

# OLED lighting - light where it never has been before

M. Klein<sup>\*a</sup>, K. Heuser<sup>a</sup>, F. Schindler<sup>a</sup>, B. Krummacher<sup>a</sup>, T. Dobbertin<sup>a</sup>, R. Pätzold<sup>b</sup>, C. Gärditz<sup>b</sup>

<sup>a</sup>Osram Opto Semiconductors GmbH, Leibnizstr. 4, 93055 Regensburg, Germany

<sup>b</sup>Siemens AG, CT MM1, Günther Scharowsky Str. 1, 91052 Erlangen, Germany

## ABSTRACT

"Optical Technologies have conquered the world" - their economic key data showed an impressive growth in the past couple of years, and the predictions for the up-coming years keep the expectations high<sup>1,2</sup>. In the case of OLED (Organic Light Emitting Diode) lighting, e.g. IDTechEx is predicting a worldwide market growth from 50 million USD in 2009 to 3.3 billion USD in 2012<sup>3</sup>.

LED and OLED technology, although both being referred to as solid state lighting, are rather complementary in their characteristics. Whereas LEDs are high efficient point light sources, OLEDs cover large area, diffuse lighting applications which can follow the increased awareness for creation of personalized atmosphere. Ambience and mood lighting can be perfectly realized by the means of OLED large area illumination which will pave the way for applications that up to now could not have been realized.

OLED lighting technology rests on three pillars at the same time, the basic performance like efficiency and lifetime, the unique features, and costs. These key challenges and their impact on various applications will be discussed.

**Keywords:** Organic light-emitting diode, OLED, lighting, white light, OLED lighting applications, unique selling points, specifications, key challenges

## 1. INTRODUCTION

### 1.1 The OLED function principle

Since the first report of efficient electroluminescence (EL) in amorphous thin films<sup>4</sup> and the first light emitting polymers in 1990<sup>5</sup>, organic light emitting diodes (OLEDs) have been the subject of intense research activities. OLEDs are ultra-thin multilayer film devices, with the active layer stack comprising a total thickness of typically less than 500 nm. Charge transport in these usually amorphous films is a carrier hopping mechanism between localized states associated with certain  $\pi$ -electron structures under the influence of an external field. Electrons and holes migrate in opposite directions and are driven to the emissive zone where they form excitons, which decay radiatively under emission of light. OLEDs have proven to be efficient solid-state light sources and their power efficiencies have by far surpassed those of the incandescent bulbs by improved device architectures, smart molecular engineering in synthesis of new materials, improved light out coupling, the introduction of conductivity doping<sup>6</sup>, and the incorporation of phosphorescent emitters.

White light now can be generated by e.g. a 2-color-mixing of greenish-blue and orange emitters stacked on top of each other, by using a three color approach with red, green and blue emission, or, similar to inorganic white LEDs, by combining a blue OLED pump light with external converter materials. Color coordinates, efficiency, and color rendering indices usually differ between the above approaches.

Today's lumen efficiencies at reasonable lifetimes of 25 lm/W and more (even 62 lm/W and 64 lm/W have been reported for

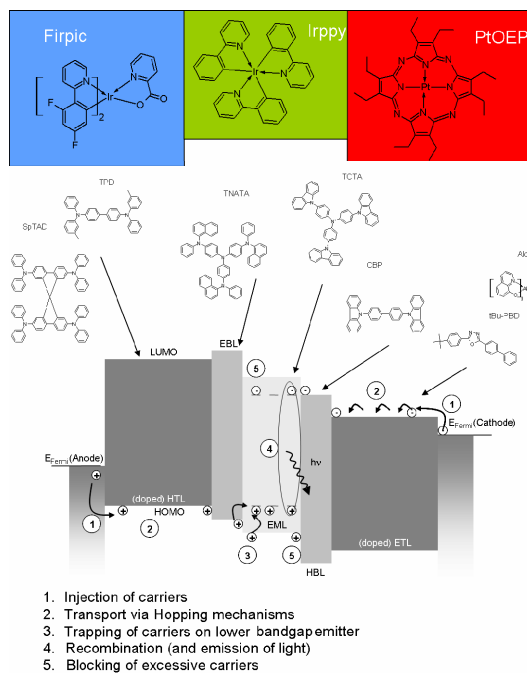


Fig. 1. Basic function principle of OLEDs (sample).

white OLED<sup>7, 8)</sup> have been demonstrated for brightness values of 1000 cd/m<sup>2</sup> and fixed white color coordinates. White OLED technology is drawing most attention due to its application for general lighting and was amongst others pioneered by the group of Prof. Kido at Yamagata University.

## 1.2 The unique features of OLED lighting

The ultra-thin and typically transparent architecture of the amorphous OLED layers is the key asset enabling most of the unique selling points of OLED lighting. The devices are thin, flat, and light-weight, are potentially transparent and flexible, and can be controlled by electronic gear quite easily, both in brightness and color. These are the features which offer an entirely new paradigm for the infrastructure of artificial illumination - "light where it never has been before". The infrastructure of light now can easily integrate into e.g. building materials such as glass or steel.

Moreover, since OLEDs are free of hazardous substances like e.g. mercury, they have already solved one of the major issues of conventional light sources.

With growing maturity of OLED technology in performance, in maintaining the unique features of the OLED throughout the production process (substrate, electrode, encapsulation), as well as in production capability, applications will range from less demanding applications such as signage, decorative lighting, over archtainment, automotive applications, safety, and LCD backlighting, up to large area flexible illumination (e.g. illuminated wallpaper) and general lighting with higher requirements in terms of efficiency and reliability at high luminance levels.

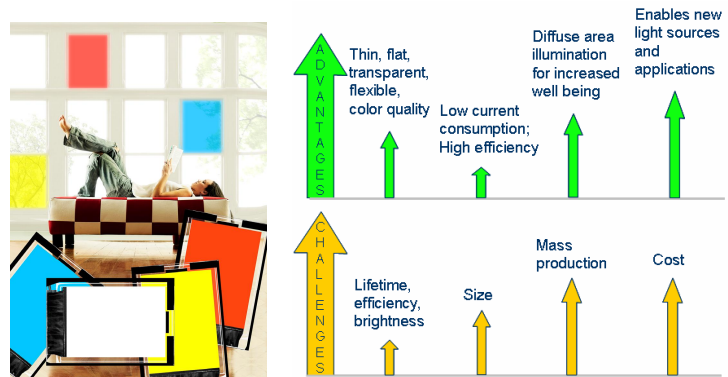


Fig. 2. The unique features of OLED (thin, flat, transparent, and flexible) will enable completely new applications which can follow the increased awareness for creation of atmosphere, ambience, and mood with flexible area lighting (well-being).

## 2. THE KEY CHALLENGES OF OLED LIGHTING

OLED lighting technology rests on three pillars at the same time also reflecting the three key challenges of this technology. At first, the common lighting requirements, mainly reliability, efficiency, and color quality, have to be met. Secondly, the unique OLED features need to be maintained by the manufacturing process and the materials used. E.g. achieving 50 lm/W white (CRI > 80) with a lifetime of several 1000 h needs to be accomplished by also using a flexible or transparent substrate, the appropriate electrodes, and a flexible and/or transparent thin film encapsulation process. Last but not least, all of the above must meet cost targets which for lighting are far more than an order of magnitude below the cost of today's manufacturing OLED displays, the first mass production application of OLED technology. The cost of producing OLED light sources with, compared to point sources like e.g. LED, rather low brightness levels is determined by the area rather than by the lumen output. Here, low cost electrode structuring, high deposition rate OLED evaporation, and low cost encapsulation are the key areas for further development.

### 2.1 OLED Performance - Meeting the "common lighting requirements"

As the performance is highly dependent on the device architecture used, a short summary over the most commonly approaches will be given. To obtain white light, broadband or a two or three color emission is needed. The superposition of blue, green and red appears white to the human eye. For display applications saturated RGB emission is necessary to provide a large gamut in order to display graphics in high quality. As this is not true for lighting devices, white emission can also be generated by using only two colors like a turquoise and red, although the color rendering will suffer from



Source: Siemens CT

Fig. 3. White light is the main type of light for room lighting, so this is the main focus for research and development.

reducing to fewer colors. Thus possible technical implementations are based on either two or three color emission or on an emission material that internally generates broadband white light. The most relevant design options including their advantages and disadvantages are shown in Figure 4 and discussed in the following (left to right).

The technically simplest way to fabricate a white OLED is based on a single, white-emitting OLED stack (e.g. polymer) as emission layer. These polymers can be blends of different emitting polymers or copolymers in which the emission centers for either two or three colors are located as co-monomers on one polymer chain. This concept is the least complicated one in terms of manufacturing compared to the other technologies described below.

Different organic emitters stacked on top of each other also provide the opportunity of color adjustment but, without intermediate electrodes, not in an active way. By varying the thickness of each layer the color can be tuned to produce different shades of white. Since there is a risk of re-dissolving the lower layers in the case of polymers, cross-linkable materials<sup>9</sup> are most promising for multi-layer setups.

Another option is to laterally pattern the different color OLED stacks next to each other. The big advantage of this configuration is active color tunability as the brightness of each color can be adjusted separately by modulating the respective drive current. Depending on the requirement of the user, color can be tuned in a wide range. So, special atmosphere illumination and active signage applications can be realized. However, this lateral patterning ends up in longer tact times, the necessity of (fine) lateral structures and therefore increased cost of production.

A very promising technology which is key to the success of white inorganic LEDs and which also has been successfully demonstrated with OLED<sup>10,11</sup> is the use of a blue pump source and the subsequent generation of white light by additional down-conversion layers. As the overall efficiency is directly related to the efficiency of the pump, the use of high efficient (phosphorescent) OLED is almost mandatory. Easy fabrication and the lack of differential color aging inside the OLED stack are the huge benefits of this method. By varying the thickness of the conversion layers the color can also be tuned in a wide range. However, today's limited stability of the blue (phosphorescent) OLED materials is limiting the wide application of this approach. Due to its high relevance to future OLED lighting applications, aspects of this approach will be discussed in more detail in the subsequent chapter.

Other more complex ideas to generate white light by utilizing e.g. exciplex emission<sup>12</sup> or up-conversion are not included into Figure 4 but are also under investigation by several groups.

### Blue & conversion OLED

In a down-conversion device a luminescence converting material (phosphor) coated on a blue light source absorbs a part of photons emitted by the light source and emits them at a longer wavelength. The non absorbed fraction of the photons emitted by the light source and the photons emitted by the phosphor constitute the output spectrum of the coated device. In 1997 Schlotter et al. were the first who introduced the down-conversion concept into inorganic solid state lighting technology<sup>10</sup>. In 2002 Duggal et al. presented an OLED-device offering illumination quality white light emission based on the same principle<sup>11</sup>. Finding appropriate luminescence converting materials for devices with underlying blue OLED characteristics is much more challenging than in the case of an inorganic LED, since organic EL spectra are typically about ~4 times broader than classical inorganic LED. For example, in most cases it is not possible to reach the Planckian locus by applying standard YAG:Ce3+ phosphor on a blue OLED (see fig. 5). To overcome this limitation more reddish phosphorescing converters have to be introduced such as nitridosilicates<sup>13</sup>. Using phosphor mixtures offers more freedom in creating individual colors of device emission (see fig. 5). This approach also allows generation of white light based on a variety of phosphorescent blue OLEDs typically emitting in the bluish green range of the visible spectrum.

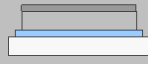
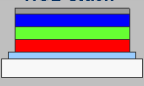
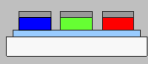
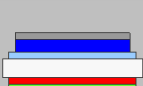
|             | single white emission                                                                                                                                                                                               | vertical RGB stack                                                                                                                                                                                                                | horizontal RGB stack                                                                                                                                                                                                       | blue & conversion                                                                                                                                                                                                                         |
|-------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Performance | <div>  </div> <ul style="list-style-type: none"> <li>o Performance defined by the polymer</li> <li>- Differential aging</li> </ul> | <div>  </div> <ul style="list-style-type: none"> <li>+ High efficiency</li> <li>- Differential aging</li> <li>- Complex device stack</li> </ul> | <div>  </div> <ul style="list-style-type: none"> <li>+ Active tunability</li> <li>+ Each color can be optimized individually</li> </ul> | <div>  </div> <ul style="list-style-type: none"> <li>+ No differential ageing</li> <li>+ Easy optimization</li> <li>o Depends on phos. blue</li> </ul> |
| Process     | <ul style="list-style-type: none"> <li>+ Easy process (printing)</li> </ul>                                                                                                                                         | <ul style="list-style-type: none"> <li>- Complex multi layer stacks deposited in vacuum</li> </ul>                                                                                                                                | <ul style="list-style-type: none"> <li>- Complex process with low fill factor</li> <li>- Topography needed?</li> </ul>                                                                                                     | <ul style="list-style-type: none"> <li>+ Easy blue printed or evaporated stack &amp; converter layers</li> </ul>                                                                                                                          |
|             | <ul style="list-style-type: none"> <li>+ High CRI</li> </ul>                                                                                                                                                        | <ul style="list-style-type: none"> <li>+ High CRI</li> <li>+ (active) tunability</li> </ul>                                                                                                                                       | <ul style="list-style-type: none"> <li>+ Active tunability</li> </ul>                                                                                                                                                      | <ul style="list-style-type: none"> <li>+ Customization</li> <li>+ Signage</li> </ul>                                                                                                                                                      |

Fig. 4. Different approaches could fulfill different application demands in time.

An advantageous side-effect of a down-conversion layer applied on top of a blue OLED can be enhanced light extraction due to scattering by the phosphor particles. Using a ray tracing model the extraction efficiency  $\eta_{s-a}$  as a function of normalized layer thickness was simulated for devices which comprise of a blue PLED panel and down-conversion layers containing YAG:Ce<sup>3+</sup> powders with different particle size distributions  $v_1(r)$ ,  $v_2(r)$ ,  $v_4(r)$  (see fig. 6). Here, we define  $\eta_{s-a}$  as the fraction of photons that is coupled into the substrate that is extracted into the ambient. Light extraction enhancement due to volumetric light scattering by particles in diffusive layers has already been investigated by Gärditz et al.<sup>14</sup> and Shiang et al.<sup>15</sup>. However, major differences between down-conversion layers and diffusive layers regarding the physical processes within the layers and the purpose of the substrate surface modifications exist. First of all, while in an ideal diffuse layer photons are only scattered by the embedded particles, in a down-conversion layer a fraction of the photons also undergoes *absorption and isotropic reemission*. Furthermore, the primary purpose of a phosphor layer is the color conversion from blue to white. To illustrate this, values of  $\eta_{s-a}$  related to similar color coordinates in the white region (CIE  $x/y \approx .32/.38$ ) are marked with a circle in each curve of Fig. 6. The phosphor particle distribution  $v_3(r)$  is most suitable for the efficient generation of white light. Here, according to simulation an extraction efficiency of  $\eta_{s-a} = 0.67$  can be reached, which was almost reached experimentally.

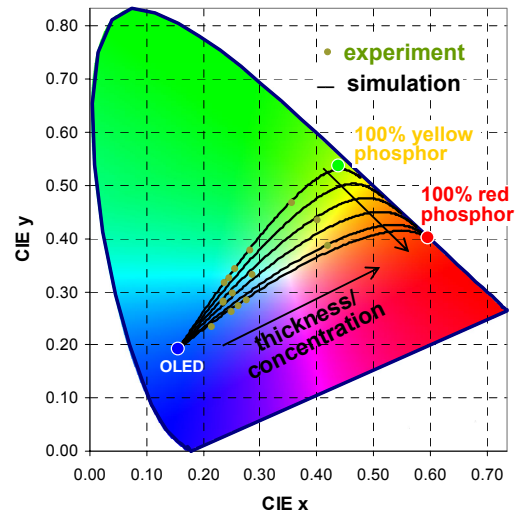


Fig. 5 CIE color-coordinates of simulated and measured down conversion OLEDs with different mixtures of yellow (YAG:Ce<sup>3+</sup>) and red (nitridosilicates) phosphors in one layer on top of a blue OLED. The pure yellow phosphor does not lead to white light generation. While the mixed phosphor layer enables a wide variety of achievable color coordinates with the same blue OLED (color on demand).

When optimizing diffuse layers for light extraction enhancement, there is complete freedom in the choice of appropriate layer parameters (layer thickness, particle loading and particle size). In contrast the optimization of down-conversion layers is restricted by the target color coordinates. In the optimum configuration the fraction of photons, which is necessary to reach the target color coordinates, is converted by the layer and at the same time scattering at the phosphor particles leads to efficient light extraction enhancement. This balance is given by the ratio between scattering and absorption within the layer. The average absorption cross section and the average scattering cross section related to a given phosphor powder are magnitudes which are determined by the particle size distribution, by the complex refractive index of the phosphor material, and by the refractive index of the surrounding matrix material. Hence, it seems hardly possible to develop general design guide-lines for the optimum phosphor particle size distribution. However, the presented results implicate a careful choice of the phosphor powder, since the particle size distribution has a significant impact on the resulting external device efficiency of white light emitting down-conversion OLEDs.

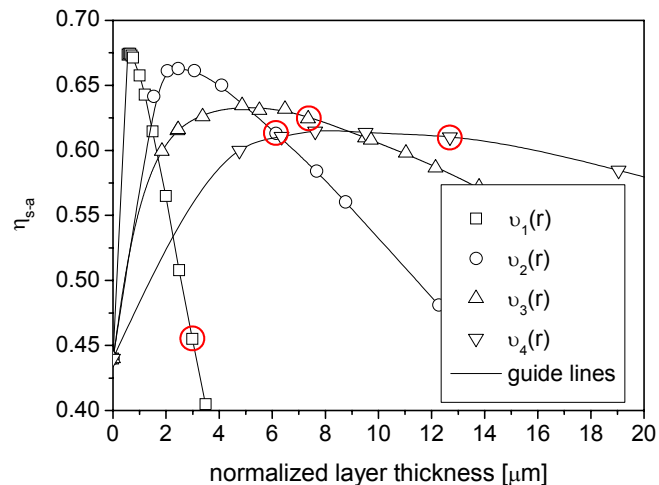


Fig. 6. Extraction efficiency  $\eta_{s-a}$  as a function of layer thickness, which has been obtained from simulation for each of the considered distributions of phosphor particle size. All data points related to similar color coordinates (CIE  $x/y \approx .32/.38$ ) are marked with a circle.

## Scaling to large areas

There are many hurdles to overcome when scaling a small, high performance OLED test device with proven efficiency and lifetime into a large area lighting panel. High performance devices typically consist of several layers, some of which are very thin and need to be kept in very narrow tolerances to maintain good device performance. For large OLED lighting panels one has to therefore guarantee these thickness tolerances over the full panel area to achieve the required homogeneity in brightness and color over the entire lifespan of the product. Simulations<sup>16</sup> can help to develop robust device architectures being less sensitive to layer thickness variations thus enabling maybe even simpler production concepts.

Another important topic when up-scaling the device area is defect density (huge field strengths across ultra-thin organic layers). E.g., 10 defects on average per  $\text{m}^2$  would still result in a excellent yield for test diodes measuring only a few  $\text{cm}^2$ , whereas for lighting tiles of about  $1\text{m}^2$  the yield will be down close to zero. Device architectures more tolerant to particles and/or approaches to healing defects after production are needed to pave the road to high yield large area OLED production.

## Current Spreading

Besides color-stability, efficiency and operational lifetime one major key to establish large area OLED lighting devices is also brightness homogeneity. The resistance of the transparent electrode, normally consisting of TCOs (transparent conductive oxides) like ITO (indium tin oxide), leads to a voltage drop across the active area. This lateral voltage drop causes variations in local driving voltage thus brightness (and maybe even color) variations, e.g. the brightness decreases with increasing distance to the well conducting supply line. To illustrate this behavior in figure 7 a cross-sectional cut through the radiance profile of a lighting tile is shown. There, a comparison of a finite element simulation of an OLED with an experiment is made. The simulation using experimentally determined LIV characteristics of a similar built small test diode, which is then put into a diode model, shows excellent agreement with the experiment. Using this powerful tool, homogeneity can now be predicted and greatly improved without having to make several large area test devices. The most straight forward approach to overcome voltage drops current spreading systems like metal bus bar structures have to be introduced<sup>17, 18, 19</sup>.

A further aspect impacting brightness uniformity ( $t_0$  as well as after lifetime), which can also be taken into account in this simulation tool, is thermal heating during device operation. This leads to both a change in the diode characteristics and a further enhancement of the radiance drop<sup>20</sup> as well as differential aging.

## 2.2 OLED Features - Paving the way towards new lighting applications

The OLED stack itself is thin, flat, and light-weight, potentially transparent and flexible, and can be controlled by electronic gear quite easily, both in brightness and color. Unfortunately, today's way of OLED production, which includes the use of glass substrates, a metal cathode, and a bulky encapsulation concept, prevents many of these features to be transferred into a product. To fulfill the desire for design flexibility and individualization, development of the substrate technology (thin and transparent), of transparent electrodes (TCO or thin metal film), and of a low cost transparent and flexible encapsulation concept are key to make OLED lighting successful not only as a niche product but as a broad scope new lighting technology.

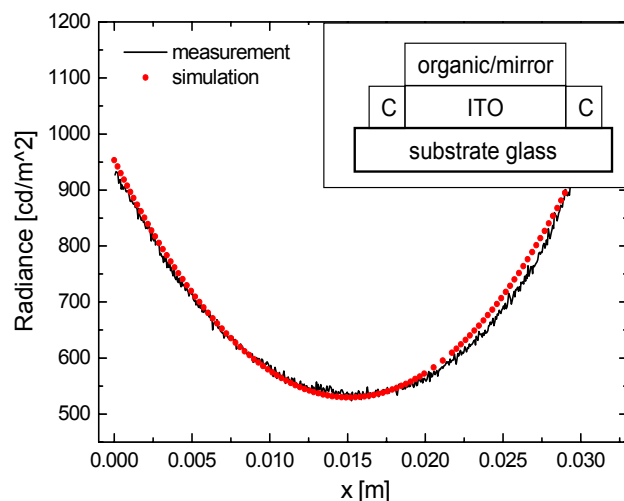


Fig. 7. Cross-sectional cut through the radiance profile of an OLED lighting tile. The inset shows schematically the geometry. C denotes the supply line to ITO.

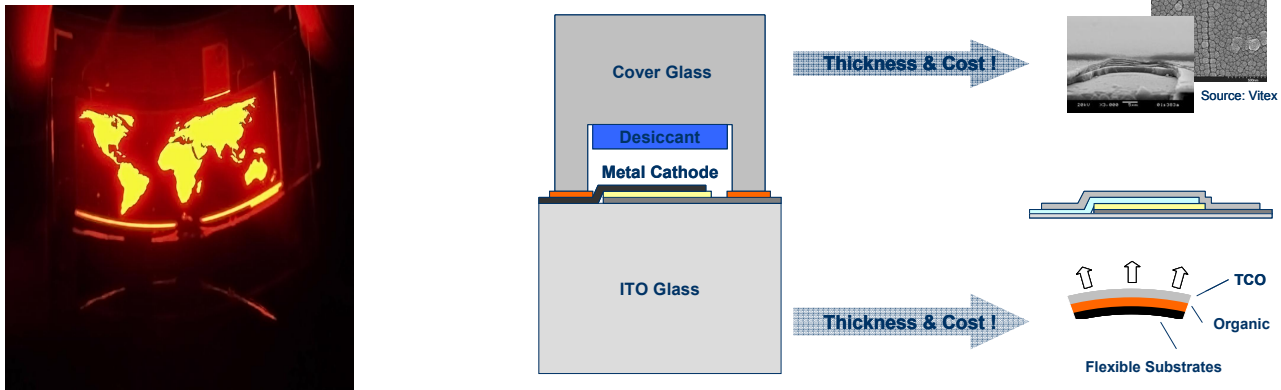


Fig. 8. Fully flexible and at the same time highly transparent OLED light sources are the holy grail of the OLED lighting community. To achieve this, flexible transparent substrates, electrodes, and encapsulation concepts are needed.

Below table gives an overview over the different features of OLED lighting technology as well as an indication on the availability and the major challenges on the way to achieve the respective feature.

| Feature                                                 | Availability (when)   | Challenges on the way                                                                                                                                                                      |
|---------------------------------------------------------|-----------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Pleasant diffused light source                          | now                   | - scaling to large area                                                                                                                                                                    |
| Instant-on feature                                      | now                   |                                                                                                                                                                                            |
| Environmentally friendly (free of Hg)                   | now                   |                                                                                                                                                                                            |
| Electronic color control                                | now / next generation | - stable device performance over dimming<br>- non laterally structured architectures that allow color tuning like intermediate electrodes or approaches with voltage depending color point |
| Transparency                                            | now / next generation | - transparent electrodes and substrate/encapsulation                                                                                                                                       |
| Thin, flat and light weight                             | now / next generation | - alternative substrate materials to glass<br>- thin film encapsulation concept suitable for large are and low cost manufacturing                                                          |
| Design flexibility: Variable shape (2D), fully flexible | now / future          | - flexible substrates (barrier layers)<br>- flexible electrodes (ITO?)<br>- flexible encapsulation                                                                                         |

Table 1. The key features of OLED lighting.

## Flexibility

Flexible OLED light source technology mainly is relying on providing sufficient permeation barriers on transparent and flexible substrates (and/or encapsulation). For today's OLEDs permeation barriers for water of less than  $10^{-6}$  g/m<sup>2</sup>·day @ RT are required which can be fulfilled by e.g. glass (but not flexible) or metal films (but not transparent - as top emitter possible). Flexible and at the same time transparent substrates are mainly plastic films but even highly engineered polymers reach only  $10^{-1}$  g/m<sup>2</sup>·day.

Coating of plastic films (mono- or multilayer) is one possible approach and first devices built on PET and PES have shown the potential of this approach. Another possibility was to make the OLED stack itself less sensitive to oxygen and water (e.g. organic photo voltaics typically only demands 1 to 2 orders of magnitude less permeation barrier quality) but less reactive injection cathode approaches need to be developed here.

Another challenge, especially with encapsulation, is obtaining a barrier layer which is free of defects. Whereas this is a challenge already for non-flexible OLEDs, it will be one of the key milestones towards flexible devices. Making the barrier itself dense enough for OLED is one thing, but achieving this over m<sup>2</sup> without generating cracks or pinholes is an

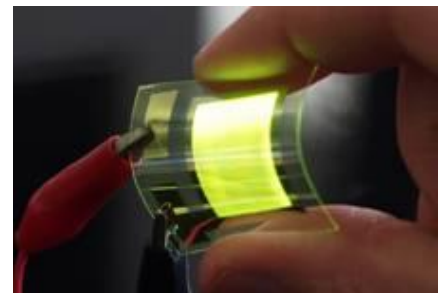


Fig. 9. Flexible OLED device made at Siemens CT with unchanged LIV performance while bending.

other. Conformal coating technologies, multi-barrier concepts, and clever planarization layers are needed to achieve good permeation barriers over large areas.

If highest flexibility (small bending curvatures) are required, even today's TCOs like ITO are no longer suitable and alternative electrode concepts (organic?) are required.

## Transparency

The most common approach towards transparency is the use of a standard transparent substrate with an integrated transparent electrode (e.g. ITO on glass) and replacing the standard metal top electrode by a transparent one. This transparent top electrode not only grants access to transparent devices but also will enable the use of opaque (but flexible or cheap) substrates where the light needs to be coupled out through the 'backdoor'. Many OLED display players like Samsung SDI and Sony have already demonstrated top emission and/or transparent displays. The approaches used vary from using TCOs (ITO, ATO, ZnO, etc.) or thin metal films, TMFs (on top of which subsequently an anti-reflection coating could be applied). The major challenges here are homogeneity of brightness and color, both over area as well as over viewing angle, making the transparent structures conductive enough for the current driven OLED devices, and, finally, finding a deposition process that is compatible with the sensitive OLED stack and that is robust and fast enough to be transferred into mass production.

OLEDs in general typically show less or more pronounced color-shifts over the viewing angle. This behavior is mainly due to interference effects between directly emitted photons and photons reflected at the metal electrode. In diodes containing broadband emission a blue shift of the spectrum with increasing viewing angle is observed as the red part of the spectra is suppressed by destructive interference<sup>21</sup>. Also influences of the wavelength dependent refraction indices may be present. Without taking countermeasures like tuning the so-called  $\mu$ -cavity, thin metal films, which from the view of processing on top of the organics have many advantages, would be inferior compared to TCOs. Another disadvantage of TMFs is the thinness requirements of the metal film (about 10 nm for silver) making it difficult to accurately control the thickness over large areas as well as getting enough current through the electrode to drive the OLED. There is no clear trend visible in the community, whether TCOs or TMFs finally will make their way into mass production of OLED lighting.

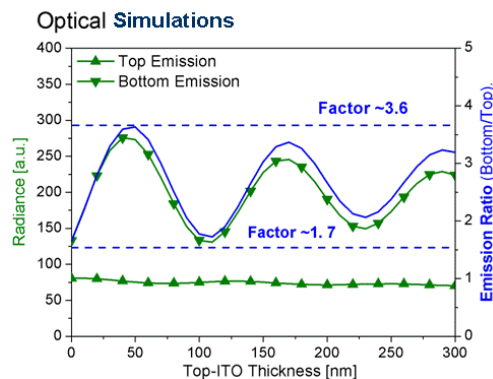
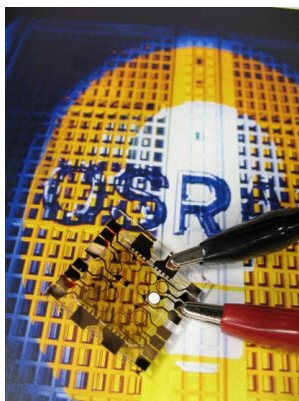


Fig. 10. Transparent OLED test diode. A package transmissivity of more than 68 % (average 450-750nm) was achieved. Moreover, by tuning the thickness of the transparent top ITO contact, the ratio of emission to top and bottom could be changed by more than a factor of 2.

## 2.3 OLED production costs - The route towards low cost manufacturing

And then we have to make it affordable. First OLED niche applications may tolerate higher production costs, which still should be well below those for OLED displays per unit area, but real breakthrough concepts need to clearly show the potential to get in the range of typical lighting applications.

Next to the need of suitable front-of-line (FoL, i.e. substrates with first electrode structures) and end-of-line (EoL, i.e. the encapsulation) processes, the key challenge of low cost OLED manufacturing is high rate deposition of the OLED stack itself at high yield without sacrificing the molecules and the performance of the mainly very complex multi-layer systems.

High rate deposition of the organic layers likely will, by its growth kinetics, have a major impact on the resulting layer morphology. As the basic device characteristics are dominated by the layers' morphology as well as the interface properties, the device performance (initial or over lifetime) is likely to be influenced by the deposition and therefore production concept. Alternative source concepts and/or suitable post treatment of the organic layers for achieving a well-controlled morphology and interface need to be developed to fulfill the requirements of low cost OLED lighting production.

Other important cost contributors are FoL and EoL. Today's lithographically structured ITO glass is too expensive to be used beyond pilot production. This has mainly two reasons, the lavish photolithography process itself, which is needed for the small feature sizes of OLED displays but is not necessary for defining lighting features, as well as the indium prices, which rose from below 100 USD/kg in 2003 to more than 1000 USD/kg in 2005. This trend will continue as limited Indium also fuels for the flat panel display industry. Litho and ITO free substrates are to be developed with a surface roughness suitable to deposit the ultra-thin OLED stacks on top. Also OLED display state-of-the-art EoL, glass plates exhibiting a cavity filled with desiccant, need to be replaced by low cost solutions. Conformal, low cost thin film encapsulation processes, as being developed by e.g. Vitex and OTB<sup>22,23</sup> are required to get production cost in the target range.

Other important areas of interest for cost reduction are a well adapted test concept, choice of mechanical and electrical components for module assembly, standardization of the mechanical and electrical interfaces, as well as a deep understanding of the defect mechanisms of large area organic diodes.

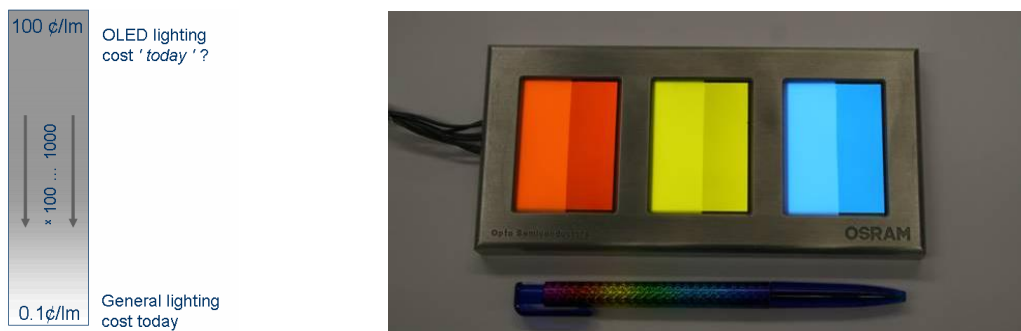


Fig. 11. A proper production concept, improvement of efficiency (more light at the same area cost) and improvement of lifetime (sustain more light at the same cost) are needed to fulfill the cost requirements. E.g., a cost effective and color independent light extraction significantly reduces the cost per lumen. This is shown on the right of Fig. 11, the same light extraction means is applied to 3 different colors on the respective left half of the lighting tile.

### 3. OLED LIGHTING APPLICATIONS

Large area diffuse OLED lighting is a perfect technology to realize applications that can follow the increased awareness for creation of atmosphere, ambience, and mood lighting. The unique features of OLED, based on the extremely thin, flexible, and transparent OLED stack itself, enable the infrastructure of light to integrate into materials which offers designers and customers highest degree in individualization, differentiation, and customization.

Not all features will be accessible from the very beginning of the technology and 1<sup>st</sup> generation applications will be based on those features which can be more easily realized. This maybe include signage and accessoires applications based on the thin, flat, and diffuse nature of the OLED tech-

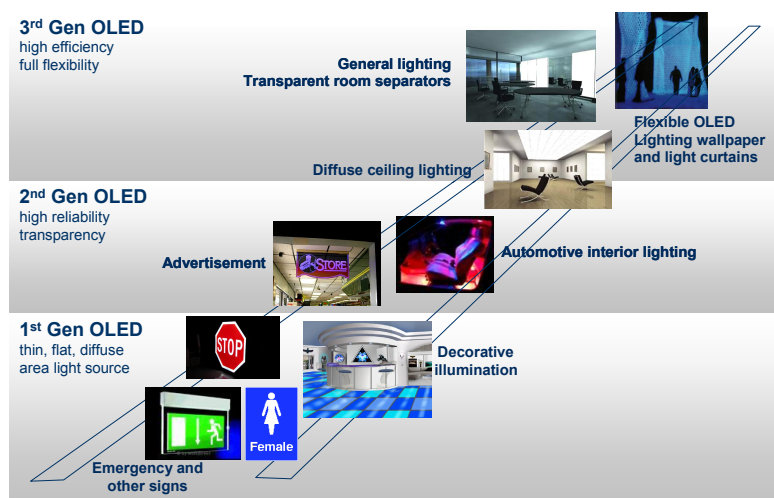


Fig. 12. Street in the future of illumination with OLED technology.

nology

With growing maturity of the technology, more demanding applications like e.g. automotive and luminaires will join in driven by completely new degrees of design flexibility. Finally, general illumination applications indoor and outdoor will be accessible which, next to the re-definition of the aesthetics of architectural materials will also allow the reduction of visible obstacles by the diffuse, glare free area illumination and thereby generate a comfortable ambience.

It are the unique features of OLED lighting:

- Thin, flat, and light weight
- Pleasant diffused light source
- Transparency
- Electronic control
- Design flexibility: variable shape, bendable, flexible
- Instant-on feature
- Environmentally friendly (free of Hg)

which form the basis of new lighting applications but not all applications will demand all those features all at once.

Possible OLED applications will not only differ in features they also differ in their basic performance requirements. Figure 13 shows three exemplary areas of application including a summary of their specifications.

Whereas signage applications are typically in the 100 nits range, the requirements for LCD backlighting would be some 2 orders of magnitude higher. For high brightness applications, efficiency clearly will play a more dominant role than for lower brightness purposes.

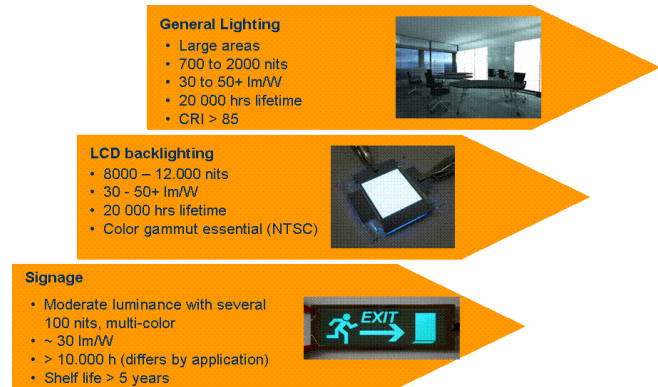


Fig. 13. Summary target specifications of exemplary OLED lighting applications.

## 4. SUMMARY

Large area diffuse OLED lighting is a perfect technology to realize applications that can follow the increased awareness for creation of atmosphere, ambience, and mood lighting. The unique features of OLED enable the infrastructure of light to integrate into materials which offers designers and customers highest degree in individualization, differentiation, and customization.

But before OLED lighting becomes a mainstream technology, it will have to master its three key challenges. First, meeting the common lighting targets reliability, efficiency, and color quality. Secondly, maintain the unique features offered by the OLED film itself (e.g. flexibility, thinness), and last but not least meet the cost targets.

Not all of the above challenges will be fully mastered in the beginning of OLED technology finding its way into early applications. There will be maybe first signage and accessoires applications and with growing maturity of the technology, more demanding applications like e.g. automotive and luminaires will join in. Finally, general illumination applications indoor and outdoor will be accessible.

OLED area illumination will pave the way for applications that up to now could not have been realized – light where it never has been before.

## ACKNOWLEDGEMENTS

The authors would like to thank the German Federal Ministry of Education and Research (BmbF) for funding part of this work under contract FKZ 13N8995 (OPAL).

## REFERENCES

1. Frost & Sullivan, EMERGING LIGHTING SYSTEMS - A TECHNOLOGY ANALYSIS, D389 (2005)

2. Website of the German Federal Ministry of Education and Research (BmbF), <http://www.bmbf.de>
3. P. Harrop, R. Das, IDTechEx, "Organic Electronics: Forecasts, Players, Opportunities, 2005-2025" (2006)
4. C. Tang, S. VanSlyke, Appl. Phys. Lett., **51**, 913-15 (1987)
5. J. Burroughes, D. Bradley, A. Brown, R. Markus, K. Mackay, R. Friend, P. Burns, and A. Holmes, Nature, **347**, 539-41 (1990)
6. G. He, K. Walzer, M. Pfeiffer, and K. Leo, Proc. SPIE, **5464** (1), 26-31, Strasbourg, France (2004)
7. Press release - <http://www.heise.de/tr/artikel/mail/75112> (2006)
8. Press release - [http://www.digitalworldtokyo.com/2006/06/konica\\_minolta\\_claims\\_oled\\_bre\\_1.php](http://www.digitalworldtokyo.com/2006/06/konica_minolta_claims_oled_bre_1.php) (2006)
9. C.D. Müller, N. Reckefuss, P. Rudati, K. Meerholz, H. Becker, A. Falcou, S. Heun, J. Steiger, M. Rojahn, V. Wiederhirn, and O. Nuyken, Proc. SPIE, **5214**(1), 21-30, San Diego, USA (2004)
10. P. Schlotter, R. Schmidt, and J. Schneider, Appl. Phys. A **64**, 417 (1997)
11. A.R. Duggal, J.J. Shiang, C.M. Heller, and D.F. Foust, Appl. Phys. Lett. **80**, 3470 (2002)
12. J. Feng, Appl Phys. Lett. **78** (2001)
13. B. Krummacher, V.-E. Choong, M.K. Mathai, S.A. Choulis, F. So, F. Jermann, T. Fiedler, and M. Zachau, Appl. Phys. Lett. **88**, 260611 (2006)
14. C. Gärditz, R. Paetzold, D. Buchhauser, R. Bathelt, G. Gieres, C. Tschamber, A. Hunze, K. Heuser, A. Winnacker, J.R. Niklas, J. Amelung, and D. Kunze, Proceedings of the SPIE, **5937**, 94-105 (2005)
15. J.J. Shiang, T.J. Faircloth, and A.R. Duggal, J. of Appl. Physics, **95**, 2889-2895 (2004)
16. J. Staudigel, M. Stößel, F. Steuber, J. Simmerer, J. App. Phys. **86**(7), 3895 (1999)
17. C. Gärditz et al. Appl. Phys. Lett. submitted (2006)
18. C. Piliego et al., Appl. Phys. Lett. **89**, 103514 (2006)
19. C. Gärditz, R. Paetzold, D. Buchhauser, J. Wecker, and A. Winnacker, Proceedings of the SPIE **6192**, 61920W (2006)
20. R. Sprengard et al., Proc. SPIE **5519**, 173 (2004).
21. H. Becker, S. E. Burns, N. Tessler, and R. H. Friend, J. Appl. Phys. **81**, 2825-2829 (1997)
22. Vitex Systems Inc. - <http://www.vitexsys.com/encapsulation.html> (2006)
23. OTB - [http://www.otbdisplay.com/display/technologies/technologies\\_pecvd.html](http://www.otbdisplay.com/display/technologies/technologies_pecvd.html) (2006)

**PROCEEDINGS VOLUME 6486**

INTEGRATED OPTOELECTRONIC DEVICES 2007 | 20-25 JANUARY 2007

**Light-Emitting Diodes: Research,  
Manufacturing, and Applications XI**

Editor(s): [Klaus P. Streubel \(/profile/Klaus.Streubel-12567\)](/profile/Klaus.Streubel-12567), [Heonsu Jeon \(/profile/Heonsu.Jeon-14544\)](/profile/Heonsu.Jeon-14544)

[Editor Affiliations + \(\)](#)

INTEGRATED OPTOELECTRONIC  
DEVICES 2007

20-25 January 2007

San Jose, California, United States

[View the SPIE Conference + Exhibitions  
Calendar \(https://spie.org/conferences-and-  
exhibitions?webSyncID=d4053e3e-812d-  
20a2-8794-  
b014226a769c&sessionGUID=bad1c6eb-  
c282-353c-2873-b562454d0ede\)](https://spie.org/conferences-and-exhibitions?webSyncID=d4053e3e-812d-20a2-8794-b014226a769c&sessionGUID=bad1c6eb-c282-353c-2873-b562454d0ede)

**IN THIS VOLUME**

*10 Sessions, 36 Papers, 0 Presentations, 0 Posters*

**Front Matter: Volume 6486** (1)

**Novel Technologies for LEDs** (4)

**Fabrication of LEDs and OLEDs** (2)

**Organic LEDs** (5)

**LED Characterization and Reliability** (5)

**Photonic Crystals: LED Modeling** (4)

**LED Modeling: Phosphors** (4)**Session 7** (5)**Session 8** (3)**Poster Session** (3)[Subscribe to Digital Library \(/subscribe-page\)](/subscribe-page)[VIEW ALL ABSTRACTS](#) + ()**FRONT MATTER: VOLUME 6486****Front Matter: Volume 6486** (/conference-proceedings-of-spie/6486/648601/Front-Matter-Volume-6486/10.1117/12.727556.full)

Open Access Paper

Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 648601 (2007) <https://doi.org/10.1117/12.727556>  
(<https://doi.org/10.1117/12.727556>)[Read Abstract +](#)**NOVEL TECHNOLOGIES FOR LEDS****Fundamental mechanisms of electroluminescence refrigeration in heterostructure light-emitting diodes**

(/conference-proceedings-of-spie/6486/648604/Fundamental-mechanisms-of-electroluminescence-refrigeration-in-heterostructure-light-emitting-diodes/10.1117/12.701301.full) Paper

*S.-Q. Yu* (/profile/Shui-Qing.Yu-38852), *J.-B. Wang* (/profile/Jiangbo.Wang-38850), *D. Ding* (/profile/Ding.Ding-38853), *S. R. Johnson* (/profile/Shane.Johnson-22886), *D. Vasileska*, *Y.-H. Zhang* (/profile/Yong-Hang.Zhang-14445).

Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 648604 (2007) <https://doi.org/10.1117/12.701301>  
(<https://doi.org/10.1117/12.701301>)

[Read Abstract +](#)

### **Nonperiodic binary optical structures for enhancing light extraction of emitters** (/conference-proceedings-of-

spie/6486/648605/Nonperiodic-binary-optical-structures-for-enhancing-light-extraction-of-emitters/10.1117/12.701783.full)  Paper

*Liming Hong*, *Xiaodong Hu* (/profile/Xiaodong.Hu-35692), *Tao Yu*, *Tao Dai*, *Zhensheng Zhang*, *Jun Xu*, *Guoyi Zhang*

Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 648605 (2007) <https://doi.org/10.1117/12.701783>  
(<https://doi.org/10.1117/12.701783>)

[Read Abstract +](#)

### **High light-extraction efficiency in GaInN light-emitting diode with pyramid reflector** (/conference-proceedings-of-

spie/6486/648606/High-light-extraction-efficiency-in-GaInN-light-emitting-diode-with/10.1117/12.707267.full)  Paper

*J.-Q. Xi* (/profile/Jingqun.Xi-49540), *Hong Luo*, *Jong Kyu Kim* (/profile/Jong-Kyu.Kim-61280), *E. F. Schubert* (/profile/E.-Fred.Schubert-16285).

Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 648606 (2007) <https://doi.org/10.1117/12.707267>  
(<https://doi.org/10.1117/12.707267>)

[Read Abstract +](#)

### **LED engine hosted on a THS** (/conference-proceedings-of-spie/6486/648607/LED-engine-hosted-on-a-THS/10.1117/12.705258.full)

 Paper

*Maurizio Checchetti* (/profile/Maurizio.Checchetti-10516).

Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 648607 (2007) <https://doi.org/10.1117/12.705258>  
(<https://doi.org/10.1117/12.705258>)

[Read Abstract +](#)

## **FABRICATION OF LEDS AND OLEDS**

### **Dicing of high-power white LEDs in heat sinks with the water jet-guided laser** (/conference-proceedings-of-

spie/6486/64860A/Dicing-of-high-power-white-LEDs-in-heat-sinks-with/10.1117/12.701059.full)  Paper

*Tuan Anh Mai* (/profile/Tuan-Anh.Mai-23609), *Roy Housh*, *Arnaud Brulé* (/profile/Arnaud.Brule-91789), *Bernold Richerzhagen*

Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 64860A (2007) <https://doi.org/10.1117/12.701059>  
(<https://doi.org/10.1117/12.701059>)

[Read Abstract +](#)

---

**Integration of high-efficiency PIN organic light-emitting devices in lighting and optoelectronic applications**[\(/conference-proceedings-of-spie/6486/64860C/Integration-of-high-efficiency-PIN-organic-light-emitting-devices-in/10.1117/12.697341.full\)](https://doi.org/10.1117/12.697341.full) Paper

*J. Amelung* (</profile/Jorg.Amelung-17135>), *M. Toerker* (</profile/Michael.Toerker-68258>), *Y. Tomita* (</profile/Yuto.Tomita-68259>), *D. Kreye* (</profile/Daniel.Kreye-74545>), *C. Grillberger*, *U. Vogel*, *A. Elgner*, *M. Eritt*, *Ch. May*, *et al.*

Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 64860C (2007) <https://doi.org/10.1117/12.697341>  
(<https://doi.org/10.1117/12.697341>)

[Read Abstract +](#)

## ORGANIC LEDS

---

**New architectures for high performance polymer light-emitting diodes introducing a solution-processed**

**titanium oxide layer** ([/conference-proceedings-of-spie/6486/64860D/New-architectures-for-high-performance-polymer-light-emitting-diodes-introducing/10.1117/12.714662.full](https://doi.org/10.1117/12.714662.full))  Paper

*Sun Hee Kim* (</profile/Sun-Hee.Kim-57020>), *Jin Young Kim* (</profile/Jin-Young.Kim-69330>), *Sung Heum Park* (</profile/Sung-Heum.Park-65454>), *Kwanghee Lee* (</profile/Kwanghee.Lee-19380>).

Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 64860D (2007) <https://doi.org/10.1117/12.714662>  
(<https://doi.org/10.1117/12.714662>)

[Read Abstract +](#)

**OLED lighting: light where it never has been before** ([/conference-proceedings-of-spie/6486/64860E/OLED-lighting-light-where-it-never-has-been-before/10.1117/12.715299.full](https://doi.org/10.1117/12.715299.full))  Paper

*M. Klein* (</profile/Markus.Klein-81714>), *K. Heuser* (</profile/Karsten.Heuser-29238>), *F. Schindler*, *B. Krummacher* (</profile/Benjamin.Krummacher-89856>), *T. Dobbartin* (</profile/Thomas.Dobbartin-44988>), *R. Pätzold*, *C. Gärditz*

Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 64860E (2007) <https://doi.org/10.1117/12.715299>  
(<https://doi.org/10.1117/12.715299>)

[Read Abstract +](#)

**See-through OLED displays** ([/conference-proceedings-of-spie/6486/64860F/See-through-OLED-displays/10.1117/12.696402.full](https://doi.org/10.1117/12.696402.full))  Paper

*W. Kowalsky*, *P. Görrn*, *J. Meyer* (</profile/Jens.Meyer-30020>), *M. Kröger* (</profile/Michael.Kroger-51279>), *H.-H. Johannes*, *T. Riedl*

Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 64860F (2007) <https://doi.org/10.1117/12.696402>  
(<https://doi.org/10.1117/12.696402>)

[Read Abstract +](#)


---

**Fabrication of polymer LEDs by resonant infrared pulsed laser ablation** ([/conference-proceedings-of-spie/6486/64860G/Fabrication-of-polymer-LEDs-by-resonant-infrared-pulsed-laser-ablation/10.1117/12.701295.full](#))  Paper  
*S. L. Johnson* ([/profile/Stephen.Johnson-60847](#)), *C. T. Bowie*, *B. Ivanov* ([/profile/Borislav.Ivanov-31545](#)), *H. K. Park* ([/profile/Hee.Park-104874](#)), *R. F. Haglund Jr.* ([/profile/Richard.Haglund-5456](#))  
 Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 64860G (2007) <https://doi.org/10.1117/12.701295>  
<https://doi.org/10.1117/12.701295>

[Read Abstract +](#)


---

**Employing a 2D surface grating to improve light out coupling of a substrate emitting organic LED** ([/conference-proceedings-of-spie/6486/64860H/Employing-a-2D-surface-grating-to-improve-light-out-coupling/10.1117/12.701344.full](#))  Paper  
*Peter Vandersteegen* ([/profile/Peter.Vandersteegen-78285](#)), *Angel Ullan Nieto*, *Carl Van Buggenhout*, *Steven Verstuyft*, *Peter Bienstman*, *Peter Debackere* ([/profile/Peter.Debackere-78279](#)), *Kristiaan Neyts* ([/profile/Kristiaan.Neyts-37176](#)), *Roel Baets* ([/profile/Roel.Baets-8966](#))  
 Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 64860H (2007) <https://doi.org/10.1117/12.701344>  
<https://doi.org/10.1117/12.701344>

[Read Abstract +](#)

## LED CHARACTERIZATION AND RELIABILITY

---

**Measurement of the internal quantum efficiency of InGaN quantum wells** ([/conference-proceedings-of-spie/6486/64860J/Measurement-of-the-internal-quantum-efficiency-of-InGaN-quantum-wells/10.1117/12.700829.full](#))  Paper  
*A. Laubsch* ([/profile/Ansgar.Laubsch-78337](#)), *M. Sabathil* ([/profile/Matthias.Sabathil-78307](#)), *G. Bruederl*, *J. Wagner* ([/profile/Hans-Joachim.Wagner-6115](#)), *M. Strassburg* ([/profile/Martin.Strassburg-5239](#)), *E. Baur*, *H. Braun* ([/profile/Harald.Braun-79070](#)), *U. T. Schwarz* ([/profile/Ulrich.Schwarz-46260](#)), *A. Lell*, et al.  
 Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 64860J (2007) <https://doi.org/10.1117/12.700829>  
<https://doi.org/10.1117/12.700829>

[Read Abstract +](#)


---

**Design and implementation of real-time LED spatial radiance measurement systems** ([/conference-proceedings-of-spie/6486/64860K/Design-and-implementation-of-real-time-LED-spatial-radiance-measurement/10.1117/12.701665.full](#))  Paper  
*Gao-Wei Chang* ([/profile/Gao-Wei.Chang-22837](#)), *Zong-Mu Yeh*, *Chia-Cheng Liao* ([/profile/Chia-Cheng.Liao-73842](#))  
 Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 64860K (2007) <https://doi.org/10.1117/12.701665>  
<https://doi.org/10.1117/12.701665>

[Read Abstract +](#)


---

**Studies of InGaN LEDs degradation** (</conference-proceedings-of-spie/6486/64860L/Studies-of-InGaN-LEDs-degradation/10.1117/12.697277.full>)  Paper

*O. I. Rabinovich* (</profile/Oleg.Rabinovich-77593>), *F. I. Manyakhin*, *E. K. Naimi*, *S. G. Nikiforov*, *V. P. Sushkov*, *I. G. Ermoshin*, *A. V. Shishov*

Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 64860L (2007) <https://doi.org/10.1117/12.697277>  
(<https://doi.org/10.1117/12.697277>)

[Read Abstract +](#)


---

**Prediction of intensity and color degradation of LEDs** (</conference-proceedings-of-spie/6486/64860M/Prediction-of-intensity-and-color-degradation-of-LEDs/10.1117/12.698987.full>)  Paper

*Miran Bürmen* (</profile/Miran.Burmen-78159>), *Franjo Pernuš*, *Boštjan Likar* (</profile/Bostjan.Likar-22053>)

Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 64860M (2007) <https://doi.org/10.1117/12.698987>  
(<https://doi.org/10.1117/12.698987>)

[Read Abstract +](#)


---

**Thermally induced stresses resulting from coefficient of thermal expansion differentials between an LED sub-mount material and various mounting substrates** (</conference-proceedings-of-spie/6486/64860N/Thermally-induced-stresses-resulting-from-coefficient-of-thermal-expansion-differentials/10.1117/12.697489.full>)  Paper

*Charles DeMilo*, *Corey Bergad*, *Ronald Forni*, *Thomas Brukilacchio* (</profile/Thomas.Brukilacchio-7147>)

Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 64860N (2007) <https://doi.org/10.1117/12.697489>  
(<https://doi.org/10.1117/12.697489>)

[Read Abstract +](#)

## PHOTONIC CRYSTALS: LED MODELING

---

**Manufacturing implications for photonic crystal patterning using imprint lithography** (</conference-proceedings-of-spie/6486/64860Q/Manufacturing-implications-for-photonic-crystal-patterning-using-imprint-lithography/10.1117/12.715220.full>)  Paper

*Chris Jones* (</profile/cejones>), *David Lentz*, *Gary Doyle*, *Mike Miller*, *Maha Ganapathisubramanian*, *Xiaoming Lu*, *Doug Resnick* (</profile/Douglas.Resnick-6536>), *Dwayne L. LaBrake*

Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 64860Q (2007) <https://doi.org/10.1117/12.715220>  
(<https://doi.org/10.1117/12.715220>)

[Read Abstract +](#)

---

**Photonic quasi-crystal LEDs: design, modelling, and optimisation** ([/conference-proceedings-of-spie/6486/64860R/Photonic-](/conference-proceedings-of-spie/6486/64860R/Photonic-quasi-crystal-LEDs-design-modelling-and-optimisation/10.1117/12.715025.full)[quasi-crystal-LEDs-design-modelling-and-optimisation/10.1117/12.715025.full](/conference-proceedings-of-spie/6486/64860R/Photonic-quasi-crystal-LEDs-design-modelling-and-optimisation/10.1117/12.715025.full))  Paper[M. D. B. Charlton](/profile/Martin.Charlton-26087) (</profile/Martin.Charlton-26087>), [M. E. Zoorob](/profile/M.E.Zoorob), [T. Lee](/profile/T.Lee)Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 64860R (2007) <https://doi.org/10.1117/12.715025>  
(<https://doi.org/10.1117/12.715025>)[Read Abstract +](#)

---

**Modeling of GaN based resonant-cavity light-emitting diode** ([/conference-proceedings-of-spie/6486/64860S/Modeling-of-GaN-](/conference-proceedings-of-spie/6486/64860S/Modeling-of-GaN-based-resonant-cavity-light-emitting-diode/10.1117/12.696651.full)[based-resonant-cavity-light-emitting-diode/10.1117/12.696651.full](/conference-proceedings-of-spie/6486/64860S/Modeling-of-GaN-based-resonant-cavity-light-emitting-diode/10.1117/12.696651.full))  Paper[Z. Simon Li](/profile/Zhiqiang.Li-69481), [Z. Q. Li](/profile/Zhiqiang.Li-69481) (</profile/Zhiqiang.Li-69481>), [Ray-Hua Horng](/profile/Ray-Hua.Horng-118943) (</profile/Ray-Hua.Horng-118943>).Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 64860S (2007) <https://doi.org/10.1117/12.696651>  
(<https://doi.org/10.1117/12.696651>)[Read Abstract +](#)

---

**A generalized 2D and 3D white LED device simulator integrating photon recycling and luminescent spectral****conversion effects** ([/conference-proceedings-of-spie/6486/64860T/A-generalized-2D-and-3D-white-LED-device-simulator-](/conference-proceedings-of-spie/6486/64860T/A-generalized-2D-and-3D-white-LED-device-simulator-integrating/10.1117/12.698687.full)[integrating/10.1117/12.698687.full](/conference-proceedings-of-spie/6486/64860T/A-generalized-2D-and-3D-white-LED-device-simulator-integrating/10.1117/12.698687.full))  Paper[Wei-Choon Ng](/profile/Wei-Choon.Ng-34136) (</profile/Wei-Choon.Ng-34136>), [Gergö Letay](/profile/Gergoe.Letay-70911) (</profile/Gergoe.Letay-70911>)Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 64860T (2007) <https://doi.org/10.1117/12.698687>  
(<https://doi.org/10.1117/12.698687>)[Read Abstract +](#)

---

**LED MODELING: PHOSPHORS**

---

**Statistical analysis and yield management in LED design through TCAD device simulation** ([/conference-proceedings-of-](/conference-proceedings-of-spie/6486/64860U/Statistical-analysis-and-yield-management-in-LED-design-through-TCAD/10.1117/12.698850.full)[spie/6486/64860U/Statistical-analysis-and-yield-management-in-LED-design-through-TCAD/10.1117/12.698850.full](/conference-proceedings-of-spie/6486/64860U/Statistical-analysis-and-yield-management-in-LED-design-through-TCAD/10.1117/12.698850.full))  Paper[Gergö Létay](/profile/Gergoe.Letay-70911) (</profile/Gergoe.Letay-70911>), [Wei-Choon Ng](/profile/Wei-Choon.Ng-34136) (</profile/Wei-Choon.Ng-34136>), [Lutz Schneider](/profile/Lutz.Schneider-32298) (</profile/Lutz.Schneider-32298>), [Adrian Bregy](#), [Michael Pfeiffer](#)Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 64860U (2007) <https://doi.org/10.1117/12.698850>  
(<https://doi.org/10.1117/12.698850>)[Read Abstract +](#)

---

**Self-consistent modeling of resonant PL in InGaN SQW LED-structure** ([/conference-proceedings-of-spie/6486/64860V/Self-](/conference-proceedings-of-spie/6486/64860V/Self-consistent-modeling-of-resonant-PL-in-InGaN-SQW-LED/10.1117/12.700461.full)[consistent-modeling-of-resonant-PL-in-InGaN-SQW-LED/10.1117/12.700461.full](/conference-proceedings-of-spie/6486/64860V/Self-consistent-modeling-of-resonant-PL-in-InGaN-SQW-LED/10.1117/12.700461.full))  Paper

[M. Sabathil \(/profile/Matthias.Sabathil-78307\)](#), [A. Laubsch \(/profile/Ansgar.Laubsch-78337\)](#), [N. Linder \(/profile/Norbert.Linder-9994\)](#)

Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 64860V (2007) <https://doi.org/10.1117/12.700461>  
(<https://doi.org/10.1117/12.700461>)

[Read Abstract +](#)

### **A new wafer level coating technique to reduce the color distribution of LEDs** ([/conference-proceedings-of-](#)

[spie/6486/64860X/A-new-wafer-level-coating-technique-to-reduce-the-color/10.1117/12.697972.full](#))  Paper

[B. Braune \(/profile/Bert.Braune-21034\)](#), [K. Petersen](#), [J. Strauss](#), [P. Kromotis](#), [M. Kaempf](#)

Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 64860X (2007) <https://doi.org/10.1117/12.697972>  
(<https://doi.org/10.1117/12.697972>)

[Read Abstract +](#)

### **Reference-based optical characterization of glass-ceramic converter for high-power white LEDs** ([/conference-](#)

[proceedings-of-spie/6486/64860Y/Reference-based-optical-characterization-of-glass-ceramic-converter-for-high/10.1117/12.705334.full](#))  Paper

[A. Engel \(/profile/Axel.Engel-31444\)](#), [M. Letz \(/profile/Martin.Letz-37017\)](#), [T. Zachau](#), [E. Pawlowski \(/profile/Edgar.Pawlowski-12586\)](#),  
[K. Seneschal-Merz](#), [T. Korb](#), [D. Enseling](#), [B. Hoppe](#), [U. Peuchert](#), et al.

Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 64860Y (2007) <https://doi.org/10.1117/12.705334>  
(<https://doi.org/10.1117/12.705334>)

[Read Abstract +](#)

## **SESSION 7**

### **Requirements on LEDs for advanced optical systems** ([/conference-proceedings-of-spie/6486/64860Z/Requirements-on-LEDs-for-](#)

[advanced-optical-systems/10.1117/12.696128.full](#))  Paper

[Joachim Reill \(/profile/Joachim.Reill-59128\)](#), [Alexander Wilm \(/profile/Alexander.Wilm-78059\)](#)

Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 64860Z (2007) <https://doi.org/10.1117/12.696128>  
(<https://doi.org/10.1117/12.696128>)

[Read Abstract +](#)

### **Warm white LEDs lighting over Ra=95 and its applications** ([/conference-proceedings-of-spie/6486/648610/Warm-white-LEDs-](#)

[lighting-over-Ra95-and-its-applications/10.1117/12.698197.full](#))  Paper

[Katsuya Kobashi \(/profile/Katsuya.Kobashi-30260\)](#), [Tsunemasa Taguchi \(/profile/Tsunemasa.Taguchi-27909\)](#)

Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 648610 (2007) <https://doi.org/10.1117/12.698197>  
(<https://doi.org/10.1117/12.698197>)

[Read Abstract +](#)

---

**Development of light distribution controllable luminaire using high-power LEDs** ([/conference-proceedings-of-](#)
[spie/6486/648611/Development-of-light-distribution-controllable-luminaire-using-high-power-LEDs/10.1117/12.698914.full](#))  Paper

[Hisashi Asakawa](#) ([/profile/Hisashi.Asakawa-5369](#)), [Junko Baba](#), [Asami Yaeda](#), [Moriaki Wakaki](#) ([/profile/Moriaki.Wakaki-6226](#))

 Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 648611 (2007) <https://doi.org/10.1117/12.698914>
[\(https://doi.org/10.1117/12.698914\)](https://doi.org/10.1117/12.698914)
[Read Abstract +](#)


---

**A novel temperature compensated operation scheme for trichromatic LED backlights** ([/conference-proceedings-of-](#)
[spie/6486/648612/A-novel-temperature-compensated-operation-scheme-for-trichromatic-LED-backlights/10.1117/12.710757.full](#))  Paper

[Dong-Woo Lee](#), [Jin-Ha Kim](#) ([/profile/Jin-Ha.Kim-20090](#)), [Moo-Youn Park](#) ([/profile/Moo-Youn.Park-35610](#)), [Hee-Dong Kim](#), [Jae-Kyuk](#)
[Park](#) ([/profile/Jae-Hyuk.Park-29693](#)), [Soo-Ryong Hwang](#), [Sung-Min Cho](#)

 Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 648612 (2007) <https://doi.org/10.1117/12.710757>
[\(https://doi.org/10.1117/12.710757\)](https://doi.org/10.1117/12.710757)
[Read Abstract +](#)


---

**Silicon carbide white light LEDs for solid-state lighting** ([/conference-proceedings-of-spie/6486/648613/Silicon-carbide-white-light-](#)
[LEDs-for-solid-state-lighting/10.1117/12.724918.full](#))  Paper

[Sachin Bet](#) ([/profile/Sachin.Bet-65839](#)), [Nathaniel Quick](#), [Aravinda Kar](#) ([/profile/Aravinda.Kar-8573](#))

 Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 648613 (2007) <https://doi.org/10.1117/12.724918>
[\(https://doi.org/10.1117/12.724918\)](https://doi.org/10.1117/12.724918)
[Read Abstract +](#)

## SESSION 8

---

**Excitonic effects in ZnO nanowires and hollow nanotubes** ([/conference-proceedings-of-spie/6486/648614/Excitonic-effects-in-](#)
[ZnO-nanowires-and-hollow-nanotubes/10.1117/12.714005.full](#))  Paper

[M. Willander](#), [Y. E. Lozovik](#), [Q. X. Zhao](#), [O. Nur](#), [Q.-H. Hu](#), [P. Klason](#)

 Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 648614 (2007) <https://doi.org/10.1117/12.714005>
[\(https://doi.org/10.1117/12.714005\)](https://doi.org/10.1117/12.714005)
[Read Abstract +](#)


---

**Fabrication of high-power AlInGaP-based red light emitting diodes with novel package by electroplating**
[\(/conference-proceedings-of-spie/6486/648616/Fabrication-of-high-power-AlInGaP-based-red-light-emitting-diodes/10.1117/12.697854.full\)](#)
 Paper

*K. C. Chen* (/profile/Kuan-Chun.Chen-77517), *Y. K. Su* (/profile/Yan-Kuin.Su-151709), *J. Q. Huang*, *C. L. Lin*, *Ricky W. Chuang* (/profile/Ricky.Chuang-59395).

Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 648616 (2007) <https://doi.org/10.1117/12.697854>  
(<https://doi.org/10.1117/12.697854>)

[Read Abstract +](#)

### **Low resistance and high reflectivity Al based reflectors for p-GaN flip process** (/conference-proceedings-of-

spie/6486/648617/Low-resistance-and-high-reflectivity-Al-based-reflectors-for-p/10.1117/12.698796.full)  Paper

*Seung Wan Chae* (/profile/Seung-Wan.Chae-78146), *Kun Yoo Ko*, *Dong Woo Kim*, *Seok Min Hwang*, *Hyung Jin Park*, *Je Won Kim*, *Yong Chun Kim*

Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 648617 (2007) <https://doi.org/10.1117/12.698796>  
(<https://doi.org/10.1117/12.698796>)

[Read Abstract +](#)

## **POSTER SESSION**

### **Developing a new supplemental lighting device with ultra-bright white LED for vegetables** (/conference-proceedings-

of-spie/6486/64861A/Developing-a-new-supplemental-lighting-device-with-ultra-bright-white/10.1117/12.699604.full)  Paper

*Yongguang Hu* (/profile/Yongguang.Hu-77670), *Pingping Li*, *Jianghai Jiang*

Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 64861A (2007) <https://doi.org/10.1117/12.699604>  
(<https://doi.org/10.1117/12.699604>)

[Read Abstract +](#)

### **Development of 140-inch autostereoscopic display by use of full-color LED panel** (/conference-proceedings-of-

spie/6486/64861B/Development-of-140-inch-autostereoscopic-display-by-use-of-full/10.1117/12.703087.full)  Paper

*H. Nishimura* (/profile/Hayato.Nishimura-78590), *T. Abe*, *H. Yamamoto* (/profile/Hirotsugu.Yamamoto-23034), *Y. Hayasaki* (/profile/Yoshio.Hayasaki-8936), *N. Nishida*

Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 64861B (2007) <https://doi.org/10.1117/12.703087>  
(<https://doi.org/10.1117/12.703087>)

[Read Abstract +](#)

### **High refractive index nanoparticle-loaded encapsulants for light-emitting diodes** (/conference-proceedings-of-

spie/6486/64861C/High-refractive-index-nanoparticle-loaded-encapsulants-for-light-emitting-diodes/10.1117/12.723305.full)  Paper

*Frank W. Mont* (/profile/Frank.Mont-81217), *Jong Kyu Kim* (/profile/Jong-Kyu.Kim-61280), *Martin F. Schubert*, *Hong Luo*, *E. Fred Schubert* (/profile/E.-Fred.Schubert-16285), *Richard W. Siegel*

Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XI, 64861C (2007) <https://doi.org/10.1117/12.723305>  
(<https://doi.org/10.1117/12.723305>)

[Read Abstract +](#)