Highly efficient, long living white PIN-OLEDs for AM displays

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Abstract

Highly efficient and stable white PIN OLED structures have been developed with a focus on possible AM display applications. Due to the use of the novel air-stable Novaled n-dopant material NDN26, the mass production compatibility of the PIN approach is improved. With both a conventional n-dopant, NDN1, and a novel air-stable n-dopant, NDN26, similar performance in efficiency and lifetime are reached.

Based on highly a stable red fluorescent emitter system, the Novaled PIN approach allows for reaching ultra-long lifetimes of 1,000,000 hours at a brightness of 1,000 cd/m^2, both for top and for bottom emission layouts.

Furthermore, inverted PIN structures for a possible use in a-Si backplane applications for AM displays are shown. With a phosphorescent green emitter system it could be demonstrated that for bottom and inverted as well as non-inverted top emission, a brightness of 1,000 cd/m^2 can be reached at below 3 V.

In addition to low operating voltages and long lifetimes, PIN OLEDs also enable for device structures with extremely low operating voltage drifts, a feature of increasing importance for future AM display developments.

1. Objectives and Background

For a broad commercial market penetration of AM OLED display panels several technological challenges have to be overcome. Besides improved lifetimes and device efficiencies, a cheap and robust manufacturing process especially for large to medium size panels has to be established.

Even though the OLED performance of RGB monochrome devices is constantly improving, the still limited options for an RGB patterning at larger substrate sizes is a severe obstacle for a successful mass production. These problems are mainly caused by the difficulties with shadow masking, especially for larger size substrates. It has therefore been suggested in the past to manufacture displays based on white OLEDs with colour filters [1, 2], where well established colour filter patterning processes from the LCD display technology can be used. Using the so-called RGBW technique, where besides the three primary colours an additional pixel for white is foreseen, is an especially favourable approach. Such RGBW OLED displays have only a 50 % higher power consumption as an AM display based on red, green and blue individual pixels if video content is taken as basis for evaluation [3]. Displays with colour filters rely on highly efficient and long living white OLEDs with a large colour gamut.

A further ultimate goal for the display industry is the development of top emission displays, as here the aperture ratio of the pixels can be increased significantly. This translates directly into a large OLED area per pixel, which helps to reduce the OLED operating brightness and increases the pixel lifetime.

Preferably, the top emission structures can be realized with amorphous silicon backplanes, as for this technology large area manufacturing processes are well established in the LCD display industry and furthermore relatively simple transistor circuits can be used to drive the pixels. However, usually a-Si backplanes are based on n-channel TFTs, hence the OLED cathode preferably has to be directly connected to the driver TFT drain. Such a structure can then only be realized with inverted OLEDs, where the anode is processed as the top contact [4].

Finally, it is also desirable for AM OLED displays that the operating voltage of the OLED stays as constant as possible during the life cycle of the device. By reducing the voltage drift the TFT circuits can be designed to be operated at an overall lower voltage.

Ultimately, the goal for the OLED display development is to reach an operating voltage stability that would allow for the driver TFTs to be operated in the linear regime rather than the saturation regime, however such an approach will require not only an OLED voltage drift being close to zero but in addition also a high reliability in the TFT manufacturing process and operation stability to ensure comparable transistor characteristics for each pixel.

PIN OLEDs have demonstrated in the past that they have unique capabilities to reach very high efficiencies and long lifetimes both for top and bottom emission structures in RGB and white devices [5, 6]. Recent developments in the PIN OLED technology give rise to significant improvements in the above mentioned fields. In addition, the Novaled PIN OLED™ Technology allows for significant reductions of the voltage drift during lifetime, making the technology the ideal choice for the future of AM OLED displays.

2. Results

Based on a three-colour fluorescent white emitter system the air sensitive dopant NDN1 and the air stable n-dopant NDN26 were compared. These molecular n-dopants feature doping strengths, which are comparable to the conventional inorganic n-dopant material Cs, which is not compatible to mass production processes due to the highly reactive nature of this alkali metal. With the introduction of NDN1 already the use of n-doping in the OLED mass production process became feasible; however the introduction of the air-stable NDN26 now further eases manufacturing. This novel n-dopant can now be used in all standard processing equipment without any special precautions to avoid air exposure of the material.

Figure 1 and 2 shows the performance of a three-colour fluorescent white system, which is well suited for display applications. As can be seen, the performance for both the external quantum efficiency and the lifetime of the fluorescent white PIN OLEDs using NDN1 and NDN26 are identical. Also the OLED spectra and hence the colour coordinates stay unaffected by the change of the dopant material. The lifetime estimation of 29,000 hours at a starting brightness of 1000 cd/m^2 for NDN26 after 1300 hours of measurement is even higher than for the NDN1, where the lifetime at the same starting brightness is estimated to be 24,000 hours.

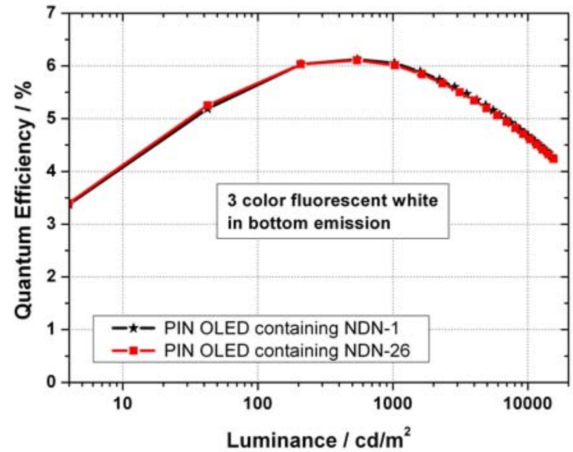

Figure 1: *External quantum efficiency of the two different white structures being based on NDN1 and the novel air-stable NDN26. The performance with the two different dopants is identical over the full brightness range.*

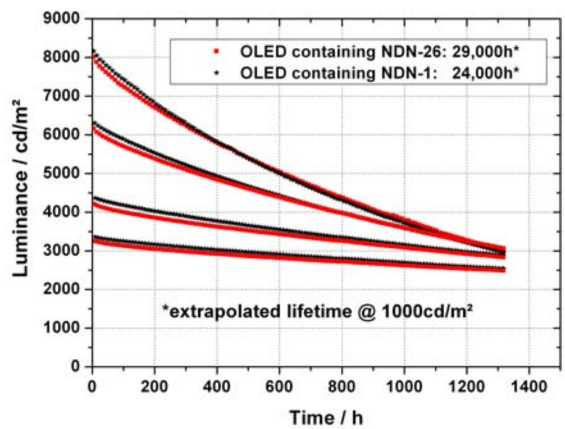

Figure 2: *Lifetime curves of the samples shown in Figure1. The ageing behaviour of the devices is very similar, the overall lifetime value for NDN26 being slightly better than for NDN1.*

Figure 3 shows the voltage shift for a white three-colour fluorescent sample with operating brightness. As can be seen, the voltage increase over lifetime is projected to be less than 0.1 V at a brightness of 1,000 cd/m^2 and a total lifetime of over 20,000 h at this brightness.

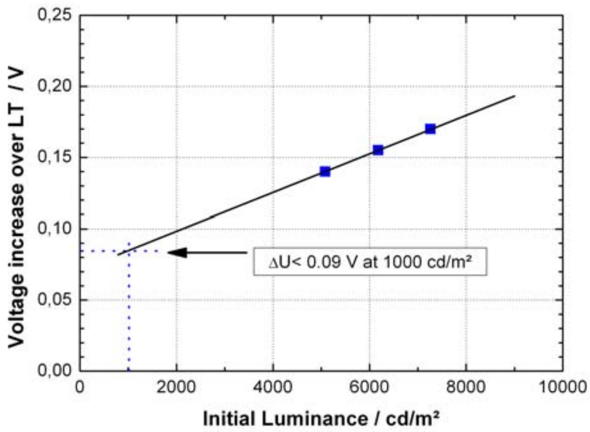

Figure 3: *Extrapolation of the voltage drift of a 3 colour fluorescent white PIN OLED. For a starting level of 1,000 cd/m², the voltage change is estimated to be only 0.9 V at a lifetime of more than 20,000 hours.*

With a further improved white structure based on the same three-colour fluorescent layout, a lifetime of over 60,000 hours with colour coordinates of 0.32/0.35 and an external quantum efficiency of 5.5% can be reached. Driven at a starting brightness of 2,850 cd/m², the sample exhibits a voltage shift of 0.04 mV/h.

To further improve the device lifetime and to minimize the voltage shift during the life cycle of the OLED, improvements are mainly needed from the emitter side. This becomes obvious when investigating the ageing behaviour of fluorescent red OLED devices, where already today extremely stable emitters are available. Figure 4 shows the lifetime of a fluorescent bottom emission device with colour coordinates 0.67/0.33. Based on a measurement running for more than 6000 hours of constant operation so far, the lifetime is estimated to be larger than 1,000,000 hours at a starting brightness of 1,000 cd/m². The diode operated at the highest starting brightness of 3,700 cd/m² is still at 96% of the initial value after 6,000 hours, therefore a lifetime estimation can only be made with a rather large uncertainty and the value of 1,000,000 hours is calculated based on a conservative assumption (acceleration constant n = 1,5). In addition to the exceptionally long lifetime the device also exhibit an extremely stable operating voltage as can be seen in Figure 5. The voltage drift for the device with the lowest brightness is only 4 µV/h, which demonstrates nicely the very high voltage stability that can be achieved with the Novaled PIN OLED™ Technology. For other colour these stabilities should be achievable as soon as the stability of the emitters improves.

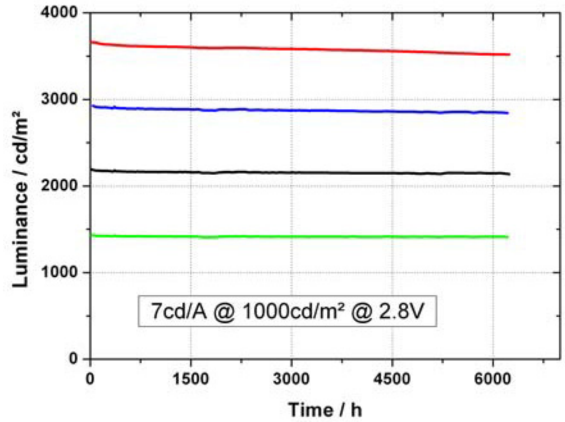

Figure 4: *Lifetime measurement for a fluorescent red PIN OLED. After more than 6,000 hours measurement, the brightest driver has only dropped by 4 %.*

This high voltage stability of PIN OLEDs is attributed to the fact, that the charge carrier injection at the interface between electrodes and the organic layers is strongly facilitated in comparison to conventional OLEDs.

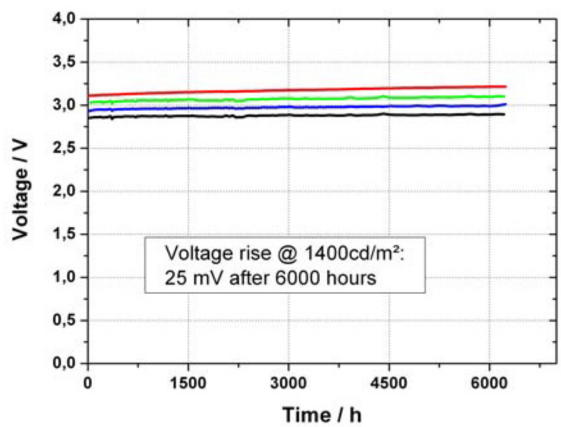

Figure 5: *Voltage drift of the red PIN bottom emission OLED from Figure 4. The voltage change for the starting brightness of 1,400 cd/m² is only 4 µV/h.*

Also in top emission very stable devices can be made using the Novaled PIN™ OLED technology. As can be seen in Figure 6, the same red fluorescent emitter system that shows a very high stability in bottom emission is also extremely stable in a top emitting configuration. Due to the better options for cavity optimization in a top emitting architecture, where the transparent electrode exhibits stronger reflective properties, the device has a current efficiency of 23.5 cd/A at a brightness of 1,000 cd/m^2. The diode driven with the lowest starting brightness of 4,750 cd/m^2 has so far shown a voltage increase of only 60 mV after almost 2,000 hours measurement.

The voltage and lifetime stability achievable with the Novaled PIN OLED™ technology can be reached both for top and bottom emitting architectures. The extreme stability of the red fluorescent emitter system together with PIN doping exemplifies that the major challenge for general lifetime improvements has to be on the field of the emitter materials rather than the transport and dopant materials. PIN doping of the charge carrier layers helps to reduce the stress on the transport layers and the interfaces with the electrodes significantly.

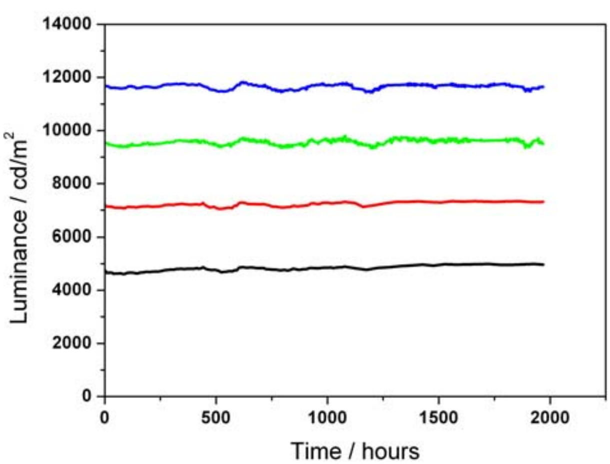

Figure 6: *Fluorescent red top emission PIN OLED device with the same emitter system as used for the device in Figure 4 and 5. The driver with the highest starting brightness of 11,900 cd/m^2 is still at 98 % of the initial level.*

PIN OLED devices are known for their high compatibility to a broad variety of electrode materials due to the drastically reduced injection barrier from electrode materials into doped organic layers. This effect, which is mainly explained by the strong band bending due to a higher amount of charge carriers in the doped layers, makes PIN OLEDs easily adaptable into non-conventional structures like transparent and top emitting OLED devices.

Especially the realization of inverted OLED devices is quite unique for this approach. However, in the past this was connected with somewhat increased operating voltages as compared to non-inverted top emitting devices [3]. It is believed, that this effect is attributed to the final top electrode deposition step, which is generally critical if the top electrode is deposited onto an organic hole transport layer, whereas it is known that the deposition of e.g. a metal electrode onto electron transport layers can in contrast be beneficial. Furthermore, it is more difficult to get a good injection from the bottom cathode contact into the organic electron transport layer.

New results with PIN OLEDs based on electron transport layers being doped with the novel air-stable n-dopant NDN26 show that is now possible to achieve very similar performance in bottom, top and inverted architectures if comparing one certain emitter system. Figure 7 shows the luminance-voltage characteristics for three OLED devices, each using the same phosphorescent green emitter system $Ir(ppy)_3$ in the same emission zone architecture.

For a brightness level of 1,000 cd/m^2 for the conventional top and bottom emission structure a driving voltage of 2.7 V in required, whereas an inverted top emitting device needs 2.9 V to reach the same brightness. At higher brightness levels the differences become negligible. All structures require 3.5 V to reach the level of 10,000 cd/m^2, at higher brightnesses the effects of ohmic losses of the device contacts become the most dominant factors.

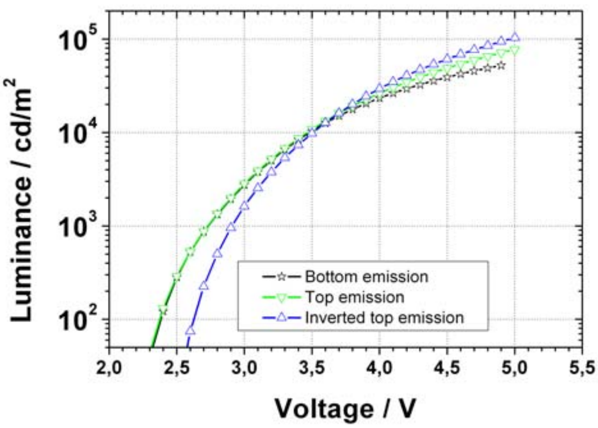

Figure 7: *Luminance-voltage characteristics for a bottom, a non-inverted top and an inverted top emission PIN OLED with the same emitter system, Ir(ppy)$_3$. As can be seen the performance for the three OLED architectures is very similar and for a brightness level of 10,000 cd/m^2 the same voltage of 3.5 V is required for all three device architectures.*

Figure 8 shows the current efficiency of the three devices from Figure 7 in a plot versus brightness. It can be seen that the conventional top emission device reaches the best efficiencies of 76 cd/A at 1,000 cd/m^2 and shows a high stability of the efficiency level up to a brightness of 10,000 cd/m^2. This high current efficiency is due to the optimised cavity of the device with an enhanced forward emission. For the bottom emission device the current efficiency is lower, reaching 58 cd/A at 1,000 cd/m^2. Furthermore the efficiency roll-off attributed to triplet-triplet quenching sets in earlier as compared to the top emitting OLED device. These effects are both attributed to the forward emission enhancing nature of the cavity optimised top emitting diode. This allows reaching a certain brightness level at a lower current density as compared with the bottom emission architecture, which has an almost lambertian emission characteristic. In the case of the inverted top emission device the efficiency level reached is comparable to the bottom emission structure; however the current efficiency is peaking at a higher brightness. From the shape of the current efficiency curve it becomes obvious, that a further optimisation of the charge carrier balance should be possible. By this, are broader maximum of the efficiency peak might be achieved and the efficiency value might also increase to reach values comparable to the conventional top emission device.

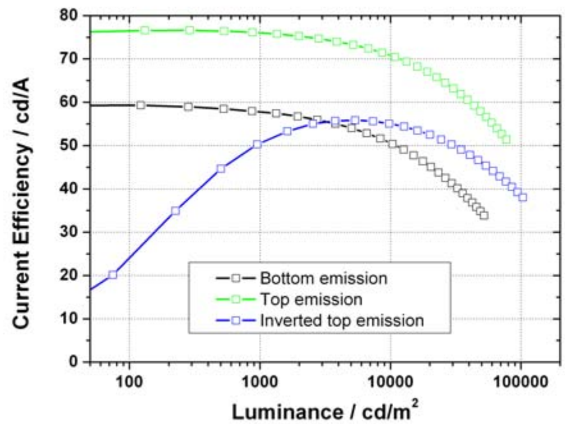

Figure 8: *Current efficiency for a bottom, a non-inverted top and an inverted top emission PIN OLED. The highest current efficiencies are achieved for the standard top emission configuration with 76 cd/A at 1,000 cd/m^2.*

The inverted top emission PIN OLED structures are subject of further development, however already as today the performance level is absolutely competitive to conventional OLED architectures.

3. Impact

With the presented results based on the novel air stable n-dopant material NDN26 the usefulness of this material for OLED mass production could be demonstrated. These effects are due to its unique features in OLED devices and its improved handling properties in comparison to alternative dopant materials which do not feature a comparable air-stability. In white fluorescent OLEDs it could be shown that the performance regarding efficiencies, operating voltage and lifetime are similar or even better than the levels achieved with the conventional n-doping material NDN1.

It is believed that based on the material NDN26 new pathways for future OLED display productions are opened up, as this material can be readily incorporated into existing mass production environments without taking special precautions to avoid contact with air.

The Novaled PIN OLED^{TM} technology allows not only to reach high efficiencies and low operating voltages, but also extremely long lifetimes together with very small changes of the operating voltage needed to support a certain drive current. With this high voltage stability the PIN OLED technology is the ideal candidate to be integrated into AM display environments. Furthermore, the voltage stability will allow for improved designs of the TFT circuits used in AM displays, as less OLED voltage increase will have to be compensated.

The results for the red fluorescent PIN OLEDs also show that improvements for the lifetime and the voltage increase are currently mostly limited by the available emitter materials. If the emitter system has a sufficient stability the PIN technology enables reaching ultra-long lifetimes and a very moderate voltage increase.

Finally the results in inverted top emission structures that have become possible with the novel NDN26 open up new options in the OLED AM display field. With the option of inverting the OLED stack without performance losses the pixel driver circuit layout can be chosen such, that the OLED cathode is directly connected to an n-channel transistor. This might help to use the existing amorphous silicon technology from LCD manufacturing plants, but the option of inverting the OLED device might open up new options for other AM backplane technologies as well.

4. Acknowledgements

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5. References

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