Highly efficient white OLEDs for lighting applications

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ABSTRACT

The use of organic light-emitting diodes (OLEDs) for large area general lighting purposes is gaining increasing interest during the recent years. Especially small molecule based OLEDs have already shown their potential for future applications. For white light emission OLEDs, power efficiencies exceeding that of incandescent bulbs could already be demonstrated, however additional improvements are needed to further mature the technology allowing for commercial applications as general purpose illuminating sources. Ultimately the efficiencies of fluorescent tubes should be reached or even excelled, a goal which could already be achieved in the past for green OLEDs.[1] In this publication the authors will present highly efficient white OLEDs based on an intentional doping of the charge carrier transport layers and the usage of different state of the art emission principles. This presentation will compare white PIN-OLEDs based on phosphorescent emitters, fluorescent emitters and stacked OLEDs. It will be demonstrated that the reduction of the operating voltage by the use of intentionally doped transport layers leads to very high power efficiencies for white OLEDs, demonstrating power efficiencies of well above 20 lm/W @ 1000 cd/m^2. The color rendering properties of the emitted light is very high and CRIs between 85 and 95 are achieved, therefore the requirements for standard applications in the field of lighting applications could be clearly fulfilled. The color coordinates of the light emission can be tuned within a wide range through the implementation of minor structural changes.

Keywords: white OLED, stacked OLED, high power efficiencies, PIN, doped transport layers

1. INTRODUCTION

During the last years, organic light emitting diodes have gained constantly increasing attention in the scientific and industrial community. Numerous OLED based applications have entered the display market now, mainly focusing on small passive matrix driven displays in handheld applications. However also active matrix solutions are gaining momentum and a further market penetration of OLEDs will be observed.

So far the OLED development was mainly triggered by the applications in the display segment, therefore focusing on improvements for red, green and blue devices regarding the power efficiency and lifetimes. The development of white OLEDs only lately attracted more attention, leading to some exceptional results during the last years. White OLEDs have been reported that show long lifetimes of more than 15000 hours at a brightness level of 1000 cd/m^2, while other reported white OLED devices that show power efficiencies at a brightness level of 1000 cd/m^2 exceeding 15 lm/W, the efficiency of a conventional incandescent bulb.[2, 3, 4]

Therefore a move of the OLED technology into the lighting market as well as the backlighting market for displays is to be expected. However, critical issues remain to be solved before a widespread use for such applications becomes feasible. White OLEDs need to be able to compete with existing lighting technologies with respect to lifetimes, power efficiencies and cost effectiveness.

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In this report the authors will demonstrate that the usage of the PIN concept for white OLEDs proves to be very beneficial for white OLEDs. Here, the acronym PIN refers to an OLED structure with a p-doped hole transport layer, an intrinsically conductive emission zone and an n-doped electron transport layer.[5] The PIN approach has demonstrated to result in very low operating voltages close to the thermodynamical limit, high power efficiencies and long lifetimes. [6, 7, 8] PIN structures for white OLEDs allow for high power efficiencies beyond 20 lm/W at a brightness level of 1000 cd/m^2 as well as for long lifetimes of the devices. Furthermore the PIN approach can be used within a variety of white OLED concepts, such as the usage of triplet emitters, fluorescent emitters and stacked OLEDs.

2. EXPERIMENTAL

The devices presented in this report were fabricated in a single-chamber research thin film vacuum deposition tool. The stacked device presented was fabricated in a multi-chamber vacuum deposition tool. All layers were deposited by thermal evaporation at a pressure below $5 \cdot 10^{-7}$ mbar. The general structure of the devices was: Glass substrate/ITO/p-doped hole transport layer (HTL)/interlayer/emission layer (EML)/interlayer/n-doped electron transport layer (ETL)/Aluminum. For the stacked device the layer order was as follows: Glass/ITO/p-HTL/interlayer/EML/interlayer/n-ETL/metal interlayer/p-HTL/interlayer/EML/interlayer/n-ETL/metal interlayer/p-HTL/interlayer/EML/ interlayer/n-ETL/Aluminum.

All devices were encapsulated under an inert gas atmosphere in a glove box. The spectral measurements were carried out using an Instrument Systems CAS 140 spectrometer with calibrated measurement head. Power efficiencies were determined using an integrating sphere with a diameter of 50 cm. For these measurements the OLED backside and the edges of the glass substrate were optically sealed to ensure that only light emitted in forward direction was taken into account.

The lifetime measurements were carried out with the encapsulated OLED devices at ambient temperatures by a series of measurements of the luminance and the driving voltage at a constant DC current.

3. FLUORESCENT WHITE PIN OLEDS

Fluorescent white emitter systems have demonstrated their ability to deliver very pure white color coordinates combined with long lifetimes.[2, 9] However the power efficiencies of these devices are limited owing to various facts. Most importantly, the use of fluorescent emitters limits the internal quantum efficiency to a theoretical maximum value of 25 % due to well known spin statistics. Furthermore, the operating voltage in some cases is far beyond the values set by thermodynamical limits.

Examples for power efficiencies reported for fluorescent white OLEDs are 10 lm/W at color coordinates 0.39/0.41 and 15 lm/W at a brightness of 100 cd/m^2 and color coordinates 0.30/0.38.[2, 10]. Whereas the first example is based on a non-doped OLED layout, resulting in high operating voltages of 8 V, the later example uses alkali metal doping of the electron transport layer resulting in low operation voltages.

Using the proprietary PIN technology of Novaled, being based on molecular p- and n-doping and suitable transport matrix materials, we were able to achieve extraordinary high efficiencies combined with very long lifetimes using a state of the art fluorescent white emitter system. The device structure is shown in Fig. 1.

Based on this device layout different spectral behavior of the OLEDs can be achieved with small structural changes. Pure white emission at the equal energy point (0.33/0.33) can be achieved as well as an emission with color coordinates having colder color temperatures.

Generally, for white OLEDs an emission at 0.33/0.33 is desired for applications in display backlights, whereas emission characteristics with a stronger yellow contribution to the emission spectrum are desirable for general illumination applications. An emission at the Illuminant A (0.45/0.40) is therefore desirable, as such a cold color temperature is psychologically perceived as “warm light” by the user. Furthermore, a more yellowish emission has a stronger overlap with the V(lambda) curve, i.e. the spectral efficacy is larger, which ultimately gives rise to higher overall device efficiencies.

Figure 2 shows three different fluorescent white emission spectra with the emissions at 0.33/0.33; 0.39/0.36 and 0.43/0.43.

Fig. 1: Fluorescent white PIN OLED structure

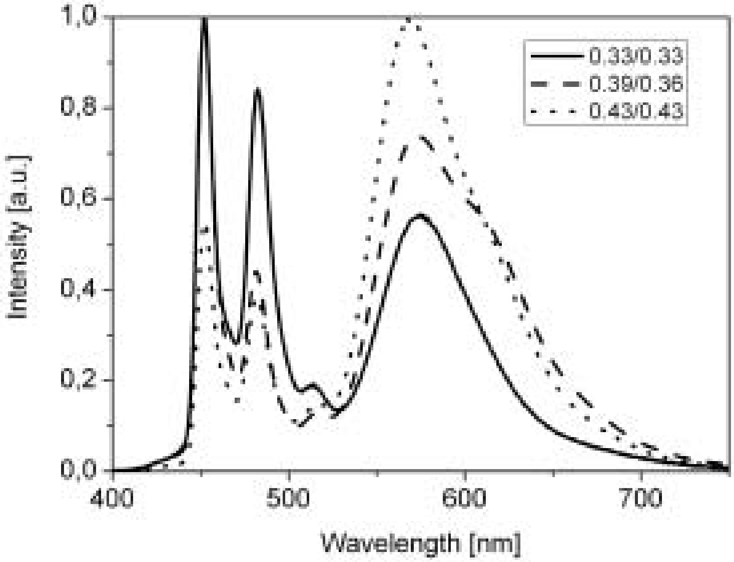

Fig. 2: EL spectra of fluorescent white PIN OLEDs

Figure 3 shows the luminance-voltage and the power efficiency-voltage characteristics of the 0.43/0.43 sample. A brightness of 1000 cd/m^2 was reached at an operating voltage of 3.05 V, the corresponding power efficiency was 17.5 lm/W. These results were achieved without any additional outcoupling measures.

Applying some additional outcoupling foil lead to an increased light output of the devices, giving rise to the following power efficiencies (all values at 1000 cd/m^2): 11.2 lm/W at 0.33/0.33; 16.0 lm/W at 0.39/0.36 and 21.1 lm/W at 0.43/0.43. The last value is the highest power efficiency ever reported for a fluorescent white OLED.

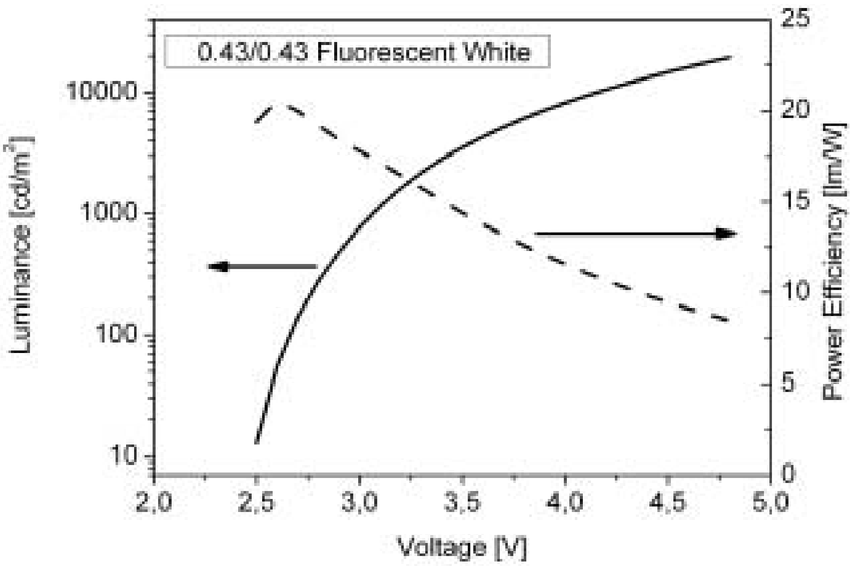

Fig. 3: Power efficiency-voltage and luminance-voltage characteristics of a fluorescent white PIN OLED

The fluorescent white PIN OLEDs exhibit a very stable longtime operation behavior. The devices were measured at a constant driving current and the luminances as well as the driving voltage were monitored over time. The devices were driven at current densities corresponding to application relevant brightnesses. Figure 4 shows the typical lifetime behavior of a fluorescent white PIN OLED. The lifetime estimation for a luminance decay to 50 % of the starting value is 15000 hours at a starting brightness of 1000 cd/m^2.

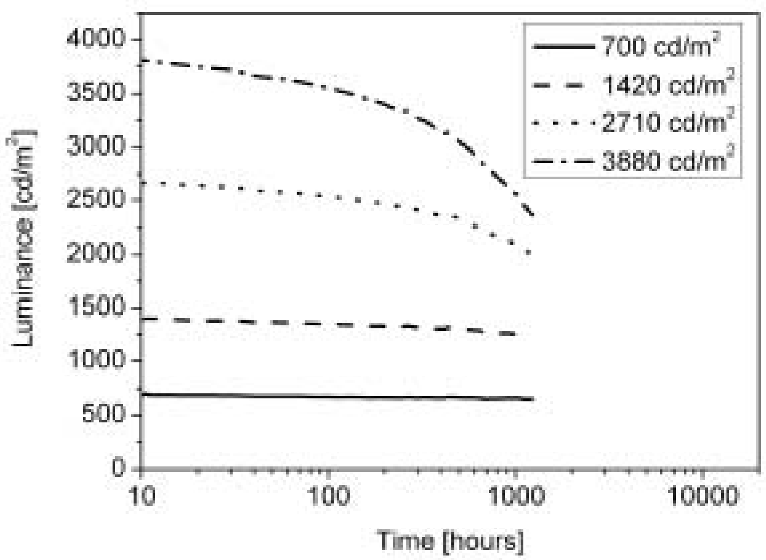

Fig. 4: Lifetime characteristics of a fluorescent white PIN OLED

4. PHOSPHORESCENT WHITE PIN OLEDS

It is well known, that phosphorescent emitter systems show significantly higher quantum efficiencies as compared to fluorescent emitters, as they harvest singlet and triplet excitons. Due to this fact, the theoretical limit for the maximum internal quantum efficiency is 100 %.

White OLEDs based only on phosphorescent emitters have been presented before, leading to high power efficiencies, the best value reported for a brightness of 1000 cd/m^2 being 18.4 lm/W.[3, 11, 12] Also triplet emitter based PIN OLEDs have been reported already, exhibiting peak power efficiencies of 11 lm/W at a brightness below 1000 cd/m^2.[13]

Using commercially available state of the art blue, green and red phosphorescent emitters, white PIN OLEDs were produced in a joint research effort by Novaled, Philips Research Laboratories and Philips Lighting. Using Novaleds PIN technology in combination with the knowledge on layer schemes and materials selections provided by Philips, very high power efficiencies could be reached.

The layout of the OLEDs was similar to the layout shown in Figure 1, however the emission zone here consists of a blue, a green and a red phosphorescent emission layer, being triplet emitter doped. Small variations of these layers allow for a tuning of the emission characteristics. Figure 5 shows color coordinates achieved with the phosphorescent white PIN OLED approach. The emission of the diodes is located near the Illuminant A point.

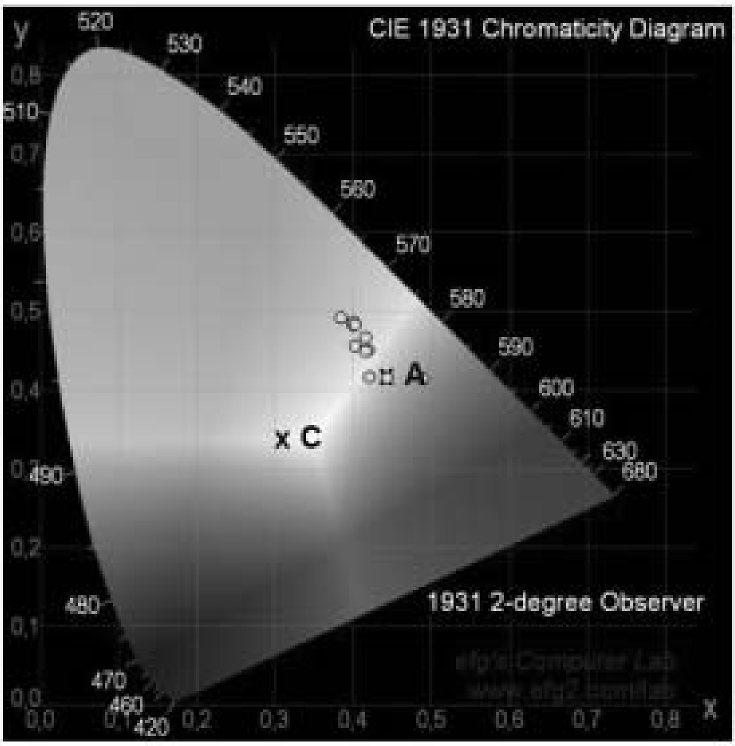

Fig. 5: Color coordinates of phosphorescent white PIN OLEDs displayed in the CIE chromaticity diagram

The best power efficiency achieved with this approach was 25 lm/W at a brightness of 1000 cd/m^2 with a color coordinate of 0.42/0.45 and a CRI of 76. Figure 6 shows the power efficiency-luminance characteristics of the device. The demonstrated efficiency of 25 lm/W is unsurpassed for white OLEDs.

The emission of the phosphorescent white OLEDs can be tuned to be located directly at the Illuminant A, giving rise to spectra with a color rendering index of 85.

Unfortunately, the utilization of phosphorescent emitters for white OLEDs suffers from a lack of suitable blue phosphorescent emitter materials that can combine a deep blue color, high current efficiencies and lifetimes suitable for commercial applications. Until such an emitter system becomes available, the use of phosphorescent blue emitter systems will not be of commercial interest from an application point of view. However the high power efficiencies achieved with a phosphorescent white PIN OLED clearly demonstrate the future potential of an “all triplet” approach for white light generation in organic light emitting diodes.

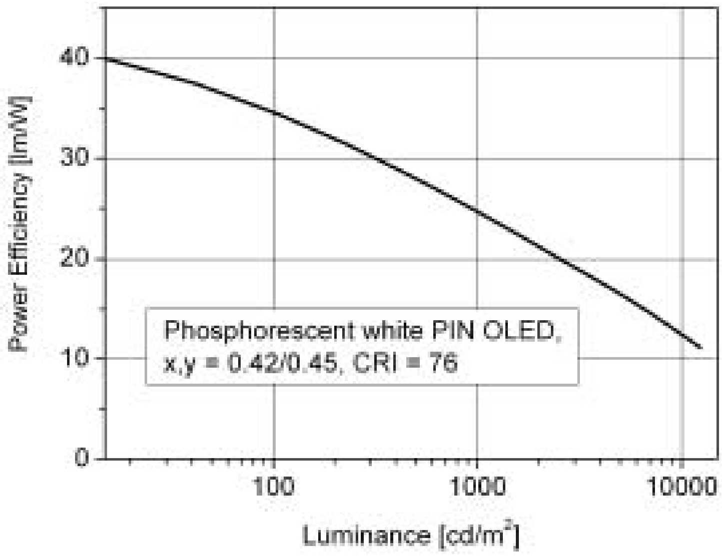

Fig. 6: Power efficiency-luminance characteristics for a phosphorescent white PIN OLED

5. STACKED WHITE PIN OLED

Stacked OLEDs consisting of separate OLED units being stacked upon each other, separated by a metallic interlayer or an insulator layer for charge generation have demonstrated their potential to achieve high quantum and current efficiencies due to so-called “multiphoton emission”. [14, 15]

The working principle of such layout is basically an in series connection of several OLEDs, therefore the same current flows through all OLED units. This increases the current efficiency and the quantum efficiency and goes along with an increase in operating voltage. Furthermore, stacked OLEDs allow for higher brightnesses, as the current density in the device needed for a certain brightness level gets reduced.

For white light generation the approach has the advantage, that different monochrome units can be combined in such a device to mix the emission to white. This avoids certain problems that arise if several colors are combined in one emission zone, such as the need for very thin layers and a precise layer thickness control or compatibility issues between fluorescent and phosphorescent emitters. It is therefore possible, to achieve a white light emission from monochrome OLEDs, that are optimized regarding the efficiency and the lifetime. It especially allows for a simple combination of stable and efficient red and green phosphorescent units with stable deep blue fluorescent emitters.

The stacked OLED presented here consists of three monochrome PIN OLED units that are stacked upon each other separated by a thin metal interlayer. The units are: a phosphorescent green layer, a phosphorescent red layer and a fluorescent blue layer.

Based on this layout we could achieve a power efficiency of 16.3 lm/W at a brightness of 1000 cd/m^2 and color coordinates of (0.35/0.37). The CRI of the spectrum was 95, which is an exceptionally high value for a white OLED.

The power efficiency-luminance characteristics and the spectrum of the device are shown in Figures 7 and 8.

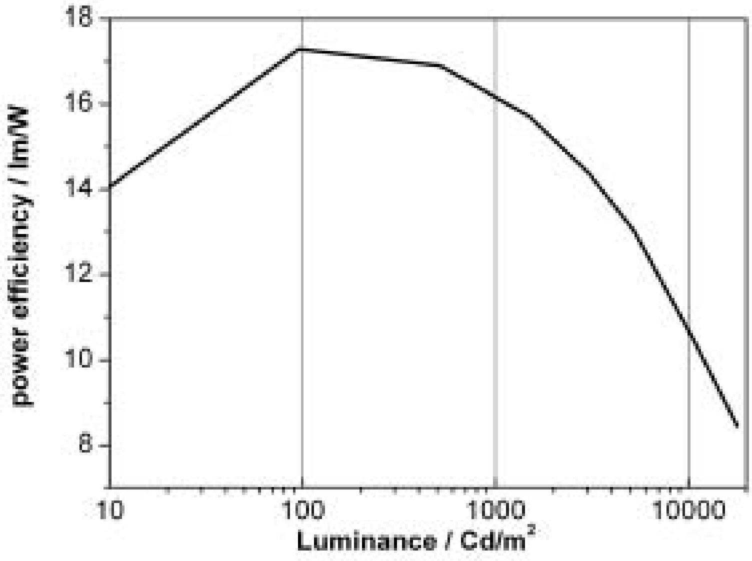

Fig. 7: Power efficiency-luminance characteristics of a white stacked PIN OLED

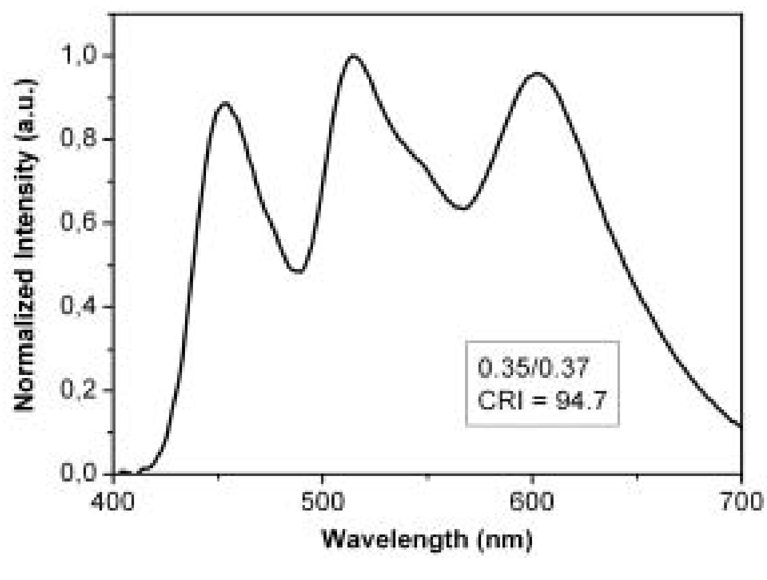

Fig. 8: EL spectrum of the white stacked PIN OLED

The results shown for the stacked white PIN OLED were achieved without any additional outcoupling improvements, therefore a further increase of the power efficiency by a factor of approximately 1.5 is to be expected. The lifetimes of stacked PIN OLEDs are currently under investigation, but due to the reduced current density as compared to conventional OLED devices, the approach should have a large potential to achieve long device lifetimes suitable for a widespread application within the lighting field.

6. CONCLUSIONS

The results in this report clearly show the benefits of the PIN technology for white OLEDs. Not only very high power efficiency levels of more than 20 lm/W at a brightness level of 1000 cd/m^2 were achieved, but it could be demonstrated that the PIN approach can be easily transferred to different OLED concepts. The lifetime results for the fluorescent white PIN OLEDs demonstrates, that the application of the PIN technology does not compromise the device lifetimes, as an operation lifetime of approximately 15000 hours at a brightness level of 1000 cd/m^2 can be achieved. CRI values of up to 95 could be achieved, demonstrating the quality of the emitted white light.
Energy saving and therefore the power efficiency will be the most important parameter for a commercial breakthrough of white OLED devices in the future. We could demonstrate, that the PIN technology has an enormous potential to improve the device power efficiencies, therefore it seems very likely, that it will be a key technology for the future commercial success of white OLEDs for lighting applications.

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