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2014 Status Report on Organic Light Emitting Diodes (OLED)

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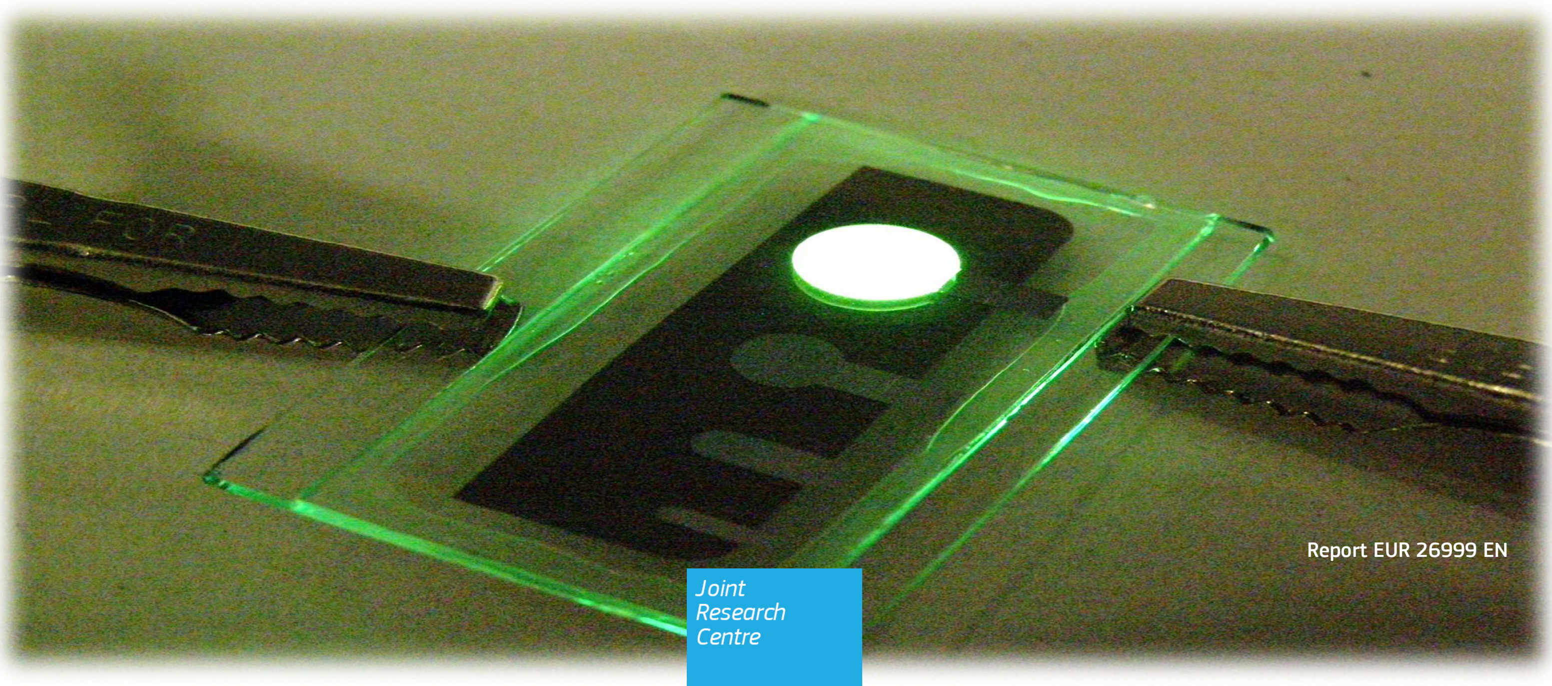

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Abstract

Organic light emitting diodes (OLED) are promising candidates for general illumination, since they offer the possibility to realize large area light sources which can even be transparent and flexible. The energy-saving potential of OLEDs is similar to that of LEDs, but the two technologies differ in a number of ways. The present report introduces the basics of the OLED technologies and its latest developments. It also describe the emerging markets, industry landscape and standardisation requirements

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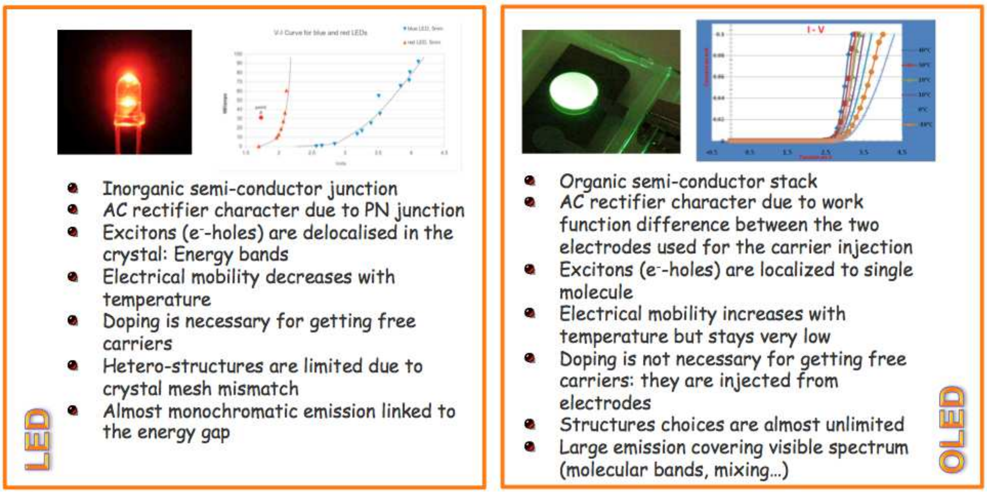
“Organic electronics are still a young area of technology that comprises applications as diverse as illuminants, photovoltaics, printed electronics and batteries. Replacing inorganic by organic materials, in particular conversion of light to electrical current (photovoltaics) and electrical current to light (light diodes), are promising basic economic and ecological benefits as well as benefits regarding application options and design, e.g. for large-area lighting, flexible displays and generation of energy” [ACA-11]. Organic light emitting diodes (OLED) are promising candidates for general illumination, too, since they offer the possibility to realize large area light sources which can even be transparent and flexible. The energy-saving potential of OLEDs is similar to that of LEDs, but the two technologies differ in a number of ways. The following table compares LED and OLED technologies.



An OLED (organic light-emitting diode) is a light-emitting diode (LED) in which the emissive electroluminescent layer is a film of organic compound that emits light in response to an electric current. OLEDs are used to create digital displays in devices such as television screens, computer monitors, portable systems such as mobile phones, handheld game consoles and PDAs. A major area of research is the development of white OLED devices for use in solid-state lighting applications. While there has recently been a dramatic expansion in the use of OLEDs for displays, a direct impact on the cost of OLED lighting products is not yet evident [DOE-13]. Partly this is because OLED lighting manufacturing is still evolving and the device architectures and performance requirements are different than those for displays. Nevertheless, today several OLED products for general lighting are already available.

	OLED lighting	Incandescentlight bulbs	Fluorescent lamps	LED
Illustration				
Principle of light emission	Emits light by applying a voltage to organic matter	Emits light by sending an electric current to a metallic filament	Ultraviolet rays generated by an electric current collide with fluorescent material to produce visible light	Emits light by applying a voltage to an inorganic semiconductor
Characteristics	○Illuminates large area (surface light source) ○Energy efficient ○Low heat-generation ○Slim, lightweight ○Flexible (when plastic substrate used) ○Environmentally sound	· Illuminates small area (point light source) ×High power consumption ×High heat-generation ○Closely approximates natural light	· Size of area illuminated is between point light source and surface light source (linear light source) ○Energy efficient ×Uses hazardous substance (mercury)	· Illuminates small area (point light source) ○Energy efficient ○Long life ○Easy to reduce size ○Environmentally sound
Uses	Anticipated applications include living spaces, offices, decorative illumination, car interior lighting, and POP lighting	Photographic lighting, living spaces such as dining rooms or bedrooms, etc.	Living spaces, offices, commercial premises, etc.	Indirect lighting, floor level lighting, spotlights for retail spaces, etc.

OLEDs offer yet another light source technology with unique spectral power densities. The broad spectrum of OLED emission peaks allows for full coverage of the visible spectrum; however, red emission in the infrared regime and the lack of efficient, long-life blue emitters

limit options in terms of optimizing the trade-off between colour quality and efficacy. [DOE-14]. Most OLED panels emit light over a complete hemisphere, with a distribution close to lambertian, this is a fundamental difference from other lighting technology. Unlike existing light sources, such as incandescent light bulbs and fluorescent lamps, OLEDs are planar light emitters that are lightweight and have thin profiles. This allows lamp manufacturers and designers to create unprecedented designs and provide dramatic effects, leading to the creation of new living environments in houses, offices, stores, and vehicles such as cars and airplanes. In principle, OLEDs emit UV-free "pleasant light" with a high Colour Rendering Index (CRI). An OLED device with broad spectrum can achieve a radiant efficacy[1] as high as 325 lm/W and, possibly, this value can goes up to 400 lm/W.
However, an early NanoMarker white paper pointed-out that Organic electronics is in no position to replace silicon, but there are many applications for which organic materials currently offer a competitive or superior mix of performance and economics, their number is growing, and the opportunity for materials firms is substantial [NAN-08].

Basics of the OLED technology

An OLED is a solid-state device consisting of a thin, carbon-based semiconductor layer that emits light when electricity is applied by adjacent electrodes. In order for light to escape from the device, at least one of the electrodes must be transparent. The intensity of the light emitted is controlled by the amount of electric current applied by the electrodes, and the light's colour is determined by the type of emissive material used. The basic structure of an OLED consists of a thin film of organic material (typical thickness in the order of 100nm) sandwiched between two electrodes, as depicted in Fig. 1, all deposited on a substrate.

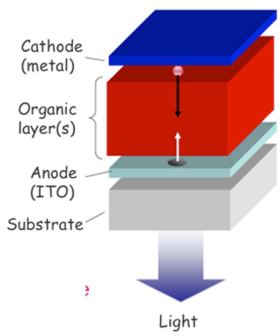


Figure 1: Typical structure of a bottom-emitting OLED

Today, different stack structures are possible:

- Bottom or top emission (Figure 2): Bottom or top distinction refers not to orientation of the OLED display, but to the direction that emitted light exits the device. OLED devices are classified as bottom emission devices, if emitted-light pass through the transparent or semi-transparent bottom electrode and substrate on which the panel was manufactured. Top emission devices are classified based on whether or not the light emitted from the OLED device exits through the lid that is added following fabrication of the device.

[1] Radiant efficacy is defined as the ratio between emitted the luminous flux (lm) over the emitted power (W) across all wavelengths

- Transparent OLEDs (Figure 2): This uses use transparent or semi-transparent contacts on both sides of the device to create displays that can be made to be both top and bottom emitting (transparent). TOLEDs can greatly improve contrast, making it much easier to view displays in bright sunlight. This technology can be used in Head-up displays, smart windows or augmented reality applications.
- Inverted OLED: In contrast to a conventional OLED, in which the anode is placed on the substrate, an Inverted OLED uses a bottom cathode that can be connected to the drain. This technology is more common for displays than for lighting.
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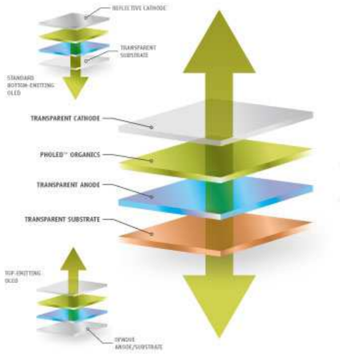


Figure 2: Bottom emitting OLED (left and top); Top emitting OLED (left and bottom); Transparent OLED (right) [from: http://www.udcoled.com/default.asp?contentID=584]

Organic electroluminescent materials, based on π-conjugated molecules may be electrically conductive as a result of delocalization of π-electrons caused by conjugation over part or the entire molecule. These materials have conductivity levels ranging from insulators to conductors, and are therefore considered organic semiconductors.
In organic semiconductors the highest occupied and lowest unoccupied molecular orbitals (HOMO and LUMO) of organic semiconductors are analogous to the valence and conduction bands of inorganic semiconductors. During operation, a voltage is applied across the OLED such that the anode is positive with respect to the cathode. A current of electrons flows through the device from cathode to anode, as electrons are injected into the LUMO of the organic layer at the cathode and withdrawn from the HOMO at the anode. This latter process may also be described as the injection of electron holes into the HOMO. Electrostatic forces bring the electrons and the holes towards each other and they recombine forming an exciton, a bound state of the electron and hole. This happens closer to the emissive layer, because in organic semiconductors holes are generally more mobile than electrons. The decay of this excited state results in a relaxation of the energy levels of the electron, accompanied by emission of radiation whose frequency is in the visible region. The wavelength depends on the band gap of the material, in this case the difference in energy between the HOMO and LUMO. An OLED emits almost monochromatic radiation (Figure 3).

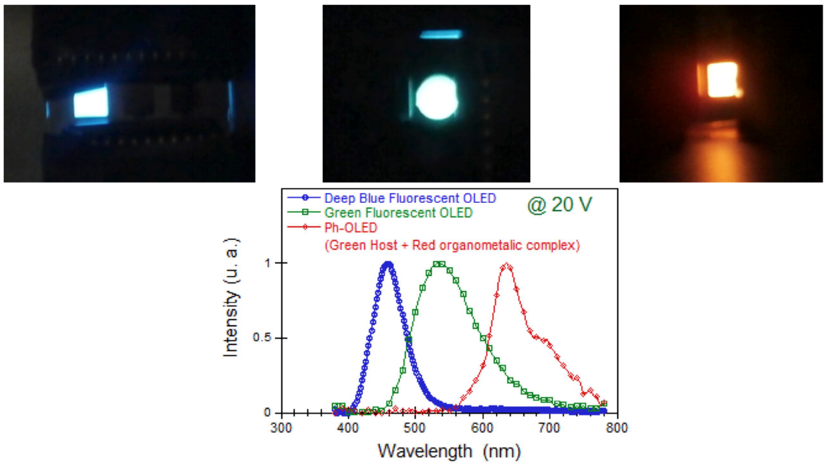


Figure 3: Emission spectra from different OLEDs [LAP-14]

White OLED (WOLED) lighting devices are designed to achieve a white colour by simultaneously emitting light from organic substances that radiate in colours such as blue, red, and green. However, changes in lighting colours due to aging (colour shift) are inevitable because the durability of devices differs from colour to colour. This is an issue that must be addressed in addition to the issue of luminance lifetime. (A comparison of OLED device structures is shown in Figure 4).

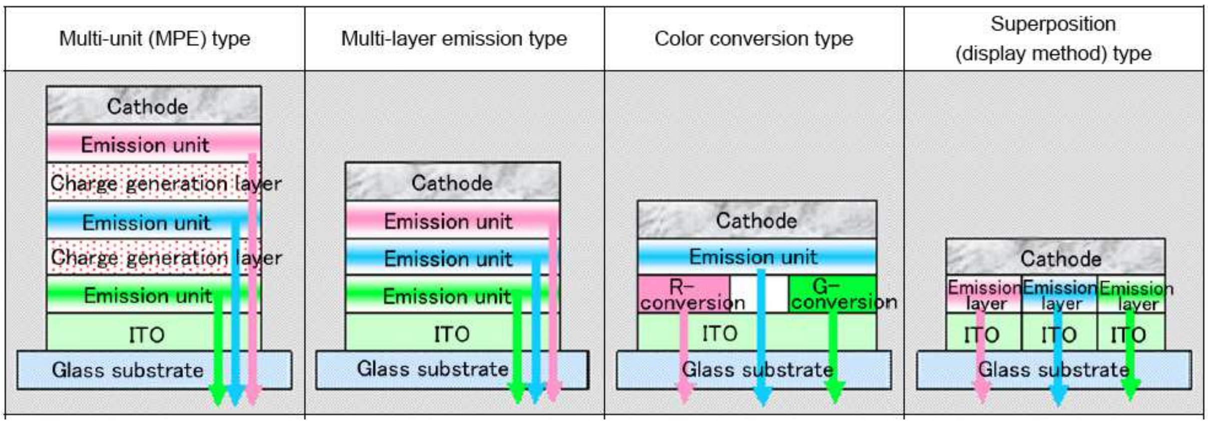


Figure 4: Possible structures for White OLEDs [HOR-12]

As for any emerging technology, a large variety of materials and OLED structures are used in production or tested. Moreover, alternatives to existing materials are still actively researched in order to improve the light performance, lifetime, and decrease manufacturing costs.

There are two main families of organic light emitting materials: those based on small molecules and those employing polymers (Figure 5 gives some typical examples). The polymer technology is usually called “Polymer light-emitting diodes” (PLED).

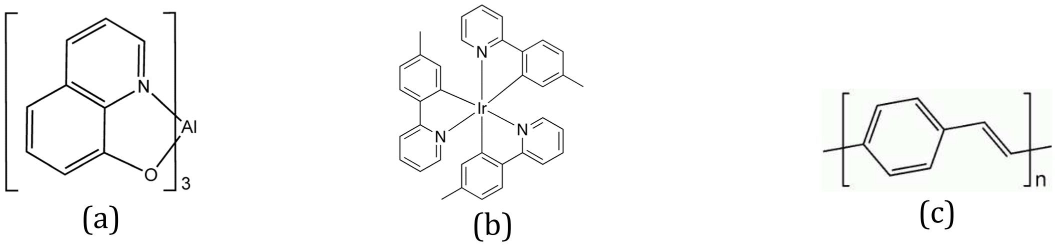


Figure 5: Examples of organic molecules used in OLEDs. (a) Alq_3 a fluorescent dye; (b) Ir(mppy)$_3$, a phosphorescent dopant which emits green light; (c) poly(p-phenylene vinylene), used in PLED technology

- In small molecule technology include organometallic fluorescent chelates (for example Alq_3), and phosphorescent dyes like Ir(mppy) are commonly used in OLEDs. Fluorescent dyes can be chosen to obtain light emission at different wavelengths, and compounds such as perylene, rubrene and quinacridone derivatives are often used. Phosphorescent organic light emitting diodes use the principle of electrophosphorescence to convert electrical energy in an OLED into light in a highly efficient manner, with the internal quantum efficiencies of such devices approaching 100% when fluorescent materials are strictly limited to 25%. The termed Ph-OLED applies to this category of molecules. Small molecules dominate the only sizeable market in organic electronics to date OLEDs. However, they suffer a serious drawback: they are difficult to make into inks. Because fabrication by printing is one of the key selling points of organic electronics, the issue clearly has commercial importance [NAN-08].
- Polymer light-emitting diodes (PLED), involve an electroluminescent conductive polymer that emits light when connected to an external voltage. They are used as a thin film for full-spectrum colour displays. Polymer OLEDs are quite efficient and require a relatively small amount of power for the amount of light produced. Polymers are easily solubilized and relatively easy to make into inks for printable electronics applications. High ‐ molecular ‐ weight materials, they consist of long chains of repeating molecular units that offer many opportunities for the control of electronic, chemical, morphological and rheological properties.

Although the uncertainty about the future winning material approach between small-molecule OLED materials and polymer materials remains, polymers continue to struggle to demonstrate the ability turning their cost and performance potential into an industrial reality. Today, the rate of lumen depreciation of red and green emitters has been reduced to acceptable levels, but significant improvements are necessary for phosphorescent blue emitters.

Some other ways are also explored since few year [NAN-08]:

- Oligomers are short-chain polymers with well-defined molecular characteristics. They are usually prepared step-wise, so that the exact chain length is well known. As low molecular weight polymers, they generally have properties that are between those of small molecules and polymers. In many cases, they can offer the advantages of both types of materials simultaneously. For example, some oligomers are both sufficiently soluble to be deposited from solution, and sufficiently volatile to be vacuum deposited. At the present time, however, there do not seem to be many attempts to commercialize oligomers for electronic applications.
- Organic/inorganic hybrids: Hybrid materials are becoming increasingly important. Many so ‐ called organic electronic products are already a kind of "hybrid," in that inorganic materials are often used as conductors and for dielectrics, but hybrid materials combine the two more intimately, the objective being to improve the performance parameters of organic electronics while maintaining its characteristic advantages. Often hybrids supply higher mobilities/conductivity, which can be achieved with the addition of carbon nanotubes, nanorods or fullerenes.

- Adding mobile ions to an OLED creates a light-emitting electrochemical cell (LEC) that has a slightly different mode of operation. It is also possible to create Organic Light Emitting Field Effect Transistors (OLEFET). OLEFETs are three-terminal devices (Drain, Source, and Gate) where the current is modulated by the gate voltage. Small molecules or polymers are used in semiconductor layer and Dielectric layer. Unlike OLEDs the light emission intensity can be modulated by the gate and drain voltage.

Concerning substrates, rigid glass maintains its exclusivity as a substrate material in OLED lighting panel production. However, progress has been made in the development of techniques, such as roll-to-roll processing, the development of flexible ultra-thin glass and flexible encapsulation solutions that will enable the progressive penetration of flexible OLED panels into the lighting market [YOL-12]. Plastics substrate major challenges, esp. thermal expansion, stability, temperature limits for processing, among others. Introduction of OLEDs on flexible substrates and the application of roll-to-roll manufacturing methods are however delayed due to several drawbacks. By far the most challenging problem in this respect is the development of reliable barriers to prevent ingress of water and oxygen through plastic substrates and covers.

Though in the near-term, competitive OLED lighting devices will likely be made using vacuum deposition or hybrid (combination of solution and evaporated layers) approaches, many of the proposed methods to reduce manufacturing costs involve the replacement of vacuum deposition methods by solution processing. This requires the development of new materials that initially exhibited much poorer performance in both efficacy and lifetime. Despite considerable effort in recent years by companies such as CDT, DuPont, and Merck, there is still a performance gap. The typical efficacy is lower by at least 50%. Figure 3 shows a schematic view of the different alternatives used today in OLED industry.

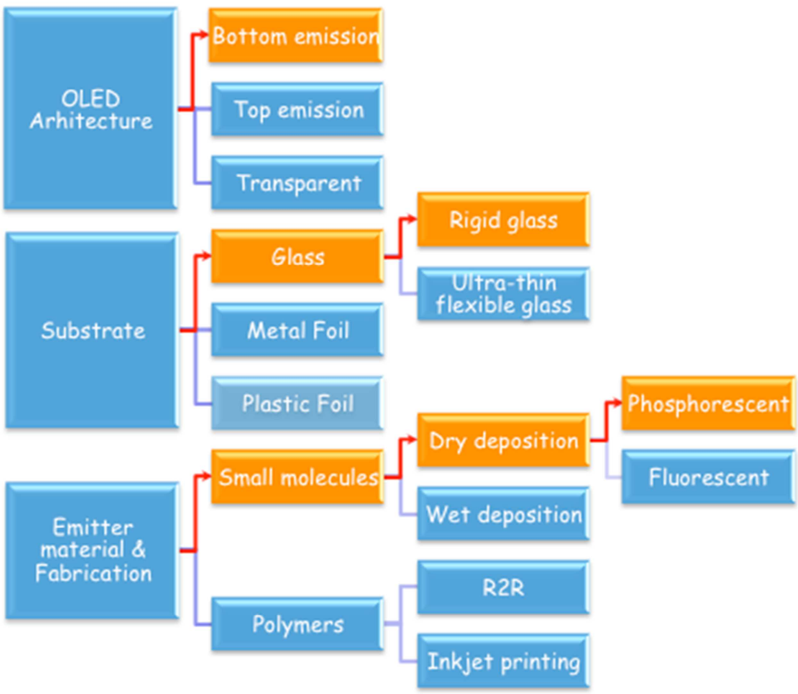


Figure 3: Todays orientations and alternatives for OLED technology (red line shows "main stream" and blue "alternative track") [ZIS-13]

Evolution of the OLED technology and targets

The electroluminescence, "the emission of electromagnetic radiation from condensed matter subjected to an external electric field", from anthracene (organic material) has been discovered in 1963. A. Hegger, A. McDiarmid and S. Shurakawa explained the possibility to obtain conductive organic thin films using π-conjugated materials (poly-acetylene)[2]. The way to light production from organic materials were open. Chemists, Ching W Tang and Steven Van Slyke, researchers at the Eastman Kodak Corporation, used organic heterostructures to demonstrate the first OLED diode in 1987. [TAN-87] Researchers from Cambridge (UK) demonstrated in 1990 the possibility to use conjugated polymers for light generation. In the early 2000s, researchers at Pacific Northwest National Laboratory and the Department of Energy invented two technologies necessary to make flexible OLEDs: first, Flexible Glass an engineered substrate that provides a flexible surface, and second, a Barix thin film coating that protects a flexible display from harmful air and moisture.
Initially, due to the moderate thickness of the vacuum-evaporated layers (≈100nm), light emission at rather low driving voltages (≈ 5V) was achieved with an external quantum efficiency (EQE) of about 1%. The first polymer OLED fabricated by spin coating had even worse characteristics: EQE of about 0,05% at driving voltages of about 15 V. Since these first steps considerable progress has been achieved in improving the performances of OLEDs as well as in studying the basic physics of such devices.
The first applications of OLEDs appeared at around 1997 with small monochrome displays for car radios. Nowadays, about 20 years after their first demonstration, OLEDs are seen as promising candidates for the next generation of display and lighting applications.

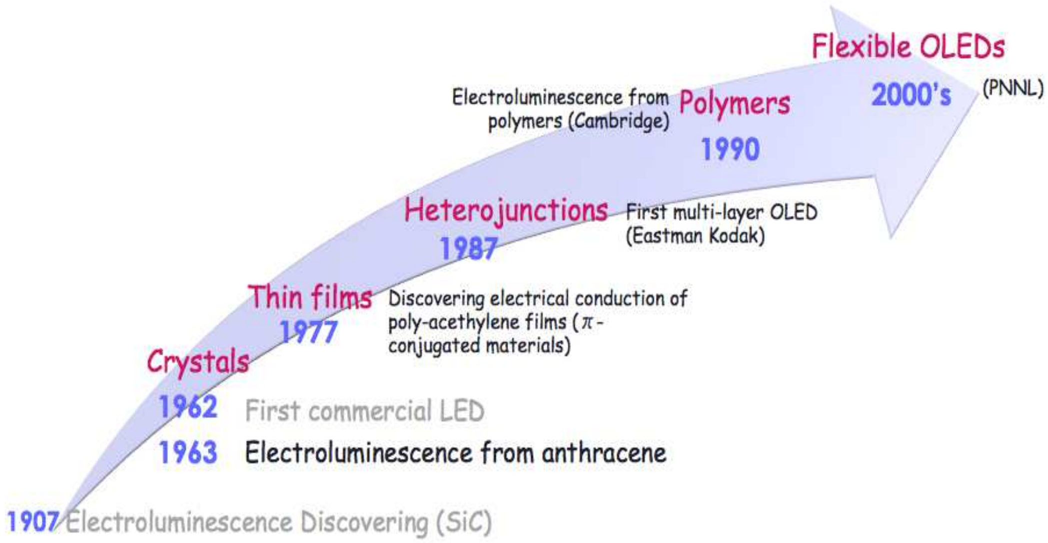


Figure 6: Schematics of OLED history [ZIS-13]

Impressive numbers have been published on white OLEDs under laboratory conditions: a device with a luminous efficacy in excess of 120 lm/W [REI-09], devices with 34% EQE [SUN-08], as well as devices with CRIs greater than 90 and lifetimes in excess of 30 000 h at a luminance of 5000 cd/m^2 [HEG-09] have been demonstrated. Figure 7, shows record efficiencies of white OLEDs (considered to be among the highest values reported

[2] A. Hegger, A. McDiarmid and S. Shurakawa obtained in 2000 the Nobel for chemistry thanks to this discovery

at the time of their publication). References and measurement details for each data point can be found in [GAT-11].

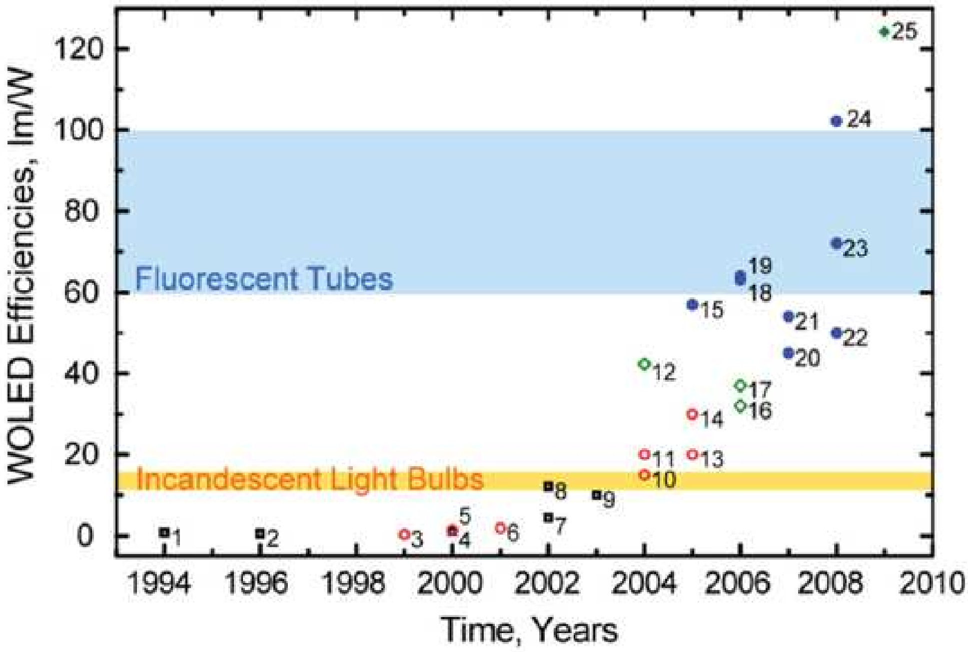


Figure 7: record efficiencies of white OLEDs (considered to be among the highest values reported at the time of their publication) from [GAT-11]

The DoE in 2011 within its Multi-Year Program Plan (MYPP) defined the targets for OLED performances as shown in table T1 [DOE-11] and more especially for the luminous efficacy in figure 8 [DOE-14].

Table T1: OLED performances targets from DoE-MYPP [DOE-11]

Metric	2010	2012	2015	2020
Panel Efficacy (lm/W)	58	86	125	168
Optical Efficiency of Luminaire	100%	100%	90%	95%
Efficiency of Driver	88%	90%	93%	93%
Total Efficiency from Device to Luminaire	88%	90%	84%	88%
Luminaire emittance (lm/m^2)	3,000	6,000	9,000	9,500
Resulting Luminaire Efficacy (lm/W)	51	77	105	148

Note: Efficacy projections assume CRI > 80, CCT 2580-3710
The values of optical efficiency quoted for 2010 and 2012 assume no light shaping optics

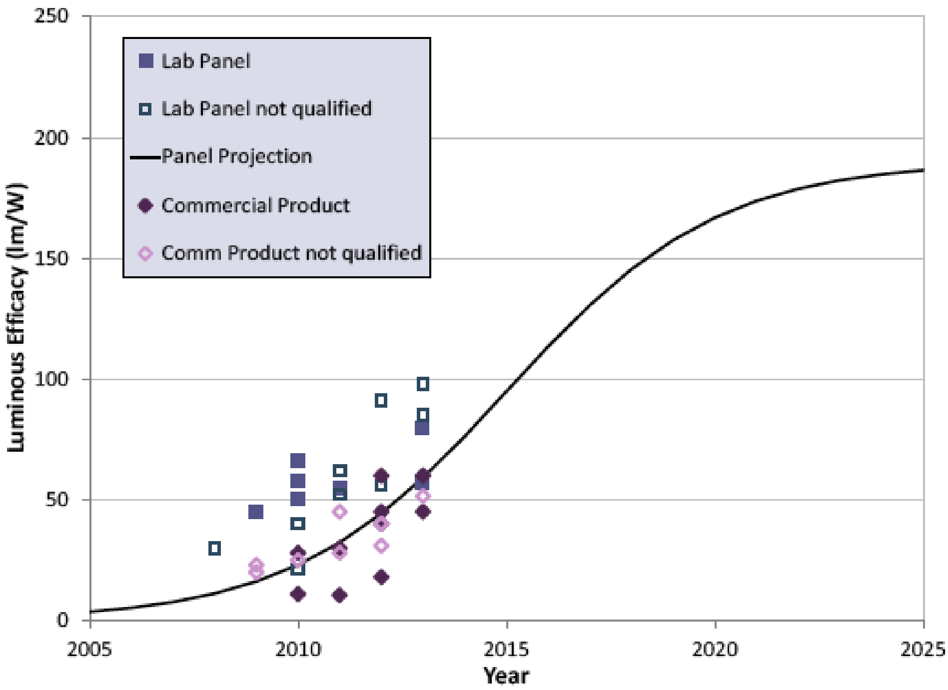


Figure 8: DoE's luminous efficacy target for OLED panel (190 lm/W by 2025)

Universal Display Corporation (UDC) has steadily achieved records in luminous efficacy, at the 'pixel' and the commercial-sized 'panel' scales. Funded in part by the US Department of Energy, these advances now meet a variety of niche performance targets and move white OLEDs closer to general lighting targets set by US DoE. As example, UDC has successfully demonstrated in 2008 a record-breaking white organic light-emitting diode (WOLED) with a power efficacy of 102 lm/W at 1000 cd/m^2 using its proprietary, high-efficiency phosphorescent OLED technology. This WOLED light source offers a white emission with a CRI of 70 and a CCT of 3 900K and highlights the potential of white OLEDs to offer significant energy savings and environmental benefits. Figure 9 shows the obtained UDC record-values compared against DoE objectives [UDC-11].

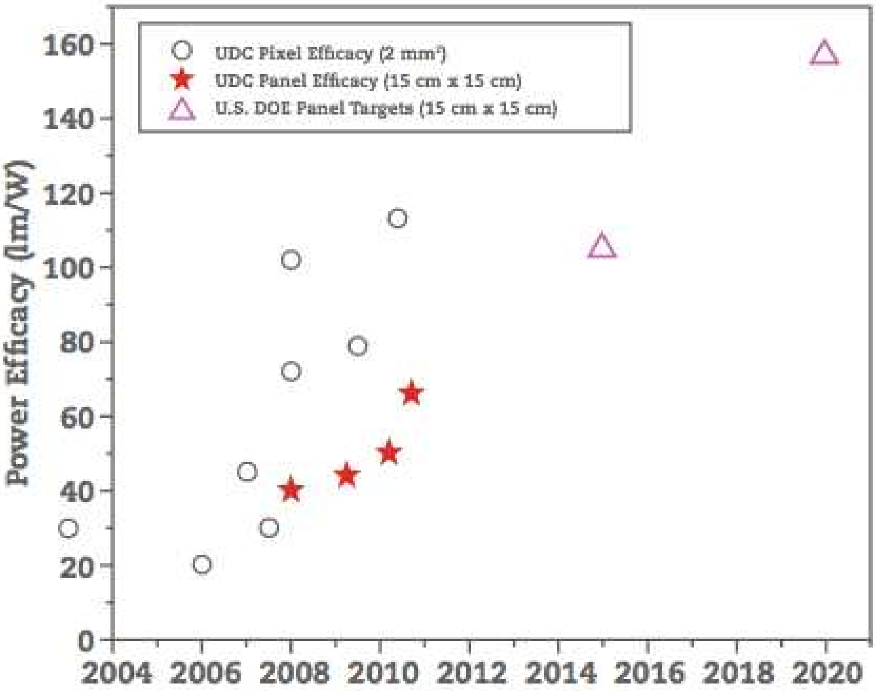


Figure 9: UDC luminous efficacy records at 'pixel' and 'panel' levels against DoE objectives [UDC-11]

Highly efficient, large-area prototype OLED panels have been recently demonstrated. Konica Minolta has shown a 15 cm^2 panel with an efficacy of 131 lm/W at 1,000 cd/m^2 and 118 lm/W at 3000 cd/m^2 [DOE-14]. Panasonic has successfully scaled their technology to an area of 25 cm^2, achieving efficacy of 112 lm/W at 1 000 cd/m^2 and 98 lm/W at 3,000 cd/m2 [KOM-13]. Lumen maintenance (L50) for both panels is acceptable at 55 000 hours for the Konica Minolta panel and over 100 000 hours for the Panasonic panel when operated at 1 000 cd/m^2.
These high-efficacy prototypes are promising, but as with LEDs, maximizing the efficacy of an OLED panel must be balanced against other important characteristics, such as lifetime, colour quality, cost, and form factor.
The first OLED lighting products have become commercially available in 2009: "Lumiblade" from Philips and the "ORBEOS" from OSRAM. The latter features an active area of 100 cm^2 at a thickness of 2,1mm and a weight of 24 g, a luminous efficacy of about 25 lm/W at 1 000 cd/m^2, a CRI of 75, and a median lifetime up to 15 000 h.
During 2011, the potential that OLED technology brings in innovative luminaire design has been confirmed with many new concepts shown on company websites, at exhibitions and in high-profile promotional installations. J.N. Bardsley reported in 2011 that new products are yet in the market with light output in the order of 12 lm corresponding to luminous efficacy of 45 lm/W, thickness of 1,8 mm, luminance of 10 000 cdm^{-2}, CCT 2 800 K and lifespan of 10 000 h and price of $175 ($14 500 per kilo-lumen) [BAR-11]. The Korean semiconductor equipment maker Jusung Engineering released today a OLED lighting panel with a size of 730×920 mm which is deposited on glass substrates [HUA-12]. The availability of high-efficacy panels has allowed luminaire manufacturers such as Acuity to focus on improvements in colour quality and lifetime, offering CRI of 89, CCT at 3 000K, and lumen maintenance (L70) at 18 000 hours from 3 000 cd/m^2. Progress has also been made on reducing panel-to-panel colour variations

to around four standard deviations in colour matching in luminaires with multiple panels. Table T2, summarizes some of the laboratory results reported since 2013 [DOE-14].

Table T2: laboratory results reported since 2013 [DOE-14].

Developer	Efficacy (lm/W)	Luminance (cd/m^2)	Area (cm^2)	CRI (Ra)	CCT (K)	L_{70} (1000 hours)	Drive (V)
Konica Minolta	131 118	1,000 3,000	15	82	2800	27.5[1]	
SEL/Sharp	113 105	1,000 5,000	81		3270	400[1]	8[3] 8.4[3]
Panasonic	110 98	1,000 3,000	25	81	2600	40 10	5.5[2] 6.0[2]
UDC	70 60	1,000 3,000	~200	85 86	3030 2880	165 25	7.1[3] 7.8[3]
LG Chem	82	3,000	16[4]	84	2900	30	8.5[3]
CDT/Sumitomo	56 48	1,000 3,000	13	80 82	2900		4.3[5] 4.8

Notes:
1. Scaled from data provided for L_{50} assuming L_{50} is two times L_{70}
2. Tandem device producing two photons per injected electron
3. Triple stack device producing three photons per injected electron
4. This technology has been scaled up to yield similar performance in 76 cm^2 panels.
5. Single-stack device with solution processed layers up to the emissive layer and an evaporated ETL/cathode

Table T3 provides estimates of the efficiency factors for three types of panels operating at 3 000 cd/m^2 [DOE-14]. Figure 10 shows the DoE's targets for these efficacy factors.

Table T3: Components of OLED panel efficacy [DOE-14].

Metric	LG Chem[1]	Panasonic[2]	CDT/Sumitomo[3]
Electrical Efficiency	80%	75%	46%
Internal Quantum Efficiency	75%	85%	72%
Extraction Efficiency	42%	50%	46%
Spectral Efficiency	90%	85%	89%
Panel Efficiency	23%	27%	14%
Panel Efficacy (lm/W)	82	98	48

Notes:
1. A hybrid triple stack with fluorescent blue emitters and phosphorescent red and green
2. A double stack with all phosphorescent emitters
3. A single stack with polymer/oligomer emitters

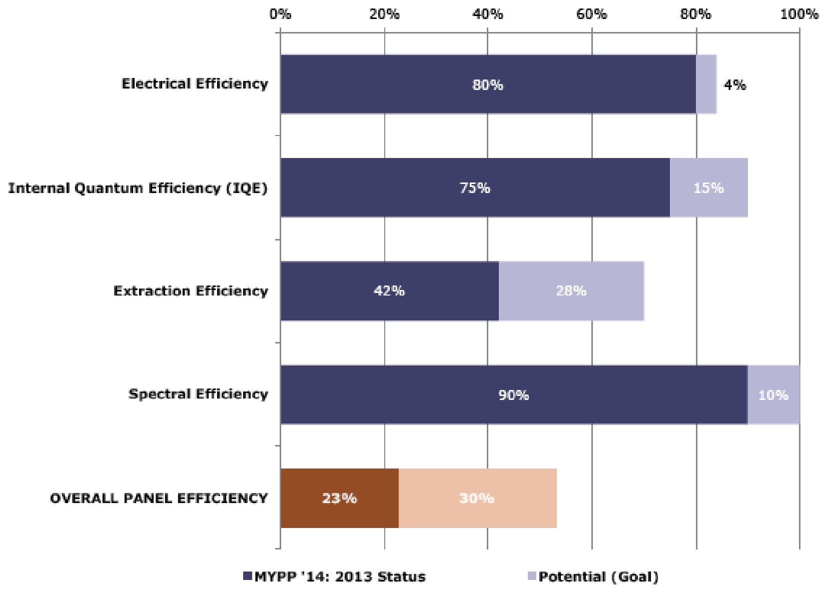


Figure 10: the DoE's targets for these efficacy factors [DOE-14]. The values for 2013 refer to the LG Chem laboratory panel, with a triple stack giving an efficacy of 82 lm/W, as shown in Table 3.8. The goal corresponds to a radiant efficacy of 360 lm/W and a panel efficacy of 190 lm/W.

Although some early proponents of OLED lighting envisaged large luminous areas, such as OLED wallpaper or OLED curtains, OLEDs are now mostly being used in modular form, as arrays of small panels of area 100 cm^2 or less. These panels can be configured either in two- or three-dimensional forms, offering light sculptures as a new form of architectural lighting. Currently, OLEDs can be difficult to use as the primary source of lighting in a room due to their limited light output and high cost. Many proponents are recommending their use in wall sconces and task lights, for example in desk lamps or under-cabinet lighting, in conjunction with ambient lighting. The low brightness of OLEDs allows them to be placed close to the task surface without being uncomfortable to the user, and improves light utilization. Methods of shaping the OLED light distribution may be required for efficient light utilization at greater distances [DOE-14]. There have been only a handful of OLED products in the market so far, so it is not clear what the full range of colour options will be. Improved understanding of colour perception will allow for products to better meet consumer demands. Figure 11 shows the performance of a 30 cm x 30 cm OLED specimen compared to the CAPLIPER round 9 tested downlights [BAR-11].

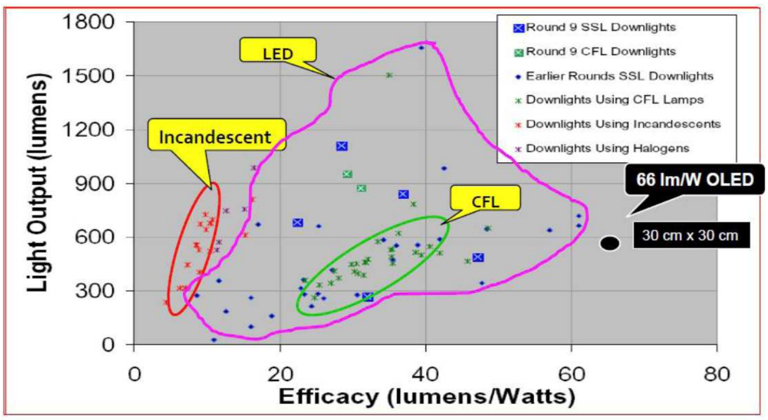


Figure 11: OLED performances compared to other downlight technologies from CALIPER round 9 [BAR-11]

Globally, OLED lighting industry is facing the following challenges for the next few years [BAR-14]:
Efficacy and Light Output:

(1) Some lab devices can compete with conventional technologies, but no products yet
(2) Work needed to develop long-lasting blue emitter
(3) Current OLED packages produce "dim" light
(4) Work needed to improve light extraction

Lifespan:

(1) Work needed on high current density and environmental degradation

Cost and Manufacturing:

(1) Lower cost device and luminaire materials are needed
(2) Infrastructure investment needed to develop commercial OLED products

Tests and Standards:

(1) Need for reliable test methods standards to establish consistency and reduce uncertainty

OLED Value Chain and Industry landscape

The chain "from material to product" – and in OLED and in general inorganic electronics, this is in particular: "from molecule to product" – reaches from material research and the development of plants and devices to implementation of research results in marketable products. It therefore comprises all stages of the product development process and connects science and economy, linking research and development at all stages of the value-added chain. Figure 12 shows this chain "from material to product" in organic electronics [ACA-11].

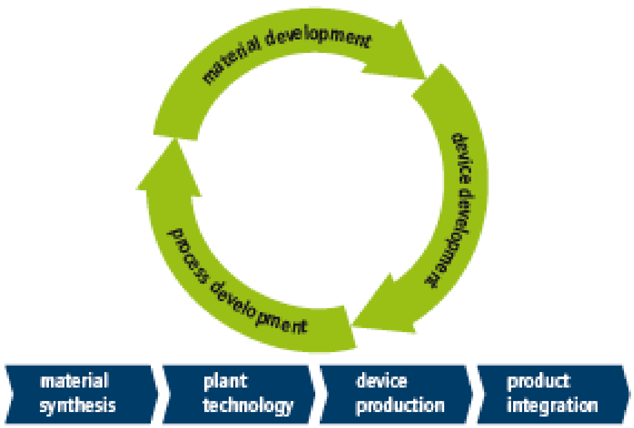


Figure 12: chain "from material to product" in organic electronics [ACA-11]

The main components of this chain are material development and synthesis, device development and production as well as the connected process development and plant technology. Product integration is a step specific to organic electronics in new products. Organic electronics are characterised by a great diversity of materials. Among others, the characteristics of organic materials depend on the molecular structure and the orientation of the molecules in the device, which in turn is influenced by the process conditions. In contrast to silicon-based electronics, in which the characteristics of the starting material are mainly known, the material and structural diversity of organic materials makes it difficult to understand the basic characteristics and interrelations of

effects. Determination of quantitative structure-characteristics relations are essential here. Applications of organic electronics always re- quire development of customised materials on a molecular level. Because the organic materials decisively influence the performance of the device, material development and synthesis is one of the main value-added steps of organic electronics, and thus an important research focus. Stability of organic materials is another issue.
The device is the core of value generation in organic electronics. Technical and economic requirements to the device indicate the direction of research and development activities on all value-added steps. Device development as such is a complicated step in the development and value-added chain. Different materials must be combined in several layers of different thickness and great uniformity in each individual layer to achieve a certain function and performance of the device. Device development therefore requires basic knowledge of the material characteristics and their interactions and, ideally, conclusions from the desired characteristics to the required molecular structure of the organic materials. This close technical link between material and device development requires a high degree of coordination and feedback along the value-added chain.
Devices are manufactured by coating and print procedures. For this, thin layers of different materials in the nanometer area are applied on top of each other. Production processes and plant technology must be optimised mainly regarding technical target figures like maximum material yield and homogeneous layer thickness. Another requirement is serial capability, i.e. quick and efficient production, which is growing more and more important. Development of the production and process technology therefore is closely related to material and device development and cannot be performed isolated from these stages of development.
Integration into an end product places organic electronics in an end-user environment. This results in essential requirements to the device, derived from the needs of the potential user. Thus, product integration and application development provide an interface between technology and market. The partially still-missing sales market is an obstacle to be overcome. In part, development of products is partially connected to development of an entirely new market in organic electronics. This gives product- and application development strong business-management characteristics.
At present, lighting panel products that are suitable for general illumination are manufactured using vapour deposition techniques on small-scale lines. These panels are built on rigid, display grade glass using batch processes and multi-emitter stacks or tandem structures. Encapsulation is accomplished with a glass cover and light output is enhanced using external extraction films. This approach is too costly, however, and many avenues are being explored to lower cost and improve performance.
Following [DOE-13] report, the capital cost of the equipment used for manufacturing OLED lighting panels is very high. The amount is strongly dependent on the size of substrate used. While pricing is uncertain, as high volume lines are not yet in use, the costs can be estimated as shown:

- $50-100 million for “Gen 2” at size 370 x 470 mm (0,17 m^2),
- $150-300 million for “Gen 5” at size 1100 x 1300 mm (1,4 m^2),
- $300-600 million for “Gen 8” at size 2200 x 2500 mm (5,5 m^2).

With traditional manufacturing techniques, approximately half of the capital cost is associated with deposition of the organic layers and the cathode. The cost of patterning equipment for integrated substrates is substantial, but this investment can be borne by the substrate supplier, rather than the panel maker.

The OLED community has not yet settled on a set of materials or a manufacturing approach for cost effective lighting panels. Materials cost reductions and innovative solutions for low-cost equipment and processes are needed. Choosing a successful approach involves optimizing performance while considering processing and tooling issues. Table T4 shows the main players in OLED material industry [NAN-14]

Table T4: Key players in OLED-chain material industry [NAN-14]

	Active OLED Materials				
	Hosts/dopants	Injectors/ Transporters	Emitters		
			Red	Green	Blue *
Key Companies Active in this Space	Cambridge Display Technology - subsidiary of Sumitomo Chemical (Polymer OLEDs)	LG Chemicals	UDC	UDC	UDC
		Sumitomo Chemicals		Merck	Merck
		Merck			
	DuPont (solution based small molecule)	Nissan Chemical Industries			BASF
	Merck (Both polymers and small molecules)	Dow Chemical			Idemitsu Kosan
		BASF			
	UDC (phosphorescent small molecules)	Hodogaya Chemical			

Global Material Suppliers

Materials	DuPont	Cheil	LG Chem	UDC	BASF	Dow Chemicals	Merck	Mitsubishi Chemicals	Mitsui Chemicals	Novaled	Samsung - Corning	Solvay	Sumitomo
Active Organic Materials	●	●	●	●	●	●	●	●	●	●		●	●
Encapsulation	●	●		●									
Substrate	●		●								●		

Along with efficacy improvements, OLED developers have been working to enable the use of less expensive fabrication and to improve the form factor through the use of ultra-thin, flexible substrates. Choosing a successful approach involves optimizing performance while considering processing and tooling issues. Increased collaboration among manufacturers is needed to narrow down the options and to enable high-volume manufacturing to be undertaken with confidence. Prices should drop substantially as new factories move into full production [DOE-14 & DOE-13].

OLED industry ecosystem

Today the main market of OLED technology is displays. For this segment, far-east manufacturers today dominate the production of OLEDs. Figure 13 shows the OLED display shipments beginning of 2012. Samsung Mobile Display with 70,7% share was number 1 and Visionox (China) became number 2 with steady growth and WiseChip (Taiwan) is number 3. At the same time, Japanese suppliers are losing market share. [COL-12]

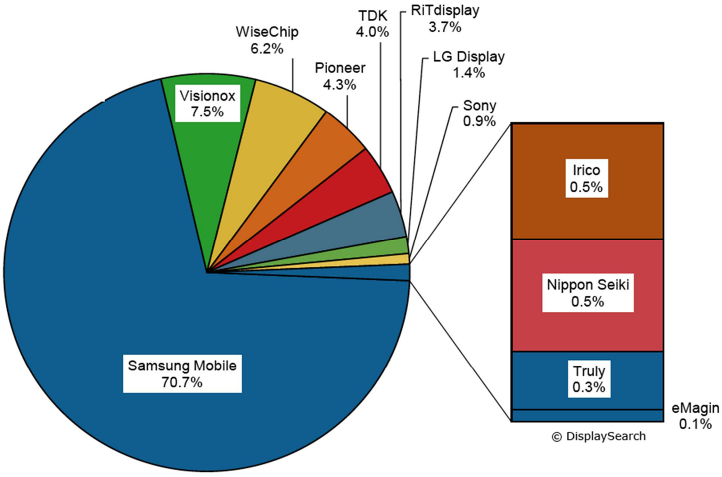


Figure 13: OLED display shipments in 2012 (Q1) [DIS-12]

Until 2009, talk of the OLED lighting market consisted mostly of important R&D projects and speculation about the future. There were clearly many firms that had a strong interest in OLED lighting, but it was hard to pin down their strategic direction or their level of commitment. It is important to recognize that the formation of an OLED lighting industry is not all "demand pull". Firms that no longer see the thrill in OLED displays are also swelling the ranks of the industry. However, in 2009 the first OLED products hi t the market and 2010 will see a lot more. Nevertheless, the OLED industry is beginning to take shape and it is now possible to write something of a "who's who" of the OLED industry, identifying who is producing what and in collaboration with who, what they plan to do in the future and when. At the early technology stages a few companies developing prototypes and pilot lines, including

- Philips – Small Molecule – Fluorescent/Phosphorescent
- Osram Opto – Small Molecule – Fluorescent/Phosphorescent
- GE – Solution Based Phosphorescent, Roll-to-Roll
- Panasonic – Small Molecule – Fluorescent/Phosphorescent
- Konica Minolta – Solution Based Phosphorescent, Roll-to-Roll
- Lumiotec – Small Molecule – Fluorescent/Phosphorescent
- Zumtobel/Thorn Lighting/Ledon/Fraunhofer – Polymer Based
- Mitsubishi/Pioneer – Small Molecule – Fluorescent/Phosphorescent, 2nd Gen Fab
- Moser Baer – Small Molecule – Phosphorescent
- Samsung – Small Molecule –Phosphorescent, 2nd Gen Fab
- LG – Small Molecule – Phosphorescent
- ModisTech – Polymer, Roll-to-Roll
- NEC Lighting – Small Molecule –Fluorescent/Phosphorescent
- Visonox - small molecule - phosphorescent

Figure 14 shows the OLED for lighting manufacturing activity all around the world as it is in 2013.

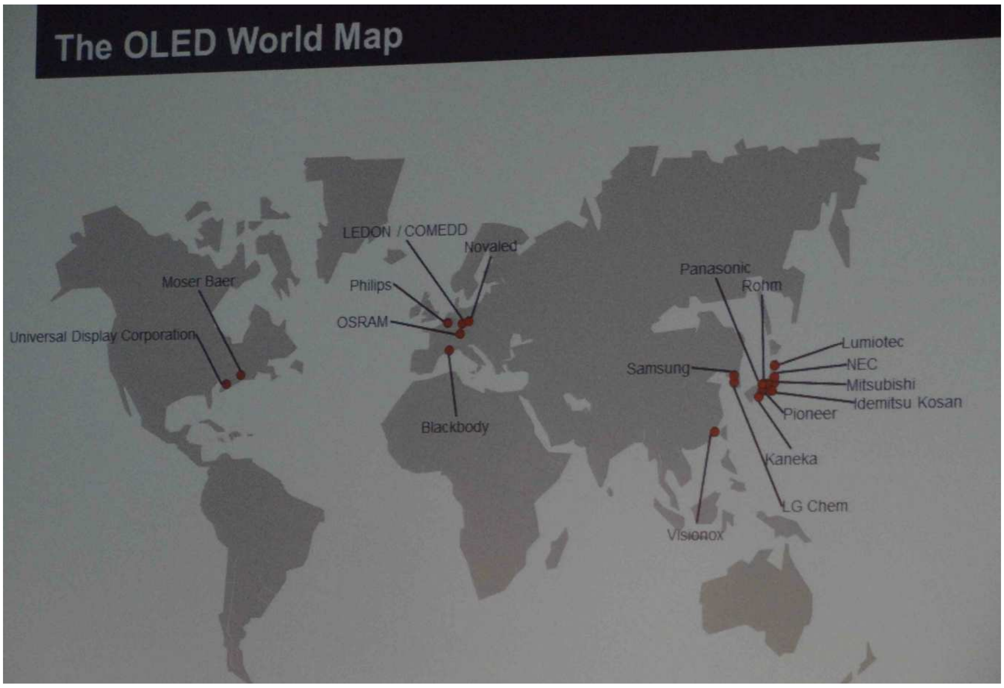


Figure 14: OLED for lighting manufacturing activity all around the world [STA-11]

Integrating OLED panels into functional luminaires represents an entirely new manufacturing challenge. Unlike LED luminaire manufacturing which can draw upon manufacturing expertise from conventional luminaire manufacturing, consumer electronics manufacturing, and semiconductor manufacturing, there is no clear analogy for OLED luminaire manufacturing. New approaches and platforms must be developed for the manufacturing of the mechanical structure of the luminaire and the electrical connection of the panel within the luminaire. These new approaches should be flexible to allow for the production of a range of lighting products for a range of lighting applications. Currently, the available OLED luminaires rely on custom, hand-assembly that is not feasible to reach the projected manufacturing costs and desired production levels. [DOE-13]

Hundreds of millions of dollars have been invested in OLED lighting in the EU, US, Japan, and Korea. Europe is currently the leading participant in the OLED lighting in terms of organization/projects numbers, government funding, and participating companies [COL-12]. Figure 15 shows historically the how these companies penetrated the OLED lighting market. With its skills, know-how, experience, and industrial base, the U.S. is in a strong position to participate in OLED lighting, with U.S. companies spanning the entire OLED supply chain, from materials suppliers to equipment manufacturers, panel manufacturers, and luminaire manufacturers. YOLE expects OLED lighiting sector growth will be driven mainly by General Lighting applications, representing more than 70% of the overall OLED lighting business in 2020 [YOL-12].

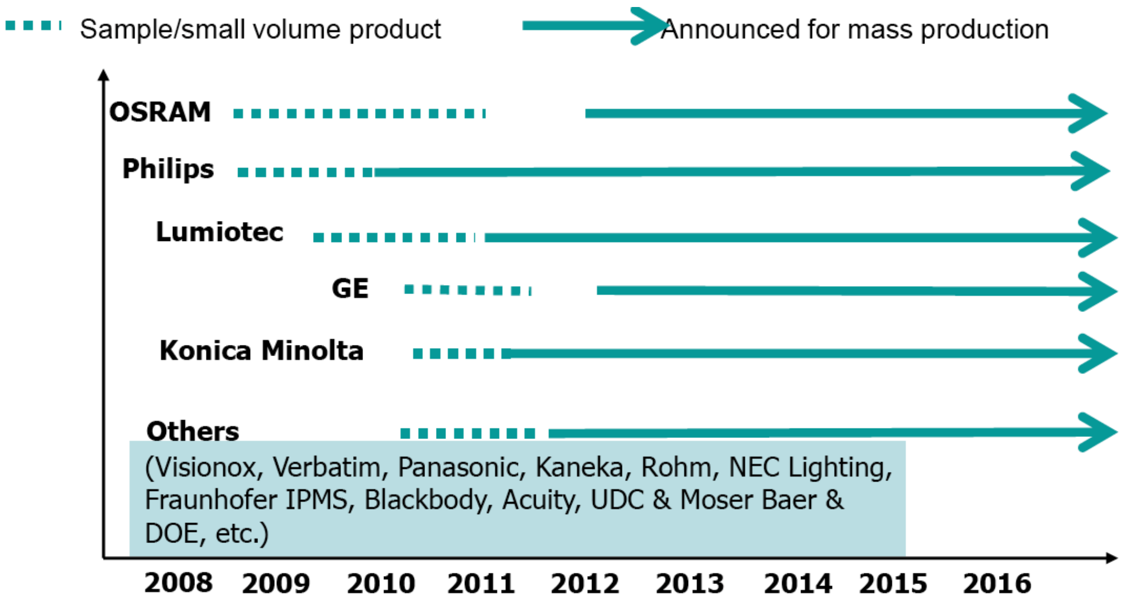


Figure 15: History and evolution of OLED-Lighting manufacturers production [COL-12]

Konica Minolta's $100 million investment in the world's largest OLED lighting panel mass production facility is another encouraging factor for OLED material providers [NAN-14].

Merck and UDC continue to remain the chief OLED material providers to major OLED manufacturers, including Samsung and LG.

Through numerous licensing and supply arrangements with major OLED panel manufacturers, UDC is likely to maintain its position as a leading manufacturer and supplier of phosphorescent emitters, especially green emitters. UDC's dominant hold over the OLED materials market is likely to strengthen given that the company is looking to expand its materials portfolio by moving into new domains, including organic vapour jet printing and single-layer barrier encapsulation system.

Playing a central role in the OLED materials space (Figure 16), UDC has already shown interest in the OLED lighting space by entering into supply arrangements with players, including Philips, Lumiotec and Kaneka Corporation. While Philips expects to improve the performance of its OLED lighting panels using UDC's emitter materials, Lumiotec intends to have ready access to UDC's proprietary Universal PHOLED phosphorescent and other OLED technologies and materials. UDC is focused on improving its PHOLEDs as well as outcoupling layer to enhance the light extraction efficiency of OLEDs. Furthermore, UDC is working on barrier film encapsulation for plastic substrates and alternate stack materials to complement its blue PHOLEDs. Further, by allowing Kaneka to manufacturer and sell UDC's proprietary OLED materials in the Asian markets, UDC has shown interest in catering to Asia that is set to become an OLED lighting panel manufacturing hub.

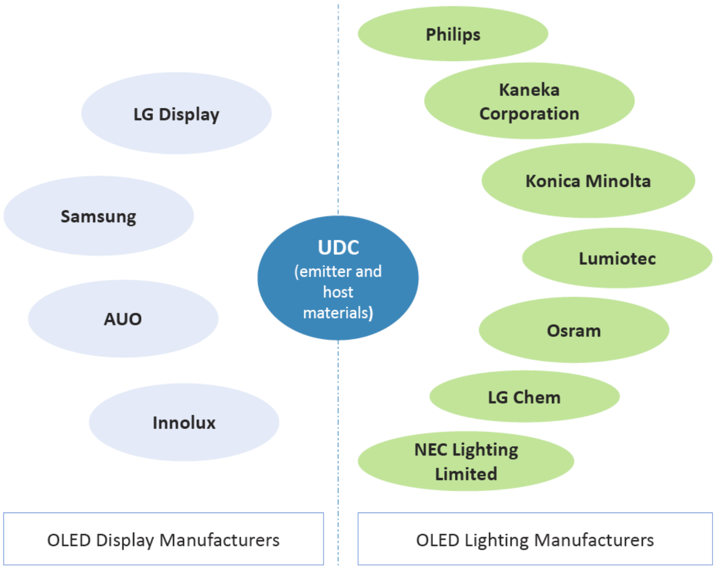


Figure 16: UDC has a central position in OLED manufacturing eco-system [NAN-14]

While DuPont, Merck and Sumitomo are developing solution process able OLED materials, the latter two are looking to transition from being material producers to OLED solution providers.
DuPont developed conductive silver nanowire ink for OLED lighting panels that is expected to reduce costs and improve conductivity. This is expected to be commercialized in 2015.
Despite primarily being a chemical company, Sumitomo has progressed across the value chain by utilizing its polymer OLED (POLED) technology and materials to develop prototype of POLED lighting panels. Mass production is expected soon.
Bracing themselves to respond to the need of cost effective OLED fabrication materials, companies such as Merck and Novaledare partnering with OLED manufacturers to come up with printable OLED material and truly flexible OLEDs, respectively [NAN-14].
Fabrication lines designed specifically for higher volumes adapted to OLE lighting have been built by LG Chem and First-O-Lite, and the main R&D lines operated by OSRAM and Philips have been upgraded to enable commercial production.
It is expected that by 2014 end, there will be at least three big OLED lighting panel dedicated mass production facilities with an annual estimated global production capacity of around 0,5 million panels per month [NAN-14].
It is of interest to notice that some companies try to introduce new ideas in the market. As example, Kenwood Company (Japan), besides signs with OLEDs, has developed ultrathin audio speakers united with an OLED panel. These speakers consuming energy by 80 % less than their analogues, are a side effect of development of evacuation signal boards united with a loudspeaker, which Kenwood developed for schools and offices [http://www.OLED-info.com/OLED-lighting-take-2011-reach-6 b-revenue-2018].

OLED development public support (from [DOE-14])

Europe: Governmental support of OLED lighting research is strong in Europe, with approximately 20 active projects, each involving multiple partners. The European Union has supported many projects involving international collaborations. One of the most recent projects of this type is Flex-O-Fab, which is promoting the development of a robust supply chain for the manufacture of OLEDs on flexible substrates, using either roll-to-roll or sheet-to-sheet processing [62]. The Ecole Polytechnique in Switzerland is

working with eight companies from six countries. The EU is supplying $9,8 million towards a total budget of $15,6 million. Flexible lighting is also the theme of the IMOLA (intelligent light management for OLED on foil applications, www.oled-info.com/imola) project. This four-year, $6,6 million program aims to realize large-area OLED lighting modules with light intensity that can be adjusted uniformly or locally according to the time of day or a person's position. The envisaged applications include wall, ceiling, and in-vehicle (dome) lighting. The EU efforts have been supplemented by national R&D programs. The European project ENAB-SPOLED involves six partners, and is coordinated by Germany-based OLED lighting developer Novaled. The project will see both commercial and academic partners work to develop solution processable OLEDs and a functional luminaire demonstrator based on the technology. The project has already been given $5.5 million of funding by Germany's Federal Ministry of Education and Research, the U.K.'s Technology Strategy Board, and the Austrian Research Promotion Agency.
Germany: The German Ministry of Education and Research has provided about $150 million over a six-year period, with the goal of encouraging corporate investment of about $520 million. For example, the goal of the Olympus project is the production of durable OLED luminaires with efficacy above 100 lm/W. The project runs through September 2015, with a budget of $47 million, and is coordinated by Osram with support from BJB, Ledon, Merck, and Trilux. The cyCESH project is focused on the development of solution-processable materials by Cynora, Novaled, and the University of Regensburg. This three-year project has a budget of $8,4 million.
Russia: In Russia a road-map “Use of Nanotechnologies in Production of Light Emission Diodes” [http://www.rusnano.com/Section.aspx/]
Show/27387.] has been developed by the initiative of the Rosnanotekh State Corporation.
South Korea: The greatest investments in OLED technology have been made in South Korea. Samsung’s OLED investments have recently averaged about $5 billion per year [JIN-11]. Although it is unclear how much of this is aimed at lighting applications, the manufacturing experience that they are gaining for displays will be of great value in reducing the cost of OLED lighting. Although LG has lagged behind Samsung in sales of OLED displays, the conglomerate is aggressively competing for the lighting markets, mainly through their materials subsidiary, LG Chem. Although the South Korean government has provided some funding for companies, primarily to encourage the development of the OLED supply chain, its principal contribution has been to support universities and research institutes. Despite the small size of the country, South Korea has by far the most extensive network of academic R&D in OLED technology.
Japan: Academic research groups in Japan have been responsible for many of the fundamental developments in OLED lighting, including those at Kyushu and Yamagata Universities, and the Japan Advanced Institute of Science and Technology. This has led to the availability of experienced young researchers in corporate R&D efforts. Japanese companies are now vigorously pursuing the OLED lighting market, having lost control of OLED display manufacturing.
Taiwan: Government support of OLED research in Taiwan has also been focused upon universities and research laboratories, such as ITRI, although Taiwanese companies have as yet been hesitant to exploit this research. In mainland China, there are few universities carrying out research, and Chinese companies have been hiring experienced OLED researchers from overseas to staff the growing corporate activities in R&D and manufacturing.

USA: DOE received $25.8 million from Congress for SSL R&D in the 2014 fiscal year (FY 2014, which began in October 2013) and has requested $25.8 million in funding for FY 2015. These levels are consistent with congressional appropriations from previous years, which have hovered around $25 million each year. In FY 2009 an additional, one-time funding of $50 million was provided through the American Recovery and Reinvestment Act of 2009, to be used to accelerate the SSL R&D Program and jump-start the manufacturing R&D initiative. From this total amount DoE will invest for 2014, $8,1 million (22,3% of the total budget) in five OLED projects as follows: $0.5 million for OLED Product Development; $0,8 million for OLED Core Technology; $6,8 million for OLED Manufacturing.

OLED Market

At the earl time of OLED technology was targeting displays and small screens for nomad applications. In this context PMOLED started shipments in 1999, AMOLED started at the end of 2002. Kodak DSC easyshare was the first AMOLED in market [COL-12]. Figure 17 shows the market evolution at those beginning stages. OLED display revenues will grow to about $44 billion in 2019, up from a total product revenue: ~$826 million in 2009 (~73 million units shipped) [BRO-11] and $4 billion in 2011, with CAGR ~40% [COL-12]. Mobile phone main display saw strong growth recently and will continue to lead in revenue for the next several years.

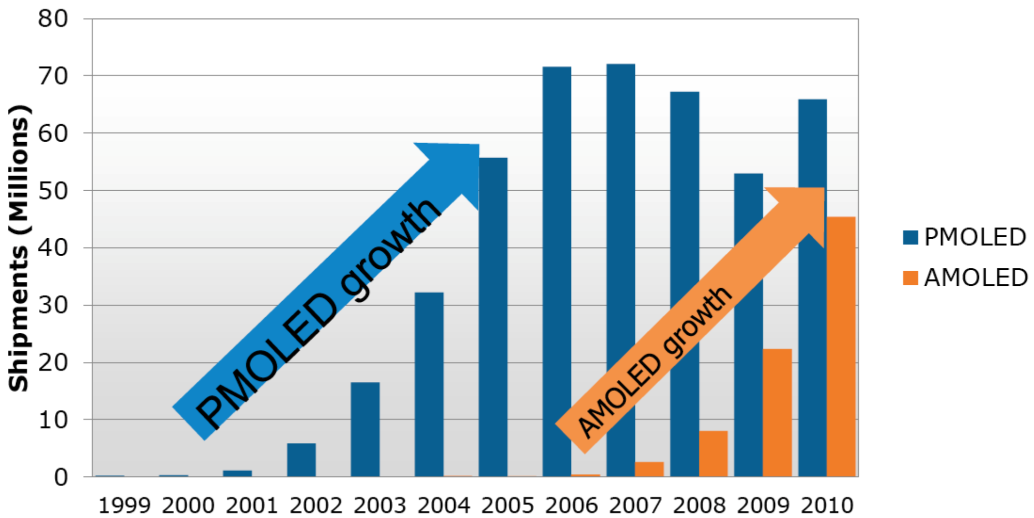
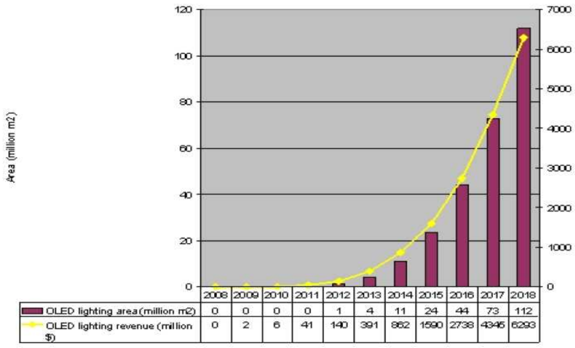


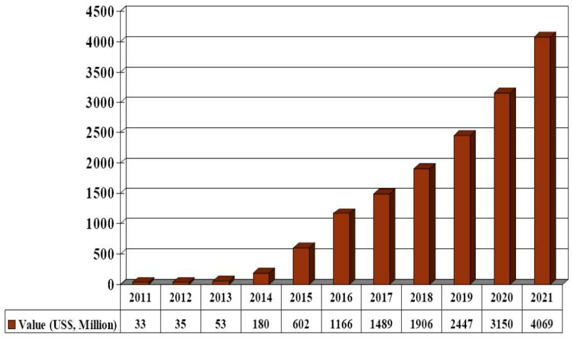
Figure 17: OLED shipments for displays [COL-12]

The OLED lighting market started to pick up around 2011 [COL-12]. Following DoE [DOE-14], OLED technology has yet to gain a measurable share of the general lighting market, but the OLED community is making strides toward commercializing products for certain applications. Most OLED prototypes have yet to attain light output levels suitable for many general lighting applications. Initial products have been largely decorative in nature although some OLED products have been developed for task lighting applications, such as desk or table lamps and automotive interior lighting. The forecasts tell that OLEDs will develop slowly in the lighting market (Automotive and General lighting) and attract mainly niche applications (specialty and high-end lighting), differentiating through design possibilities. To access traditional market segments (commercial lighting, office lighting…), OLED technology will have to find a spark, as well as combine enough different niche markets to achieve the economies of scale that

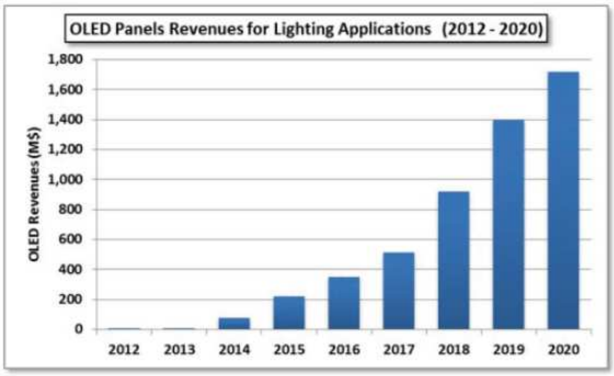
will decrease costs. According to YOLE's estimation, this should be triggered by 2014 with the use of larger substrates and better process control [YOL-12].
Predicted sales of OLED lighting panels in 2013 at $15 million correspond to a total area of less than 1000 m^2 [GHA-13]. This value is 3 times higher than the prediction made in 2009 by DisplaySearch [DIS-09]. This may be considered as the premises of important market acceleration. Figure 18a shows a forecast from Display Search established in 2009 pointing-out that OLED lighting market will reach $1,5 billion by 2015 and may attain $6,3 billion by 2018 [DIS-09]. However, figure 18b that reproduces an ElectroniCast Consulting forecast established in 2011 [ELE-11], shows that the expected revenue in 2020 is almost 3 times lower than that predicted 2 in 2009. Furthermore, a BCC study presented by K. Huang in 2012 predicts OLED revenue as low as 700 million for 2017 when at the same talk Hunag stated that Frost & Sullivan estimates market to reach $7,39 billion in 2016 with a CAGR of 34% [HUA-12]. Furthermore, YOLE forecasted that OLED lighting revenue would reach $1,7 billion by 2020 [YOL-12] when IDTechEx predicted $1,25 billion in 2023 [GHA-13]. For the moment, with such deviations, it seems very difficult to draw realistic conclusions.



(a)



(b)



(c)

Figure 18: OLED for lighting industry revenue forecast from (a) [DIS-09]; (b) [ELE-11] and (c) [YOL-12]

IDTechEx Research developed in 2013 detailed market forecasts. Here, they estimate the market share of OLEDs per lighting market segment, calculate the total lighting area per sector, estimate the lumen output per segment, and forecast the equivalent number of units sold per sector. Combining this analysis, IDTechEx forecast the monetary value of the market at module level per market segment as shown in Figure 19 [GHA-13].

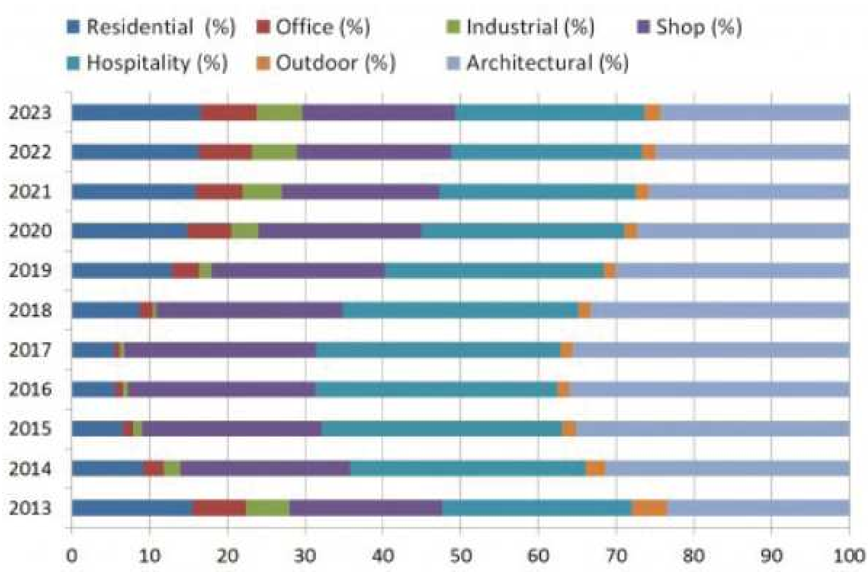


Figure 19: The relative monetary contribution of each lighting market segment to the total OLED market between 2013 and 2023 [GHA-13]

It seems clear that the main important targets of OLED devices are residential and tertiary indoor lighting sectors. This conclusion is coming straightforward looking on OLED properties and performances (Figure 20).

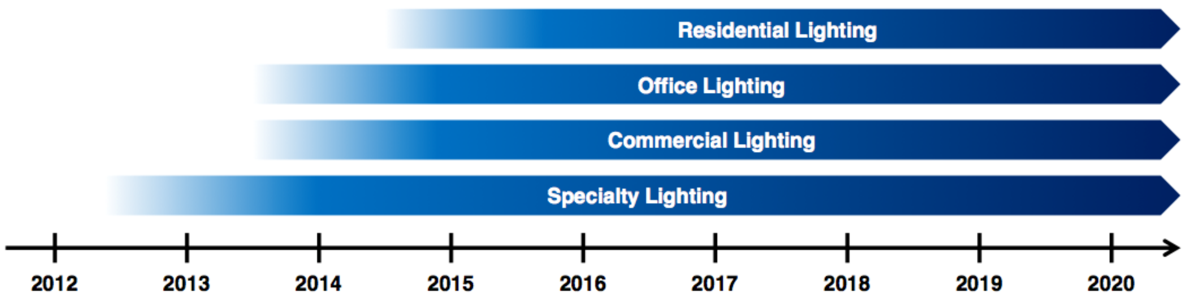


Figure 20: OLED market access Roadmap [ROS-14]

OLED Prices and potential downsizing

In the domain of OLEDs for displays, the acceptable OLED cost is typically ~$1000-2000 per m². OLED lighting costs need to be reduced and efficiency needs to be improved for mass adoption. The target cost should be $30-100 per m² [COL-12]. This is a very serious challenge for OLED manufacturers.

The production of OLED panels for lighting has mostly been accomplished in lines with much less automation, leading to even higher costs per area. The price charged by panel manufacturers is $10000/m² or more, leading to luminaire prices in excess of $20 000/m² or $2 000/klm. However, this value can be strongly affected by the production rate. Figure 21 shows the OLED-module manufacturing cost evolution as function of the production capacity.

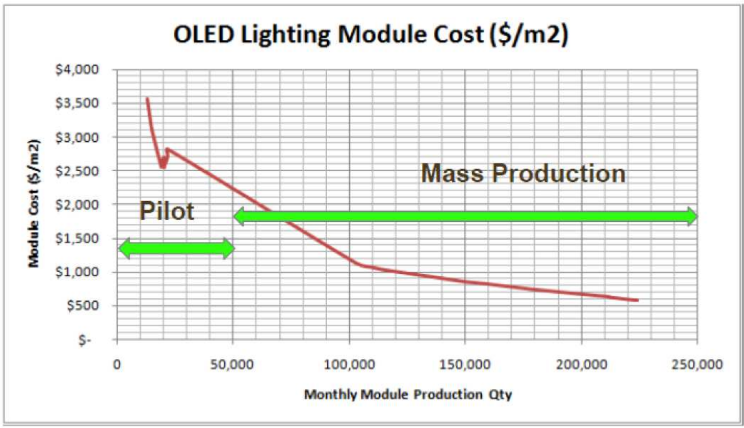


Figure 21: OLED Module Manufacturing Costs (Assumptions: OLED material utilisation: Pilot 30%, mass production 50%, product size 150mm x 150mm, module bill-of-materials: 30% of total material costs) [BAR-11]

Although samples of OLED panels have been available since 2009, most have been produced on R&D lines and are very expensive on a $/klm basis. The first OLED products are only now becoming commercially available but these products are not yet cost competitive [DOE-14]. Although lines designed for volume production are being brought up to full production, yields and throughput are still below planned levels. For example, a 10 cm x 10 cm panel from Lumiotec costing about $130 produces 55 lm (~$2 700/klm). An engineering kit from Philips at $520 contains three GL350 panels that produce 360 lm (~$1 500/klm) [DOE-13b].

The retail prices of luminaires are even higher than for the panels. Decorative luminaires, such as the K-Blade desk light from Riva 1920, which uses a Lumiblade panel from Philips, and the Bonzai from Blackbody, are priced in the range of $3 000/klm to $5 000/klm [RIV-14] [BLA-14]. More functional luminaires for commercial applications are now priced at around $1 500/klm [DOE-14]. For example, the Hanger luminaire from Lumiotec provides 130 lm from a 210 cm^2 panel and was originally priced at $450, corresponding to $2 900/klm. The V-Lux from Blackbody contains two OLED panels with total area 200 cm^2 and produces 250 lumens. The introductory price was $700. As an example of a luminaire that extends the functionality of traditional lighting, the Philips LivingShapes interactive mirror contains 72 small OLED panels, giving a total of 400 lm at a price of $10 000/klm.

Philips made substantial investment in the OLED lighting space. As a result, OLED lighting panel manufacturing time has reduced to 2 minutes per panel. Prices of OLED lighting panels have also been brought down to $1 250 per m^2.

However, today as commercial OLED products are in the beginning stages of development and prices remain high and therefore, a LCCA is premature in order to be able to define the real cost targets that will enable a mass penetration of the technology. Following Kae Hunag, these targets scale to $30/klm in 2015, $17/klm in 2017 and $10/klm in 2020 [HUA-12]. Figure 22 illustrates the cost downsizing projections for a full OLED lighting system as done by DoE in 2012 [DOE-12]. It can be seen that the cost of the OLED panel itself has to be drastically reduced; this is also true for the driver.

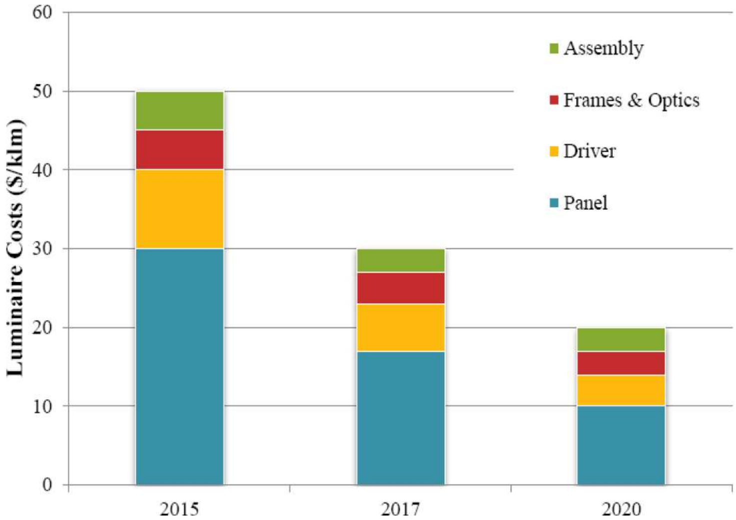


Figure 22: OLED luminaire cost downsizing projections from DoE [DOE-12]

The overall OLED cost targets in DoE Roadmaps have been set mainly by market expectations. The division of the total cost between the different components was set using community assessments of aggressive, but plausible reductions. In several editions the schedule for achieving the targets has been delayed, but the market imperatives remain. The daunting nature of the challenge is well illustrated by the comparison in T5 of targeted materials costs with the current costs faced by a small company. Table T6 shows the proposed short- and mid-term cost targets.

Table T5: Comparison of Current OLED Materials Cost against DOE Targets [DOE-13]. Note that these estimates assume 100% yield. If the yield were only 20%, the bill of materials alone would be in the neighbourhood of $5000/m².

Component	2012 (estimated)	DOE Targets (near-term)
Substrate	$35/m^2 (borosilicate)	$6 - $10/m^2 (soda lime)
Electrodes	$50 - $300/m^2 (ITO + metal grid, photolithography)	$20 - $30/m^2 (no photolithography)
OLED Materials	$300 - $500/m^2 (low materials utilization, high price)	$30 - $40/m^2
Light Extraction	$10 - $100/m^2 (low performance vs. low volume)	$20/m^2
Encapsulation	$250 - $400/m^2 (expensive adhesive/desiccant/etched glass)	$10 - $20/m^2
Other Materials		$15 - $20/m^2
Total (100% yield)	$650 - $1350/m^2	$100 - $150/m^2

Table T6: Projected OLED materials costs (excluding labour) [DOE-11b]

Stage	Units	Year		
		2011	2013	2015
Organic Materials (Material Utilization)	$/m^2	50 (30%)	20 (50%)	10 (70%)
Substrate	$/m^2	50	7	7
Electrodes	$/m^2	30	30	15
Light extraction	$/m^2	20	15	30
Encapsulation	$/m^2	100	15	10
Other materials	$/m^2	20	15	10
Total Cost	$/m^2	340	122	86
	$/klm	110	20	9

Even if based on mining reserves (100 years at a rate of 500 tn of virgin indium per year), plus residue reserves (30 years at a rate of 500 tn per year), combined with continued improvements in recoveries of virgin and reclaimed materials, and on-going exploration. The real issue for General Lighting (and Display) is anode process here the estimated Indium-based materials cost is $0,2/m^2 in sheets sold at $30/m^2 this challenges for inline continuous high volume process. Focus on ITO alternate anode materials due to high process cost $30/m^2, fear over scarcity/availability and supply interruptions causing price increases and fluctuations.
Another significant opportunity in glass for substrate cost reduction consist on switching from display glass ($40/m^2) to unpolished CFG ($6/m^2); similar low-cost for Al foil substrates (for top emitting OLED); and plastic webs [BUH-12].
The other area in which major reductions are needed is in the depreciation of equipment costs. Following the strategy pursued by the display industry, the solution would be to increase throughput by using larger substrates while reducing the cycle time modestly. ID TechEx has estimated the cost of a traditional Gen 8 line (2200mm x 2500mm) for lighting panels to be $350 million [GHA-13]. The initial capital investment is onerous, and with five-year linear depreciation, the annual charge would be $70 million. If one assumes a cycle time of 60 seconds, use of 80% of the substrate area, 80% uptime and 90% yield, the annual capacity of one line would be 1,7 million m^2/year of good panels. With a luminance of 10 000 lm/m^2, the light output of these panels would produce 17 million klm. North American manufacturers, such as OLEDWorks and Moser Baer, believe that depreciation targets could be reached with much smaller throughput levels using less expensive equipment. The scaling guidance set by OLEDWorks is that the capital cost should be $100 for each m^2 of annual production, leading to depreciation charges that would be only $20/m^2 or $2/klm. Such small panels allow for the possibility of affordable panel pricing, customizable products, malleable fabrication lines, and reasonable supply [DOE-13]. Figure 23 from YOLE shows the “way to the OLED lighting market”.

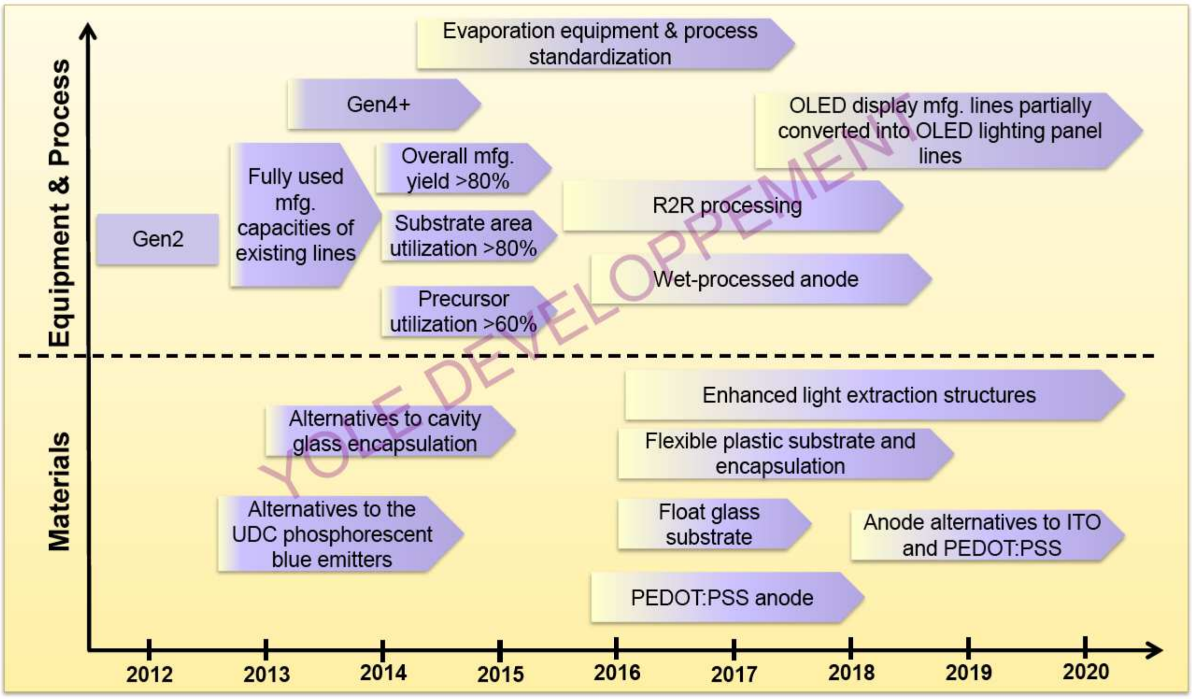


Figure 23: Milestones on the Way to the OLED Lighting Market [YOL-12]

There is an opportunity for OLED lighting to have a significant impact in short term. A combination of LED and OLED lighting will enable the greatest energy and cost savings. What is required is collaboration. OLED panel performance has been demonstrated, but the high cost of panels is slowing the market development of OLED lighting. Prices will stay high until volumes increase. But additional investment for large-scale equipment will not occur until volume increases. By thinking creatively and collaborating together, the industry can come up with lower-cost solutions. But the whole industry — from manufacturers, to materials suppliers, to equipment suppliers, to luminaire makers, to governments — must share the burden of getting started [DOE-11b].

OLED Standards

Even if OLED technology of lighting is very new some standards are in development worldwide [BAR-14]:
Underwriters Laboratory (USA)

- UL 1598 Standard for Luminaires
- UL 8752 Standard for Safety - Organic Light Emitting Diode (OLED) Panels

International Electrotechnical Commission (IEC)

- 62868 (Doc 34A/1700) OLED panels for general lighting— Safety requirements
- Doc 34A/1665: OLED panels for general lighting - Performance requirements

Commission Internationale de l’Eclairage (CIE):

- TC 2-68: Optical Measurement Methods for OLEDs used for Lighting
- TC 2-75 Photometry of Curved and Flexible OLED and LED Sources

Illumination Engineering Society – North America (IESNA)

- S404-10 Electrical and photometric measurements for OLEDs

China Solid State Lighting Alliance (CSA):

- CSA 014-2012 OLED lighting terminology and letter symbols,

- CSA 015-2012 OLED test method

Acronyms

AMOLED: Active Matrix OLED (display)
CAGR: Compound Annual Growth Rate
CCT: Correlated Colour Temperature
CFL: Compact Fluorescent Lamp
CIE: Commission Internationale de l'Eclairage
CRI: Colour Rendering Index
CSA: Chinese Solid State Alliance
DoE: Department of Energy
EQE: External Quantum Efficiency
EU: European Union
EQE: External Quantum Efficiency
FY: Fiscal Year
HOMO: Highest Occupied Molecular Orbital
IEC: International Eletrotechnics Committee
ITO: Indium Tin Oxyde
IESNA: Illuminating Engineering Society of North America
LCCA: Life Cycle Cost Assesment
LEC: Light-emitting Electrochemical Cell
LED: Light Emitting Diode
LER: Luminous Efficacy of Radiation
LUMO: Lowest Unoccupied Molecular Orbital
MPE: Multi-Photon Emission device
MYPP: Multi-year Program Plan
OLED: Organic Light Emitting Diode
OLEFET: Organic Light Emitting Field Effect Transistor
PDA: Personal Digital Assistant
Ph-OLED: Phosphorescent small-molecule OLED technology
PLED: Polymer light-emitting diode
PMOLED: Passive matrix OLED (display)
POLED: Plastic OLED
R2R: Roll-to-Roll fabrication process
SSL: Solid State Lighting
TOLED: Transparent OLEDs
UDC: Universal Display Corporation
UL: Underwriters Laboratory
US, USA: United States of America
WOLED: White OLED

Currency rates used (July 2014)

1 JPY = 0,007 €
1 US$ = 0,736 €
1 RMB = 0,118 €
1 KRW = 0,001 €
1 TWD = 0,0246€

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