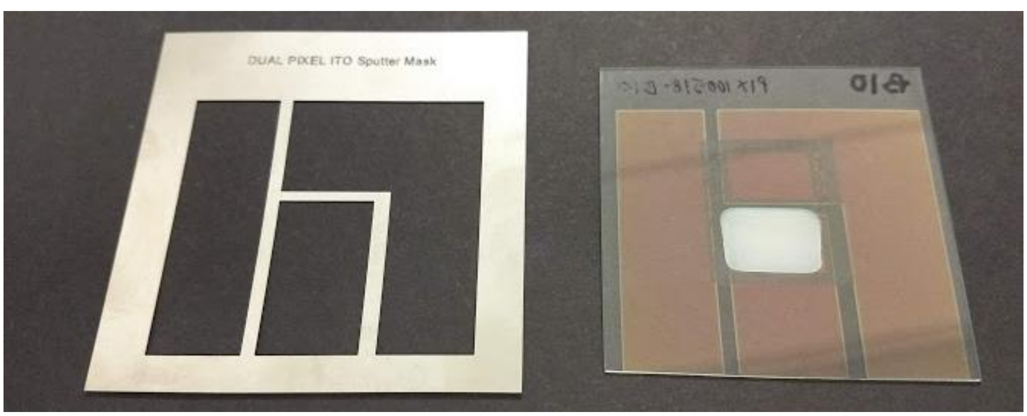


Figure 3. Dual pixel mask (left) and patterned substrate (right)

The ITO film is applied by a physical vapor deposition (PVD) DC sputtering process in vacuum. The substrate is pre-heated to 150C or less on a hotplate prior to loading into the sputter chamber and pulling vacuum. For an ITO film thickness of 110nm, typical sheet resistance is 20-30 ohms/square with > 88 %T in the visible region. Average roughness (Ra) as measured by AFM is typically < 5nm.

In the case of AgNWs, material in solution form was obtained from Cambrios Advanced Technologies. The solution was applied to the 2.5" glass samples by spin coating. The film was patterned using a laser. After application of the ITO or AgNW electrode, an insulator was printed onto the substrate by inkjet printing. The insulator was a soluble polyimide material that is cured at relatively low temperature of 120C after printing. The function of the insulator is to planarize the edges of the TC and to precisely define the OLED emitting area. The insulator pattern is faintly visible on the glass substrate in Figure 3. After curing and drying, the substrate is then ready for OLED fabrication. After depositing the OLED organics and cathode layers in vacuum, the substrate is then transferred to a nitrogen glovebox where it is encapsulated using a laminated getter film. A completed Dual Pixel OLED device is pictured in Figure 4. On the left side the device is unlit, and on the right side both OLED pixels are lit.

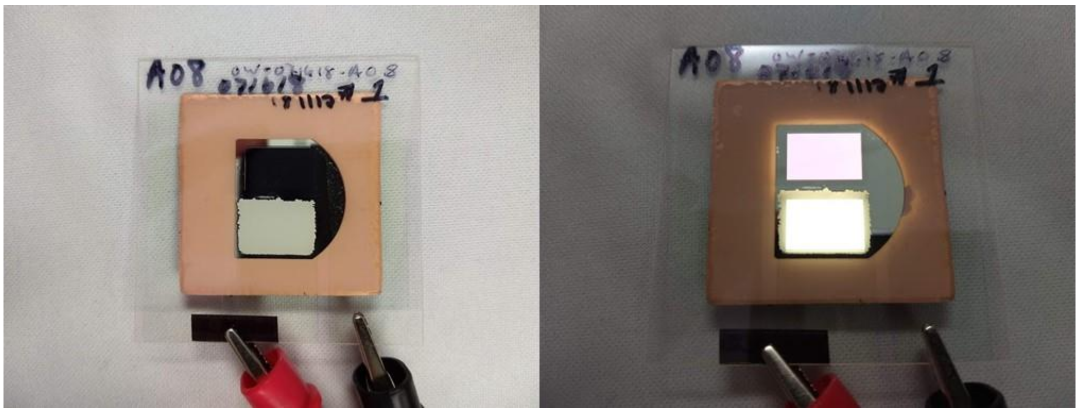


Figure 4. Dual pixel OLEDs, unlit (left) and lit (right)

Development of internal light extraction

In this project, we worked with four developers of internal light extraction materials. Two of the suppliers (Pixelligent and Corning) are developing their own proprietary versions of scattering type internal light extraction materials and structures. The ILE structure typically consists of 2 layers, a scattering layer and a high index planarization layer. The scattering layer typically contains large particles (~200-600nm) of a high index material such as TiO_2 dispersed in a polymer binder which could also have a high index of refraction. Figure 5 shows the Pixelligent ILE structure with high index nanocrystals with distributed scattering particles.

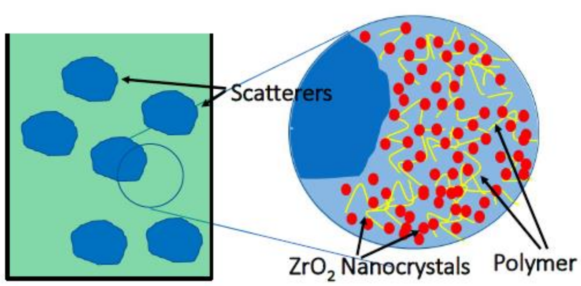


Figure 5. Pixelligent scattering ILE

The planarization layer contains much smaller particles (~5-10nm) of a high index material such as ZrO_2 or TiO_2. The planarization layer acts as a smoothing layer over the rough scattering layer, and optically couples the higher index anode and OLED layers to the scattering layer. Both ILE suppliers used inkjet printing to directly print the ILE material onto the substrate. This method is desirable from a cost perspective since it is easy to scale, and it has high material utilization as little material is wasted. The specific material composition and formulations were not shared since this is considered proprietary information by the suppliers. Figure 6 shows images of completed Dual Pixel substrates. The inkjet-printed internal extraction layers are visible, with the Pixelligent substrate on the left and the Corning substrate on the right.

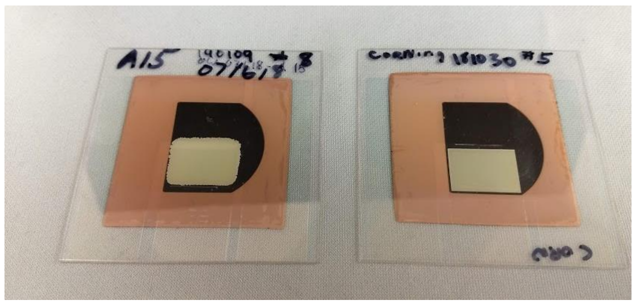
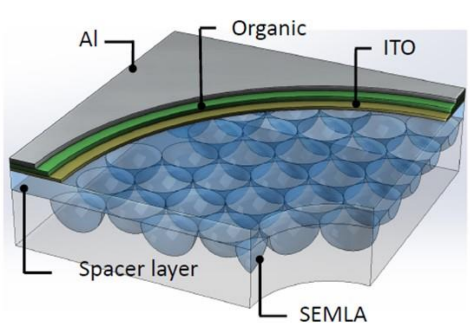


Figure 6. Dual pixel devices

We also worked with two universities that have been awarded DOE grants to develop internal light extraction technologies for OLED lighting. North Carolina State University (Profs. Franky So and Chi-Hao Chang) is developing corrugated type internal light extraction structures to enhance OLED light outcoupling as shown in Figure 7b. The University of Michigan (Prof. Steven Forrest) is also developing internal light extraction structures based on buried sub electrode micro lens arrays (SEMLA) as seen in Figure 7a. Both outcoupling structures are designed to disrupt the internal waveguiding of light through the high index organic and ITO layers, as well as minimize plasmonic absorption that occurs at the organic-metal interface. The buried microlens arrays are intended to allow the light to quickly escape into the glass substrate without scattering. In both cases an external light extraction layer such as a microlens array film attached to the opposite side of the glass will help to outcouple the substrate mode light.

(a)



(b)

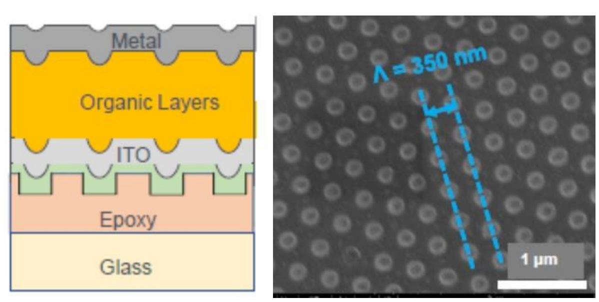


Figure 7. (a) SEMLA, (b) Photonic crystal corrugation

Several 3-stack white OLED runs were fabricated using the Dual Pixel format to test variations in the ILE. The haze level of the ILE was varied by adjusting the loading of the scattering particles in the solution. In general, we observed higher overall light output as the haze level was increased. Maximum external quantum efficiency (EQE) of 105% was observed at 80% haze level as seen in Figure 8. For a 3-stack hybrid white OLED using 2 phosphorescent (PH) red-green stacks and one fluorescent (FL) blue stack, the internal quantum efficiency (IQE) is 205% assuming 90% for each PH stack and 25% for the FL stack. The overall light extraction efficiency (EQE/IQE) is then 51% (105/205). In Figure 8, higher EQE is also observed when the binder material has a higher refractive index of 1.77 versus 1.6.

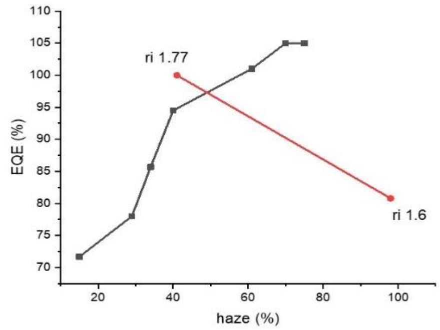


Figure 8. EQE as a function of haze and binder RI

The initial efficacy target was 90 lm/W for a 3-stack white OLED with ITO anode and printed ILE. We were able to achieve this target with ILEs from both suppliers of scattering ILEs. The charts in Figure 9 plot the efficacy as a function of luminance for both ILE types A and B. The efficacy of the ITO control is only in the range of 20-30 lm/W since the white color was not optimized for this case without light extraction. The color ends up pinkish white (lacking green) which lowers the luminance. As a result, we see more than a 3X increase in efficacy when using ILE. By itself, ILE B shows lower extraction efficiency but when combined with an external extraction layer (EEL), the overall efficacy is the same for both ILEs. This can be explained by the lower haze level for ILE B (~75%) compared to ILE A (~85%). More light is likely trapped in the glass substrate for ILE B, which can then be extracted using a scattering type EEL.

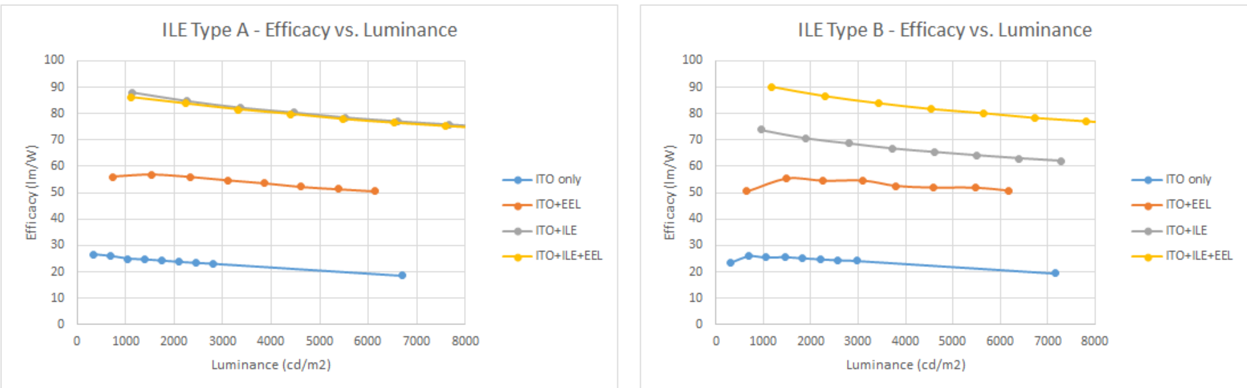


Figure 9. Efficacy as a function of luminance for scattering ILEs

To better estimate the light extraction gain, the EQE is often used since this metric is not affected by the white color unlike the luminance efficiency metrics. The efficacy (lm/W) is also a function of the drive voltage of the OLED. The charts in Figure 10 show the EQE as a function of luminance for both ILEs. We see a similar result in that ILE B has lower EQE by itself, but with the addition of an EEL the maximum EQE is the same or slightly better than ILE A.

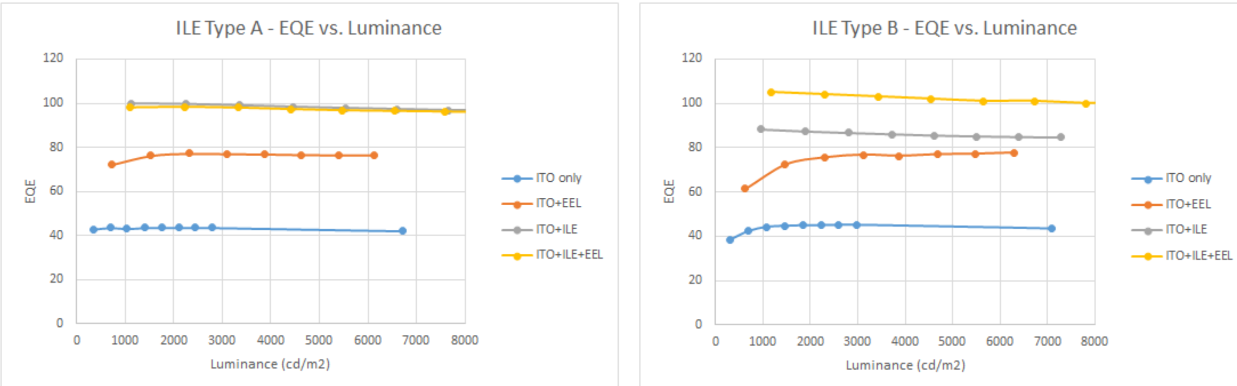


Figure 10. EQE as a function of luminance for scattering ILEs

The EQE gain for both ILEs in summarized in Table 1. Compared to the ITO control, both ILEs achieved a maximum gain of 2.3X. Since ILE A is highly scattering, it does not benefit further from the addition of an EEL film. This could be an advantage to reduce the overall cost of the OLED panel.

Table 1. EQE gain for scattering type ILEs

EQE gain	ILE A	ILE B
ITO only	1.0	1.0
ITO+EEL	1.8	1.7
ITO+ILE	2.3	2.0
ITO+ILE+EEL	2.3	2.3

The EL spectra for the white OLEDs made with ILE B are shown in the chart in Figure 11. The ITO control device tends to waveguide more green light than other wavelengths. The light waveguided in the substrate, anode, and organic layers can be extracted using internal and external scattering layers. Therefore, it appears that the highest extraction efficiency is in the green wavelengths, followed by red and blue. The blue wavelengths tend to suffer the most from absorption, which can occur in the ITO, ILE, and even the glass substrate and organic layers. Each time the light is scattered, a small portion will be absorbed and lost.

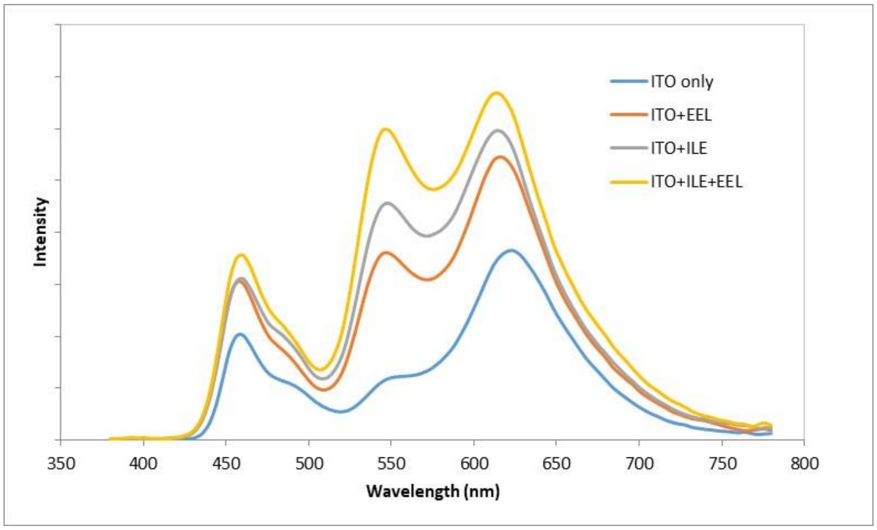


Figure 11. EL spectra for ILE B

The performance for 3-stack white OLEDs made on the SEMLA ILE is shown in the charts in Figure 12. The EQE reached as high as 110% with a microlens EEL film, with 85 lm/W efficacy at 1000 nits. The efficacy would be higher if the white color was tuned slightly more green; the color in this case was a CCT of 2850K with a Duv of -0.008. The SEMLA type ILE did not work as well with a scattering type EEL film, reaching an EQE of 95% (data not shown).

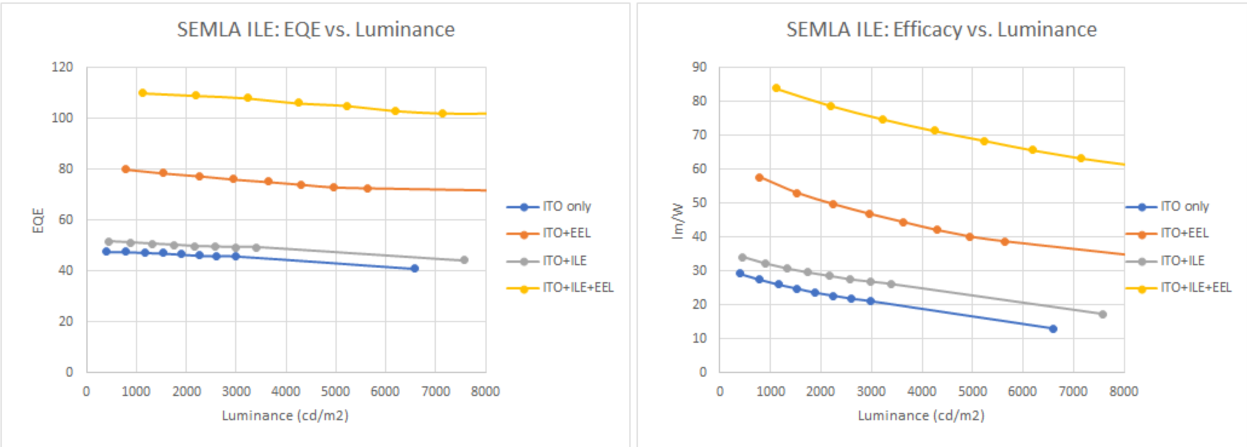


Figure 12. EQE and Efficacy as a function of luminance for SEMLA ILE

The performance for the best device made on the corrugated type ILE is shown in Figure 13. The EQE was approaching 100% with efficacy below 70 lm/W. The voltage was a little high on this device and the color was also below the blackbody, which both contribute to lower efficacy. Only a few devices were fabricated on the corrugated type ILE, with several devices having high leakage current. It is uncertain if this was the result of the rough corrugated surface or just particles or printing defects. Further assessment of this type ILE is required.

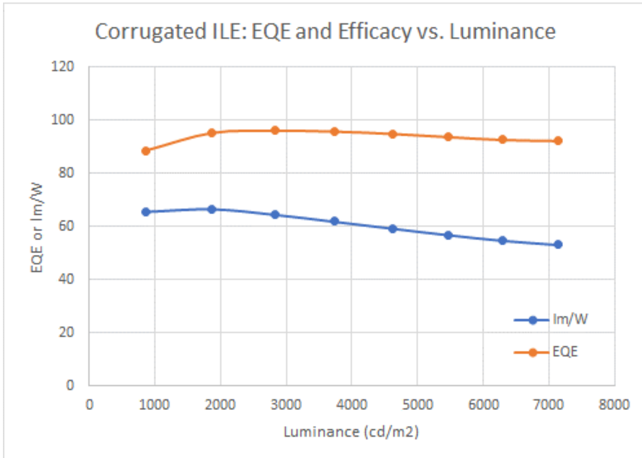


Figure 13. EQE and Efficacy as a function of luminance for corrugated ILE

Development of silver nanowire electrode

The silver nanowire (AgNW) ink was obtained from Cambrios Advanced Materials. The material (ClearOhm Ink-N G4-4x) was specifically developed for OLED applications. It is typically applied by spin coating on smaller substrate sizes, or by slot die coating on large substrates using roll-to-roll processes, such as those used in the manufacture of touch screen films. Some research has been done to demonstrate printability of the AgNWs using inkjet printing[5], however an inkjet compatible version of the ink is not commercially available at this time due to lack of demand. Cambrios has demonstrated several methods for patterning the AgNW films, such as photolithography, laser, inkjet, and screen printing[6]. A linewidth of 50um could be achieved by inkjet printing, and a linewidth of 280um could be achieved by screen printing.

For our development work on small substrates, a spin coating process was used to apply the AgNWs to the glass substrate. Spin speed was varied to adjust the density of AgNWs in the film. Sheet resistance and transmittance of the film were measured and plotted in Figure 14. At higher spin speeds, transmittance and sheet resistance both increase due to lower density of AgNWs in the film. At lower spin speeds, transmittance and sheet resistance both decrease. We achieved <10 ohms/square sheet resistance and >90 %T at a typical spin speed of 1000 rpm. This was the typical condition used for fabrication of the OLED devices with AgNW anodes.

[5] Maisch et al., "Inkjet Printing of Semitransparent Electrodes for Photovoltaic Applications", Proc. SPIE 9942, 2016.
[6] Dai H. and Spaid M., "Silver Nanowire Transparent Conductive Films for Flexible/Foldable Displays", SID Digest p.397, 2018

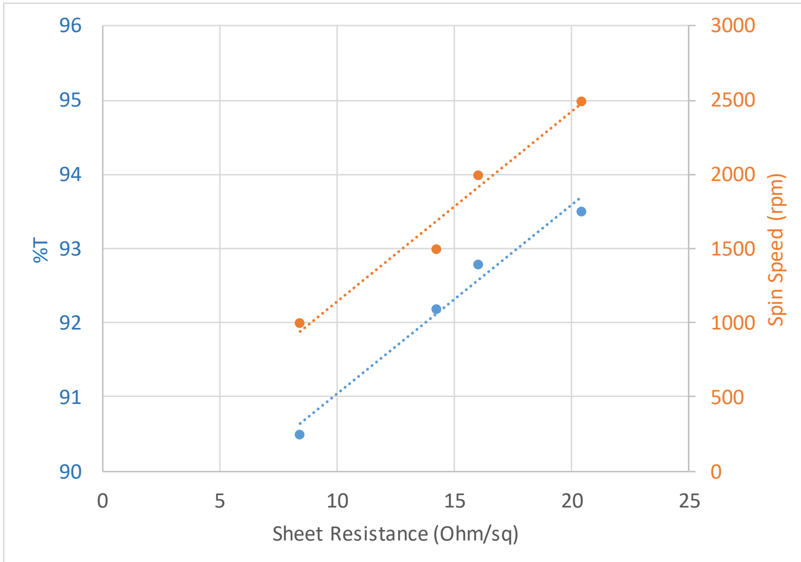


Figure 14. Effect of %T and spin speed on sheet resistance for AgNW coatings

After spin-coating, the AgNW film was dried using a low temperature 50C oven bake for 90 seconds, followed by a 140C soft bake on a hotplate for 90 seconds. The film was then patterned using a laser. Initially, coated glass samples were sent to a vendor (Laserod) for patterning using an IR or green laser. Later, samples were patterned in house using a UV laser. Figure 15 shows microscopic images of AgNW films patterned using a 355nm UV laser. The film could easily be ablated or modified to make it electrically isolated using a UV laser.

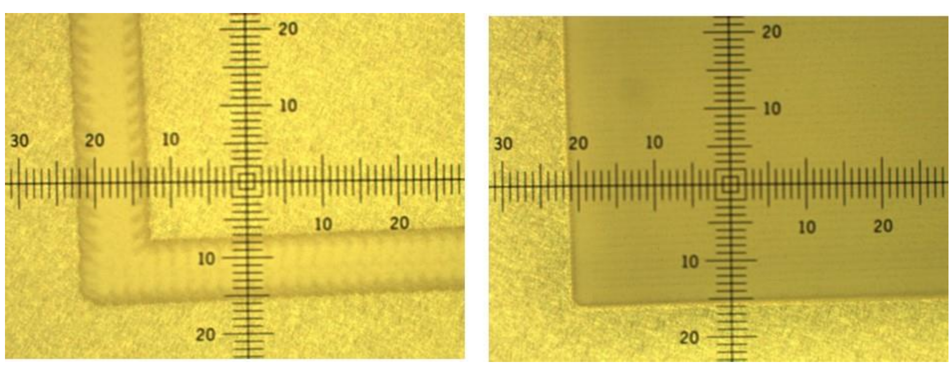


Figure 15. Laser pattern AgNW coating

After inkjet printing the insulator pattern, 3-stack white OLED devices were fabricated on the AgNW anodes using a typical hybrid white structure. The device performance is summarized in Table 3 as measured normal to the device at 2 mA/cm^2.

Table 3. White OLED performance comparison on ITO vs. AgNWs

Metric	ITO	ITO+EEL	AgNW	AgNW+EEL
Voltage (V)	9.0	9.0	8.8	8.8
Efficiency (cd/A)	73.6	155.0	96.1	152.0
EQE (%p/e)	44.6	76.2	51.8	77.8
Efficacy (lm/W)	25.4	53.5	34.2	54.0

Without any light extraction, the AgNW device has higher efficiency than the ITO device. The EQE is 16% higher and the efficacy is 35% higher. However, with the addition of an EEL film, the EQE and efficacy are essentially the same. The spectra for the same 3-stack white OLEDs are shown in Figure 16. Although the AgNW devices have higher efficiency than the ITO devices without EEL, the spectra are almost identical for ITO and AgNW devices with EEL.

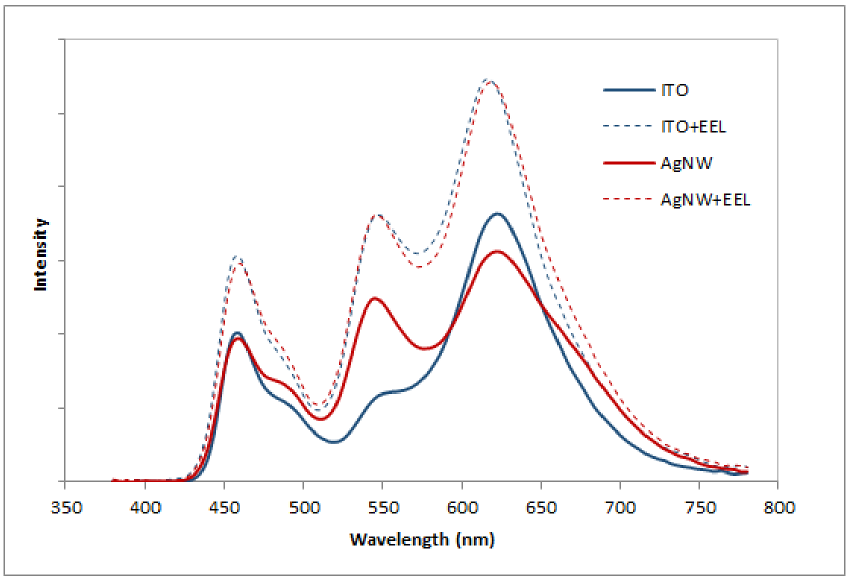


Figure 16. EL spectra for ITO and AgNW OLEDs

The same 3-stack white OLEDs were characterized for angular color change. The spectra as a function of angle are plotted in Figure 17. Because of the scattering nature of the AgNWs, there is less apparent color change as a function of angle for the AgNW devices without light extraction.

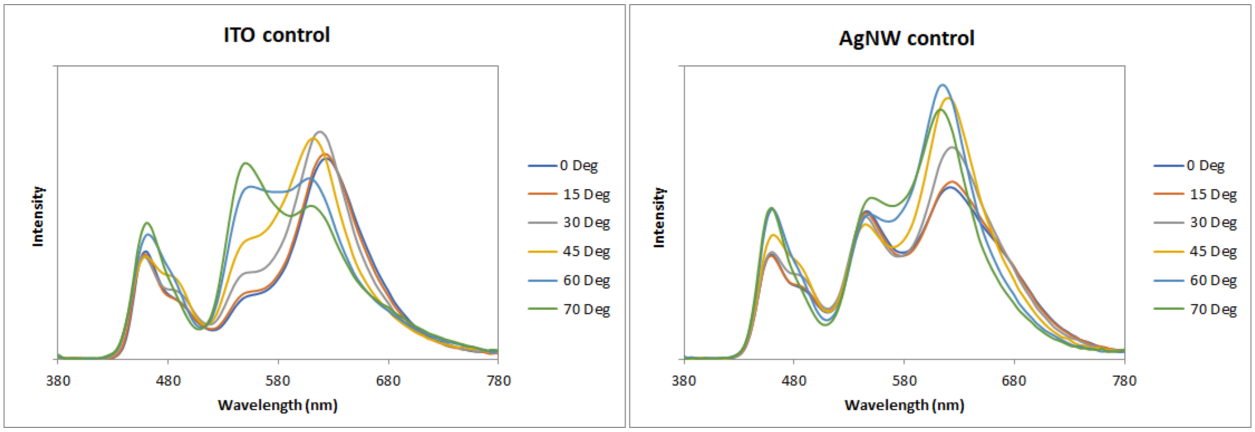


Figure 17. EL spectra vs. angle (no light extraction)

Figure 18 shows the spectra as a function of angle for the same white OLEDs with the addition of a scattering type EEL film. In both cases, the EEL strongly scatters the light such that there is no observable color change with angle for either ITO or AgNW anodes. The same is true in the presence of an internal scattering layer, with or without the EEL.

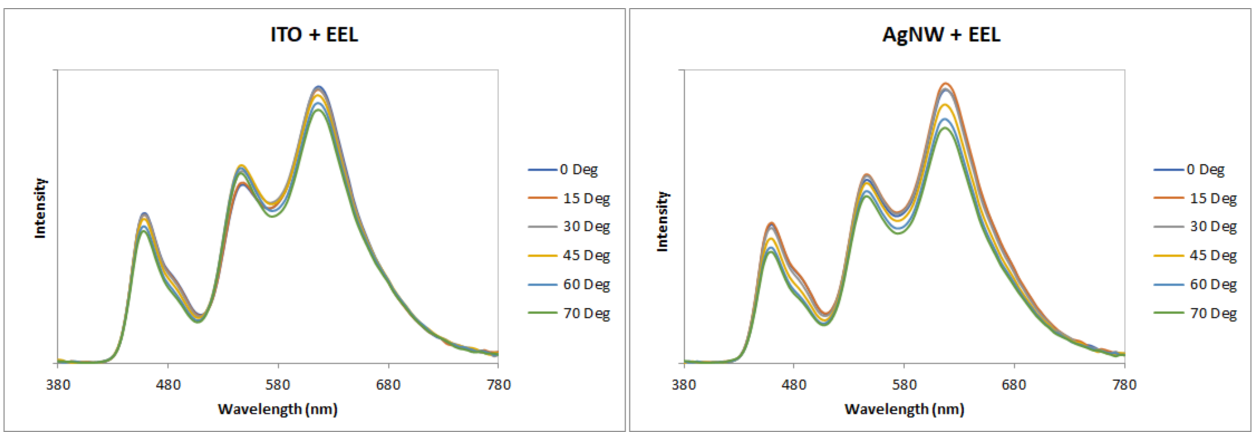


Figure 18. EL spectra vs. angle (with EEL)

It was found to be difficult to make functional OLEDs with AgNWs coated over the printable ILE. Many devices were made that were either electrically shorted or had varying degrees of current leakage. In some cases, we could attribute the failures to the laser patterning of the AgNW coating over the ILE, where the laser damage extended into the ILE layer. Although the laser patterned edges were planarized with the insulator layer, there could have been additional particles and debris created from laser damage to the ILE.

Despite the challenges, we made several good functional 3-stack white OLED devices with AgNW anodes over printable ILE. The device performance for ITO and AgNW devices from the same run is summarized at a luminance of 3000 cd/m^2 in Table 4. These devices have both ILE and

EEL. The AgNW device has higher EQE than the ITO device, but it has slightly lower efficacy since the white spectrum has lower green content.

Table 4. Performance of best ITO and AgNW white OLEDs with ILE and EEL

Metric	ITO	AgNW
Voltage (V)	8.7	8.8
Efficiency (cd/A)	236.0	227.0
EQE (%p/e)	107.0	113.0
Efficacy (lm/W)	85.6	81.0

This can be seen in the spectral plots in Figure 19. The white spectrum of the AgNW is well balanced with higher outcoupling in the red wavelengths and achieves a CCT of 3000K with a Duv of -0.004 and a CRI of 92 with R9 of 63. The ITO device has a CCT of 3300K with a Duv of +0.004 and a CRI of 82 with R9 of 33.

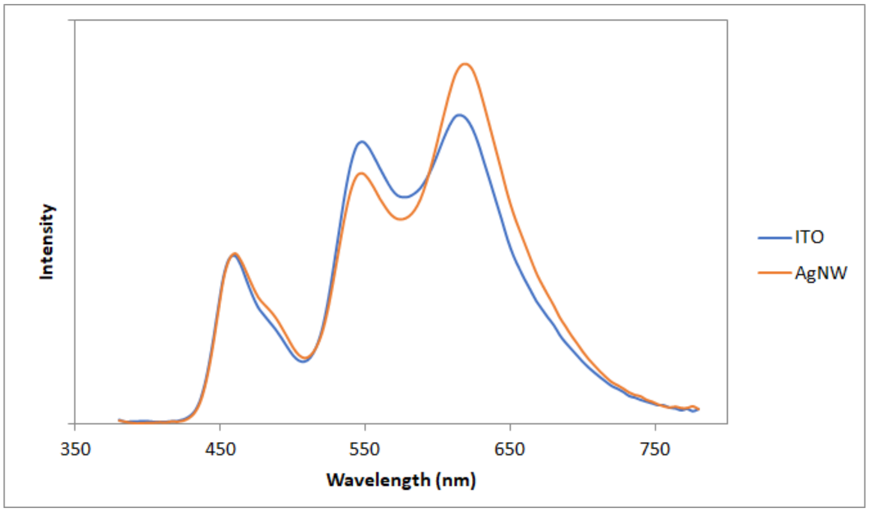


Figure 19. EL spectra for best ITO and AgNW white OLEDs

For the same devices, the EQE and efficacy as a function of luminance are plotted in Figure 20. The EQE is higher for the AgNW device. At 1000 cd/m^2, we achieved an efficacy of 92 lm/W for the ITO device and 85 lm/W for the AgNW device.

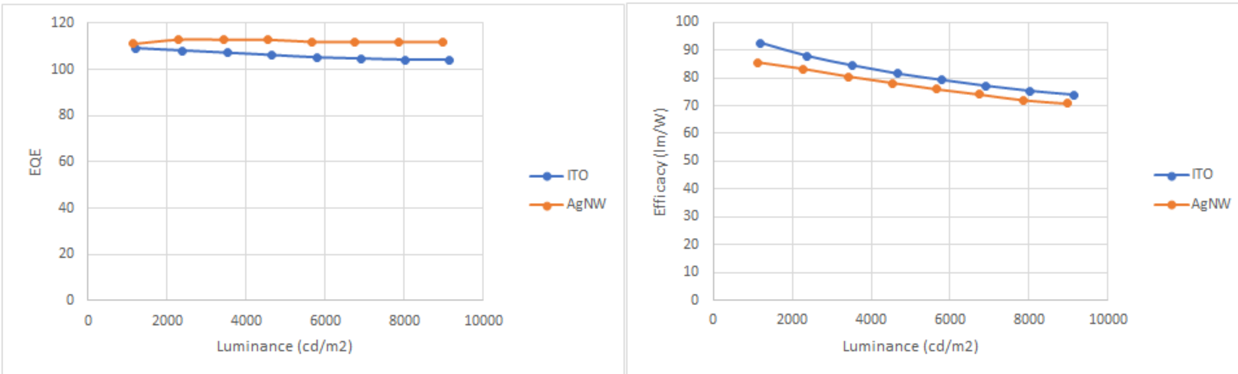


Figure 20. EQE and efficacy as a function of luminance for ITO and AgNW white OLEDs

Table 5 shows the EQE and the light extraction gain for both the ITO and AgNW devices. The gain is calculated as the EQE of the device with light extraction divided by the EQE of the control device without any light extraction ("None"). The ITO device sees higher gains in all cases. The AgNW device with ILE+EEL sees a 2.0X gain compared to 2.3X for the ITO device with ILE+EEL. However, as discussed earlier the AgNW control device starts at a 20% higher efficiency due to some scattering effect from the nanowires. In the end, the AgNW device achieves similar or better EQE with a better white spectrum than the ITO device.

Table 5. EQE gain for best ITO and AgNW white OLEDs

Type	ITO	Gain	AgNW	Gain
None	46.6	1.0	56.6	1.0
EEL only	78.8	1.7	86.2	1.5
ILE only	90.5	1.9	98.3	1.7
ILE+EEL	107.0	2.3	113.0	2.0

It is encouraging that we can achieve similar performance between standard ITO and AgNW anodes combined with printable ILE. With further work and optimization, we believe that we can achieve greater than 100 lm/W with a hybrid 3-stack white approach.

Development of stacked white OLED structure

The final task for the Phase I project was to develop higher performance stacked white OLED structures, including the development of an all-phosphorescent white structure. Theoretically, this could boost the EQE by 33% by replacing the inefficient FL blue stack with PH blue. In the current hybrid white stack as shown in Figure 21, we typically achieve 45% EQE without any light extraction (20% EQE for each PH stack and 5% EQE for the FL blue stack), which equates to an average EQE of 15% per stack. The all-phosphorescent approach would achieve 20% EQE per stack, which is 33% higher than the hybrid approach. This would be true for a 2-stack or 3-stack all-phosphorescent white OLED. It is believed that acceptable lifetime can be achieved with the multi-stack approach, where the lifetime can be increased by adding more stacks to allow the device to be operated at a lower current and still achieve the target brightness.

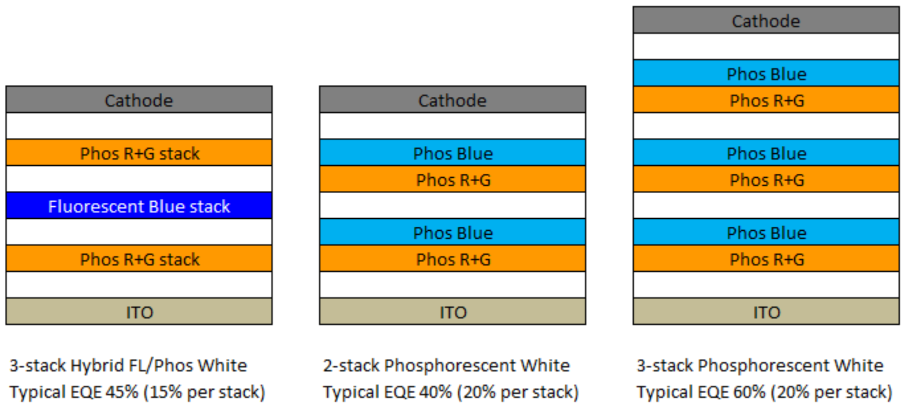


Figure 21. Hybrid and all-phosphorescent stacked white OLED structures

Work started with development of a single-stack PH white OLED. Since the PH blue materials do not have good enough lifetime as a standalone stack, it is necessary to place the PH blue emission layer (EML) adjacent to a PH red-green EML to create a combined white-emitting stack. This approach can stabilize the white emission and can result in acceptable color change over the life of the white OLED. By optimizing the PH white architecture, we were able to achieve a high efficiency of 20.7% EQE with a very good white color of 3000K, at a low voltage of 4.2V. The EL spectrum is plotted in Figure 22 below. Shown in the inset figures is the device performance at 1000 nits, and the simplified stack diagram.

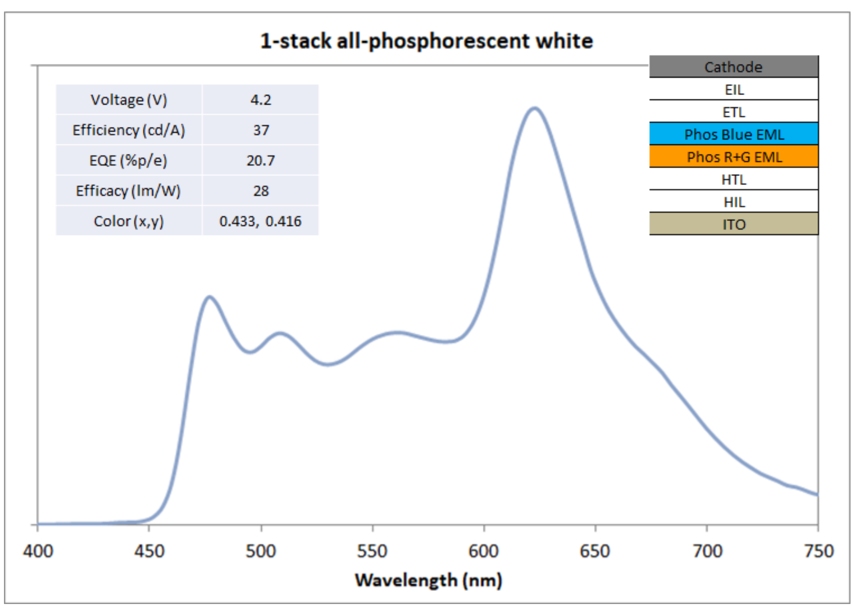


Figure 22. EL spectrum and performance of 1-stack phosphorescent white OLED

A 2-stack version of the PH white OLED was developed on ITO anodes. The performance of the devices at 3000 cd/m^2 with various types of light extraction is shown in Table 6. The ILE in this case is a scattering type ILE with a microlens type EEL. The EQE gain for the ILE+EEL device is 2.1X compared to the device with no light extraction. The ILE+EEL device reaches an efficacy of 63.6 lm/W at 3000 nits, and 75.7 lm/W at 1000 nits.

Table 6. Performance for 2-stack PH white OLEDs at 3000 nits

Type	lm/W	EQE	EQE Gain
None	28.9	38.6	1.0
EEL only	43.9	59.1	1.5
ILE only	52.2	67.6	1.8
ILE+EEL	63.6	80.9	2.1

The EL spectra for the same 2-stack PH white OLED devices is shown in Figure 23. The outcoupling enhancement is seen across the visible spectrum. The ILE+EEL device achieves a CCT of 3000K with a Duv of +0.008. Further optimization of the multi-stack phosphorescent white OLEDs is required to achieve more accurate white color with higher efficacy.

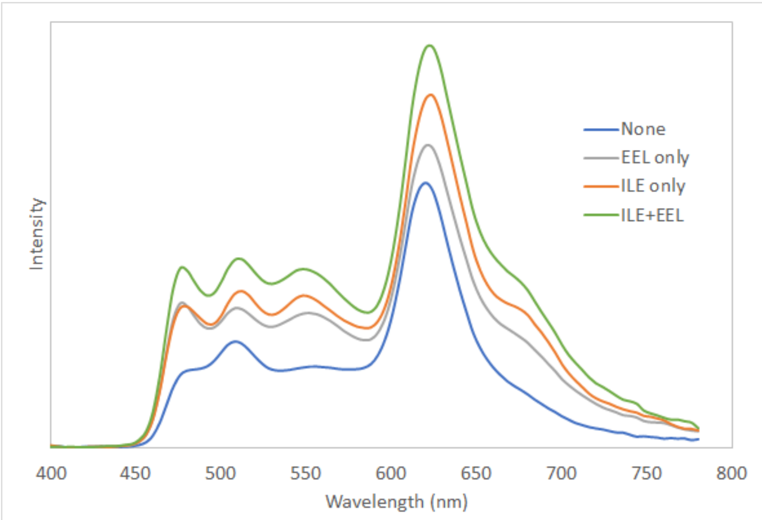


Figure 23. EL spectra of stacked PH white OLEDs

A final efficacy of 100 lm/W was targeted for this Phase I project. Although we demonstrated good performance for 1-stack and 2-stack PH white OLEDs, we were not able to further develop multi-stack PH whites during the short timeframe for the Phase I project. As a result, we did not have time to combine the highest efficiency PH white OLEDs with the printed ILE and transparent AgNW anode where we expected to exceed 100 lm/W. However, we successfully demonstrated an efficacy of 90 lm/W using the hybrid stacked white OLEDs, and we demonstrated that we could increase the EQE per stack from 15% to 20% (with no light extraction) by going to a phosphorescent white stack. Further work is required to reduce the voltage of the all-phosphorescent white stack to realize the full potential and achieve the highest efficacy. Voltage must be reduced from ~4V to ~3V per stack and greater light outcoupling must be accomplished.

If a Phase II project is awarded, higher performance internal light extraction and white OLED technology will be further developed, and a panel efficacy of 120 lm/W will be targeted.

IV. CONCLUSIONS

For the OLED lighting industry to become a significant part of the SSL market, innovative OLED lights must become widely available in both the commercial market and the consumer market. By offering high efficacy bendable OLED lighting panels at an affordable price, this will bring more high-quality OLED light into people's lives, and demand for OLED lighting in both commercial and consumer channels will grow from this. The key attributes to unlocking the OLED lighting market are:

1. High enough efficacy to close the gap with LED
2. Low enough fully assembled fixture costs to close the gap with LED
3. Unique, ultra-thin, curved products that cannot be made using LED technology

This project began the process of addressing these key attributes through the development of the technology required for a proof of principle ultra-thin, high-efficacy bendable OLED lighting panel. We successfully demonstrated that high efficacy white OLEDs could be produced using potentially low-cost components for the transparent anode and light extraction layers on a bendable glass substrate.

V. RECOMMENDATIONS

We recommend that learnings in demonstrating the proof of principle high efficacy bendable OLED of Phase I be applied to the work in Phase II to bring to market a fully commercialized ultra-thin, curved, high efficacy OLED lighting panel. Although the Phase I technology nearly met the goals set forth in the Phase I project, further improvements are needed to further increase the efficacy and to develop scaled-up processes for producing the printable ILE and silver nanowire transparent anodes on bendable glass. The improvements needed in the Phase II project include:

1. Higher efficacy to close the gap with LED lighting. Current commercially available bendable OLED light panels have an efficacy of 60 lm/W, which is significantly lower than current state-of-the-art rigid OLED panel efficacy of 85 lm/W. This is due to the lack of an internal light extraction layer in the bendable panel. In Phase II we need to introduce an internal light extraction layer on the Willow glass to close the efficacy gap with LED and break the magical 100 lm/W barrier for OLEDs.

2. Larger bendable OLED panels to deliver more lumens per light engine and close the gap with LED on cost per lumens. The current 300 lm/panel will result in a non-competitive product cost. Larger panels that can deliver 600 lm/panel are needed in Phase II.
3. Demonstration of the scalability and reliability of printable ILE and AgNW technology and assessment of the potential for cost reduction over current state-of-the-art.

If all of these improvements can be accomplished in Phase II, the size of the lighting market that will be available to OLED lighting will drastically increase beyond the high-end niche market of today into the main stream commercial and consumer markets, there-by achieving the promise predicted by the DOE for a mixture of LED and OLED solid state lighting that will significantly reduce energy consumption for lighting while simultaneously improving the quality and wellness of lighting around the world.

VI. ACKNOWLEDGEMENTS

We would like to acknowledge the support of the following companies and individuals.
Without their dedicated contributions, this work would not have been possible.

Corning Inc. for their support in Willow™ glass development and processing, and work on internal light extraction technology.

Pixelligent Technologies LLC, for their support in developing internal light extraction materials and technology.

Cambrios Advanced Technologies for their technical guidance in development of silver nanowire materials for OLED lighting applications.

Professor Steven Forrest at the University of Michigan

Professors Franky So and Chi-Hao Chang at North Carolina State University

Members of the OLEDWorks team who contributed many hours of work to this project:

Ray Kesel

Jeff Spindler

Mike Andre

Dan Arnold

Marina Kondakova

Bernadette Thomson

Michael Boroson