Ultra-Thin Surface Light Sources: Picking Up Where OLED Stalled

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1. **Objective**

This paper explores the current state of the art of OLED lighting technology covering design and manufacture, product benefits and commercialisation. The analysis continues by studying the innovative, patent-pending LED technology developed by the author, Matt Hanbury, at Lightly Technologies to solve the key limitations of OLED while maintaining the desirable characteristics of the technology.

2. **The State of OLED Lighting Technology**

Back in 2012, as LED lighting was starting to gain mainstream traction in the lighting industry, OLED (Organic Light-Emitting Diode) technology emerged as a complimentary advanced light source. In contrast to the high-intensity, point light source of LEDs, OLED modules produce a native surface light source which, among many applications, makes them suitable for diffuse, low-glare general lighting applications.

Leading development into OLED lighting technology were the major global light source manufacturers notably Philips, Osram and LG Display, with many other blue-chip firms developing OLED technology for smartphone and TV display applications.

Despite the significant commercial opportunities for OLED lighting, by 2017 Philips and Osram had divested their OLED R&D business units leaving LG Display as the remaining major player in the space. This was due to the fact that despite a collective industry investment of almost $500m, the technology had not matured to a level where it was even approaching commercial viability.

The core factors for the technology not achieving commercial viability are: 1) high production costs, 2) inferior performance compared to LED technology. These problems compound each other, to the extent that the cost per lumen is an order of magnitude greater than LED technology, and the benefits of the the OLED lighting cannot warrant this premium.

This report explores the root causes and implications of the current OLED performance.

2.1. **Fundamentals of OLED Lighting**

There are a range of OLED lighting technologies, materials, and manufacturing processes across companies and a product generations. This is beyond the scope of this report which will focus on the Philips FL300 generation which is now owned by OLEDworks. The author, Matt Hanbury, worked as a Mechanical Engineer on this product generation while on secondment to Philips OLED R&D facility in Aachen, Germany for 8 months in 2013.

As the name Organic Light-Emitting Diode implies, the fundamental physics behind the creation of photons of visible light is through a diode structure, in a similar way to a conventional LED. When a potential difference is applied over the anode and cathode of the OLED module, free electron and electron hole recombination results in a raised electron energy level. When the electron then falls back to a stable energy level a photon of light in the visible spectrum is emitted.

The material difference of the diode junction between OLEDs and LEDs is that while LEDs use silicon-based inorganic crystal substrates, OLEDs use organic (complex hydrocarbon) molecules that have electroluminescent properties.

The other major difference compared to LEDs is the design architecture of OLEDs. For OLED modules, the substrate is a glass or plastic coated with layer of transparent electrically conductive material, typically Indium Tin Oxide (ITO) which acts as the Anode. This is followed by a number of layers of the electroluminescent OLED compounds as well as carrier layers for free electrons and electron holes. The cathode is typically a metal layer such as aluminium which also serves as a reflective back film to maximise light extraction from the module.

The active layers of the OLED module including the anode and cathode are typically under 100um thick, while the OLED compounds are less than 1um, on the nanometre scale. These layers are encapsulated by the substrate on the anode side by glass or plastic at less than 1mm thickness and a thin-film plastic encapsulation on the cathode side to prevent oxygen and water contamination of the active layers. Finally a protective housing is typically added for improved robustness and thermal management, giving a final module thickness of around 3mm.

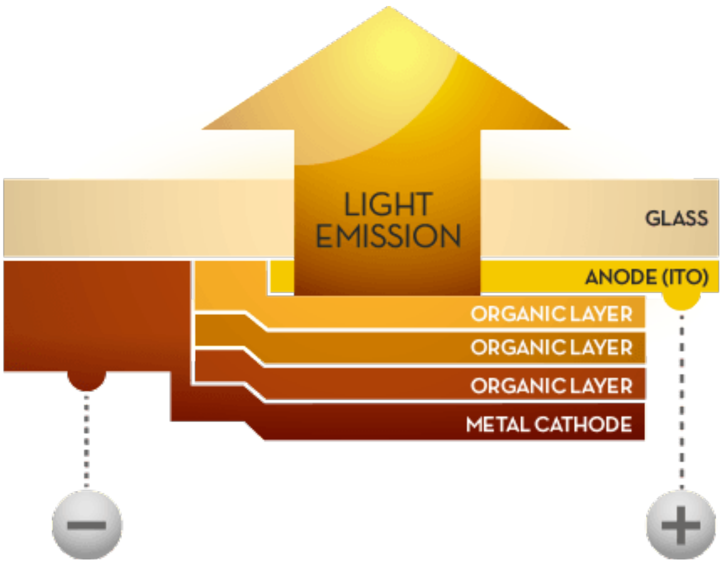

Figure 1: OLED Design Schematic from www.OLEDworks.com

2.2. Challenges in OLED Manufacture & Mass Production

The main challenge of manufacture of OLED modules are due to the precise nanometre scale application of the active layers. Essentially, the difficulty of applying a uniform layer of material at the nanometre scale thickness, over an area at the 100 millimetre scale. This is equivalent to painting a uniform 1mm layer of paint over a wall 1km squared! This difference of 6 orders of magnitude needs to be done for each of the ~8 active layers.

The manufacture process involves a technique called "vapour deposition" where the individual OLED molecules are essentially sprayed onto the substrate. This has to be done in near-vacuum conditions to prevent oxidation or contamination, within a different chamber for each material and with a curing step in between each layer. As a result, the cost of an OLED module production line is over €20m.

The final stage of the process is that of the thin-film encapsulation which prevents oxidisation and reactions with moisture in the air. Creating a robust, air tight seal over the OLED layers without damaging the compounds is a highly complex process.

In addition to the high cost of the production line required to fabricate OLED modules, there are several other factors that lead to the very high cost of the OLED units.

The materials used in production are expensive, from the high grade optical glass substrate, the purity of the electrodes to the high cost of the newly developed OLED electroluminescent compounds.

The final factor in the high unit cost is due to the low yield of the manufacturing process. Even with advanced manufacturing equipment there is a high proportion of OLED units produced that fail the quality control testing. There are many causes of this including: black spots (due to oxidisation & contamination), uniformity issues and colour consistency. The costs of these discarded OLED modules are borne by the final cost to the customer of useable units.

2.3. **Limitations of Current OLED Technology**

While the manufacturing complexities contribute to the high unit cost of OLED modules, there are major issues with the optical performance of OLED technology which have prevented the technology adoption within the lighting industry.

The three main performance limitations are in: 1) light output per cm^2, 2) lifetime, 3) efficacy in lm/W.

For light output per cm^2 there is a compromise between producing functional quantity of light and minimising glare from direct view applications (which is a native benefit of OLED lighting) and this includes the beam angle and photometry of the light source. Philips addressed this successfully by producing the FL300 OLED module at 300lm output. This enabled a functional quantity of light, but at the compromise of another OLED limitation, lifetime.

The FL300 module can run at 300lm for only 10,000hours, this is in comparison to LED technology where the minimum expected luminaire lifetime is 50,000hrs. Further to this, not only would the light output decrease to 70% (L70B50) but there would be a CCT colour shift over time, typically from the faster degradation of the blue spectrum OLED compounds with respect to the red and green compounds.

The efficacy of OLED modules is also less than that of LED technology, even with the benefits of not requiring additional optics to create a uniform, surface light source. The OLEDworks (previously Philips) FL300 achieves 57lm/W at 300lm, exceeded only by the LG Display OLED module at 90lm/W but at only 75lm output for the same size which makes it unsuitable for functional lighting applications. This is in comparison to general lighting LED luminaries which are now typically over 100lm/W.

As the technology emerged after LED, OLED has constantly been trying to catch up with the annually performance advances of LED technology. The major problem here is that technological advancement is dependant on investment, and with the ever increasing delta between LED and OLED performance, the is commercial traction with LED has led to a runaway effect where investment into LED technology is far more profitable. As a result, investment into OLED lighting has decreased and the technology has plateaued at a point where it appears it will never advance to be competitive with LED.

2.4. **Benefits of OLED and Surface Light Sources**

Excluding the performance issues, OLED lighting appears to have several benefits over LEDs for the design of luminaires. The main benefit is in the native surface light source produced which is ideal for general lighting applications. The surface light emitted decreases the apparent luminance of the light source and results in lower glare, reduced shadowing and a perception of a softer lit effect.

The other main benefit is in the ultra-thin profile of the OLED module. This enables unique designs of luminaires and allows for example the appearance of a recessed fixture when in fact the luminaire is surface mounted. This benefit extends to applications such as automotive and aerospace application where a reduced volume and mass is valuable.

Continued development in OLED modules also enabled several unique features including, mirror reflective in the off state, transparent in the off state and flexible surfaces. These features were particularly beneficial in decorative luminaire applications.

It has become clear over the last few years that OLED lighting is not likely to mature to a point where the optical performance is competitive with LED, so these unique decorative features have become the main focus of further product development and R&D.

2.5. **Commercial Traction of OLED Lighting**

With the focus on the unique, decorative features of OLED lighting, the industry has moved towards art installations and prestige luminaires where the performance is a less critical consideration than the visual impact and exceptional design that OLED enables.

This was the original positioning of OLED technology when it came to market in 2012, but then with the intention of enabling mainstream adoption as the price decreased and performance improved. As these improvements have not been realised, the positioning has remained the same, but there has been a marked decrease in OLED installations and concept luminaires as this is no longer perceived as a viable future lighting technology.

3. Development of Ultra-Thin LED Surface Light Sources

As a mechanical engineer, I have spent my career working on LED & OLED technologies at Philips Lighting, and in LCD displays technologies at Apple Inc on the iPhone 6S. These have brought together two passions of mine within engineering, the combination of emerging technologies and elegant product design, together providing value beyond functionality.

I left Apple Inc in December 2015 and moved to Ireland, I was considering my next career move and explored the option of starting an engineering company. It was then I conceptualised bringing together the opportunities created by OLED lighting combined with an alternate technology, used in LCD backlighting in smartphones. The aim was to solve the core problems with OLED modules while maintaining the benefits of the design freedom it enabled.

3.1. **Formation of Lightly Technologies**

I started concept development and research into ultra-thin LED surface light sources in January 2016. I found there was a market opportunity as only OLED modules were positioned as a surface light source component for luminaires, and I knew from experience the limitations of this technology.

I developed early engineering proof-of-concept prototypes using 3D printing techniques and off-the-shelf components and then set about creating an LED product architecture using computer aided design (CAD) software. By August 2016 I had filed a patent application for the newly developed technology and have since been working to develop the design for industrialisation. This has extended to founding the startup company Lightly Technologies and beginning to raise investment and validate the commercial opportunities with my co-founder Brian Charman, with whom I worked with at Philips Lighting.

3.2. **New Approach to Creating the OLED Form Factor**

The inspiration behind developing our new technology was the realisation that a paradigm shift was needed in how the OLED module appearance and form factor was created. The major players are already heavily invested in realising OLED technology, but the innovation I achieved was through taking a step back and out-of-the-box thinking to understand that the desire was for *ultra-thin surface light sources*, not for a light source that uses OLED technology. The market interest had been created by the OLED manufacturers, but this did not mean that OLED was the right technology for the commercialisation of ultra-thin light sources.

3.3. **Advancement in the LCD Displays Industry**

The unique insight into developing this technology was through my experience working on mass production engineering for the iPhone 6S. Liquid Crystal Display (LCD) technology utilises a homogenous backlight module to provide illumination for the pixels of the display. Millions of red, green and blue sub pixels are controlled by varying the voltage across that sub pixel, which controls the amount of light that is transmitted.

The backlights for LCD displays were originally direct lit, with an array of LEDs or fluorescent tubes behind a diffuser panel to create uniformity. With the development of smartphones, tablet and laptop displays, this moved to edge lit technology, where the LEDs would emit light into a Light Guide Plate (LGP) where they are then extracted by surface features that prevent total internal reflection. This has been continually refined over the last 10 years to their current stage of being incredibly thin so as to minimise the volume taken up by the display within the smartphone housing.

3.4. **Re-Engineering LCD Technologies for the Lighting Industry**

There were significant challenges faced in re-engineering LCD backlighting technology to be suitable for the lighting industry due to the difference requirement of the industries. The deep insights I had from working on LED OEM components greatly influenced the architecture of the technology developed.

The main optical differences were in the LED types used. Backlight applications typically have high CCT between 8000K and 10000K as this improves the saturation of the blue colours in the display. The lumen output is also lower in comparison to lighting applications so that smartphone displays are not too bright. These differences led to a change in the individual LEDs used for our technology, so that we could attain warmer colour temperatures with 90 CRI and high efficacy.

The selection of LEDs also led to changes in the thermal and electrical performance of our technology. I had to develop alternate ways of thermally managing the LEDs to prevent excessive temperatures and the lifetime effects that this has. Finally the design of the electrical layout so that our ultra-thin modules were fully compatible with LED drivers already on the market (unlike OLED modules) and be able to wire in series and parallel configurations. The electrical design also had to enable full controllability with DALI and other dimming technologies as well as being future-proofed for IoT systems.

Further, to achieve our ambitious optical performance characteristics, we developed a combination of optical films to achieve the uniformity and beam angle to suit our customers applications and reduce glare while maintaining a high, functional lumen output.

Our design architecture was also developed to enable novel features in future product generations some currently not offer by OLED lighting. This includes flexibility, dynamic white, scaling to different sizes and shapes, and a housing with a flush bezel to enable front mounting to glass.

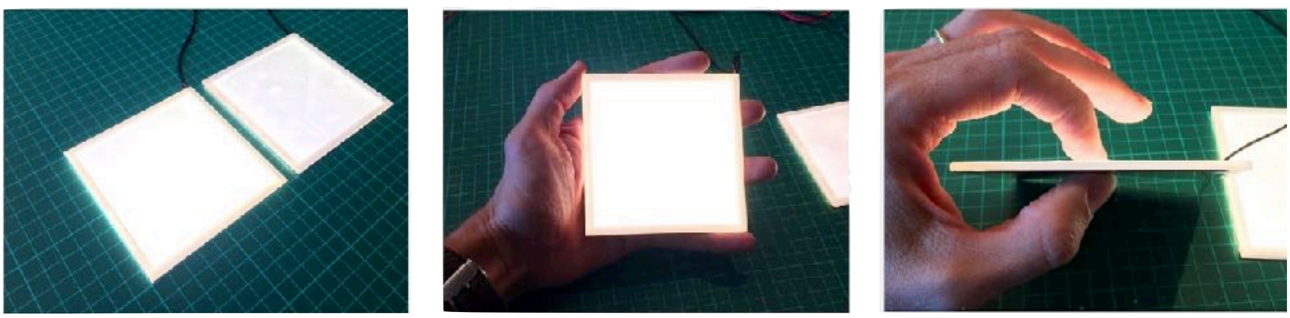

Figure 2: Ultra-Thin LED Light Modules by Lightly Technologies

3.5. **Benchmarking vs OLED Modules**

The design specification that we created was detailed to surpass OLED lighting on every single metric. This includes: light output, efficacy, lifetime, colour stability, unit cost, LED driver compatibility, full controllability, thickness of the module, bezel width, uniformity, beam angle and module robustness, all while designing with the luminaire manufacturer or lighting designer in mind for the easiest installation and creative flexibility.

We have achieved every one of these specifications to create a product that is truly disruptive to the OLED lighting sector.

	Lightly Tech	LGD	OLEDworks
	Hikari SQ	LL056RS1	FL300
Nominal Output (lm)	300	75	300
Efficacy (lm/W)	75	90	57
Lifetime (hrs L70B50)	50,000	40,000	10,000
CRI	90+	90+	90+
CCT (K)	2700, 3000, 4000	3000, 4000	3000, 4000
Beam Angle (º)	100	~120	~120
Dimensions (mm)	100x100	100x100	127x127
Bezel (mm)	5.0	~5.0	12.4
Module Thickness (mm)	3.0	N/A	3.0

Figure 3: Benchmarking Hikari SQ module performance vs OLED

3.6. **Applications for Surface Light Sources**

Our technology enables unique, modern styles of luminaires, visually impactful while still providing functional levels of light. As a result the main applications are within the lighting industry segments were decorative functional lighting are important. This includes retail, hospitality, high-end office and residential.

There are also specific luminaire types that benefit for the ultra-thin profile of the modules, including suspended luminaires, task lighting and surface mounted fittings that appear to be recessed. There are also applications beyond this in the transportation sector and in emergency signage as well as the opportunity to directly build the technology into interior design and furniture.

3.7. **Our Design Philosophy**

Everything that I design is centred around human experience. This design philosophy extends to every human interaction; from designers creating concepts, to simplified luminaire assembly, fast installation into buildings and finally the exceptional experience created by our lighting and luminaire design partners of beautiful living spaces with comfortable, low-glare lighting.

4. Conclusion

OLED technology is an exciting area of engineering development which has made a wide impact in both the Lighting and Displays industries. As the technology has industrialised over the last 8 years it has brought forward a significant benefit in the displays industry, enabling thinner display panels, richer colours and deeper contrast. In the Lighting industry, OLED has created an awareness of the opportunities in ultra-thin, surface light sources, with both the design freedom and low glare, high quality light that it enables.

The deep R&D into OLED technology has yielded the future of displays technology, but unfortunately not the future of lighting. As major lighting companies have withdrawn from OLED, a market opportunity has emerged, a desire for the benefits of modern, elegant lighting design with ultra-thin, surface modules, but with the requirement of performance comparable to LED. With founding Lightly Technologies, I have developed an innovative technology that fulfils both of these requirements and will enable the lighting industry to create this form of luminaire and lighting design with a high performance and commercially viable technology.

OLED lighting created a new generation of lighting design, but by shifting the paradigm of how this is engineered, I have developed a technology that can fulfil this exciting opportunity across the industry.

Figure 4: Prototype Luminaires using Hikari SQ

5. References

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