Highly efficient white PIN top and bottom emission OLEDs for lighting and display applications

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Abstract

Highly efficient and stable white PIN top and bottom emission organic lighting emitting diodes (OLEDs) using novel evaporation processable outcoupling enhancement materials have been developed for lighting and display applications. In white bottom emission OLED structures, outcoupling enhancement materials NE-61 is used in the electron transport layer. Processed on standard glass substrate with a standard outcoupling film, an efficiency enhancement of >1.7 can be achieved with NET-61 in a tandem OLED device, which has a high efficiency of 50.2 lm/W and color coordinates x,y of 0.46/0.41 at a brightness of 1,000 cd/m^2. Using the same approach in a single-unit fluorescent device, an efficiency of 36.8 lm/W is reached. A similar approach using a vacuum processable scattering material in top emission OLED architectures on metal substrate allows to reach a high efficiency of 36.5 lm/W, CRI of 75 and a color coordinates x.y of 0.45/0.41.

1. Introduction

For both lighting and display applications, OLEDs with high power efficiency is one of the requests among others such as device lifetime and manufacturing cost etc. To reach highest possible device efficiency, three key factors have to be addressed in OLED technology development, including efficient emitters, low operating voltage thus low power consumption and high outcoupling efficiency. By using the Novaled PIN OLED® technology, operating voltage of PIN OLEDs has been significantly reduced thus high efficiency achieved [1]. In contrast, there is still large improvement potential on light extraction, especially at low manufacturing cost. Here we report on high efficiency PIN white top and bottom emission OLEDs with efficiency enhancement by using novel evaporation processable materials. The material processing is well compatible to OLED process and has intrinsic low manufacturing cost.

2. Results

2.1. White PIN top emission OLEDs

Because of light emission from the top contact, top emission OLEDs could be easily integrated with opaque substrates. This leads to several advantages for example better heat management with metal substrates. However, the development of white top-emission OLEDs is still facing unique obstacles because of their intrinsic strong microcavity effects. As one consequence, there is always a compromise between device efficiency and emission color in white top-emission OLEDs. To reduce the microcavity effects, transparent conductive oxide (TCO) normally ITO was used as top electrode. Combined with thin film encapsulation (TFE) and external outcoupling foil, white top emission OLEDs with good performance have been developed [2]. However, one of the major disadvantages of the approach is that ITO sputter process has to be used. This makes the device manufacturing complicate and expensive. Therefore, thin metal top electrode that can be easily processed with thermal evaporation method is desired, which however introduces strong microcavity. To reduce unwanted strong microcavity effects accompanied with the thin metal electrode, Novaled has developed an organic material NLE-17 used as scattering cap material for white top emission devices [2]. As a small molecule organic material, NLE-17 can be easily deposited via thermal evaporation in vacuum and thus compatible well with OLED process. Here we report on latest results on white top emission OLEDs with NLE-17 scattering cap layer.

Optical properties of NLE-17 have been investigated by measuring diffused reflection of NLE-17. 800 nm thick NLE-17 has been evaporated on a glass substrate coated with 100 nm Ag. For comparison, a conventional index matching material (amorphous) with identical layer thickness to the NLE-17 sample is also prepared. As shown in Fig. 1, the NLE-17 has above 80% diffused reflection over the whole visible wavelength, which is attributed to its highly scattering effect. In contrast, conventional index matching material has almost no diffused reflection.

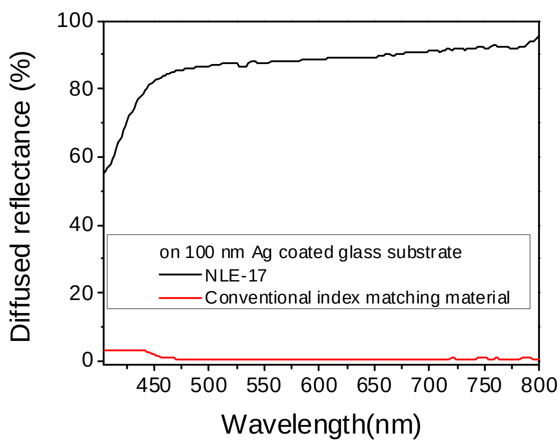

Figure 1. Diffused reflectance of organic layers on glass substrate coated with 100 nm Ag

It has been already demonstrated previously that the use of NLE-17 layer, an evaporation processed scattering organic cap layer, can help to improve the performance of white top emission OLEDs [2]. The investigation of the approach is continued and focused on increasing device efficiency in combination with achieving better light quality. Therefore, it is desired to develop top emission white OLEDs with stacked white device structure, which combines high efficiency phosphorescent red and green (1st unit) with stable fluorescent blue (2nd unit), as shown in Figure 2.

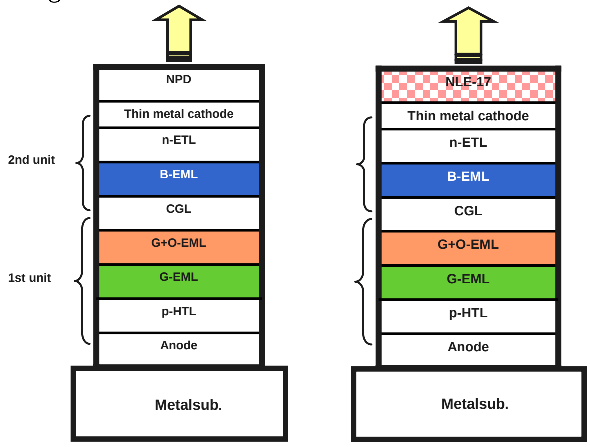

Figure 2. Structure of white top emission OLEDs with NPD (left) and NLE-17 (right) as the cap layer

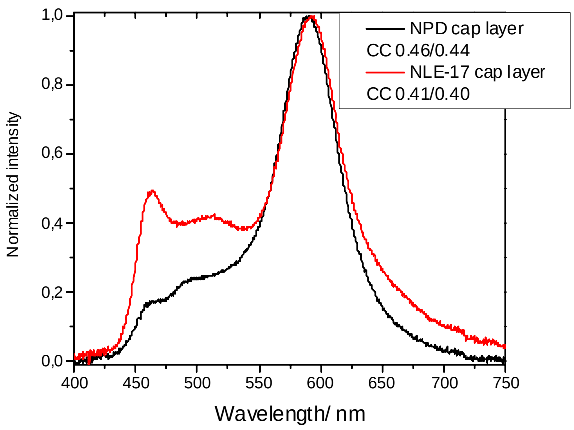

Figure 3. Spectra of OLEDs with 60 nm NPD cap layer (black) and 800 nm NLE-17 as the cap layer (red) measured in the integrating sphere.

In Figure 3, spectra of the two white top emission devices with identical device structure but different kind of cap layers are compared (measured in the integrating sphere). As expected, the device with NPD as cap layer has a quite narrow spectrum (black curve) with a dominant emission of 550-625 nm because of intrinsic strong microcavity effect although one of the emission units is blue. Consequently, the device has a bad CC of 0.46/0.44. By using NLE-17 as cap layer instead, emission in blue is partly recovered, resulting in a broader emission spectrum. The device shows nice warm white with CC of 0.41/0.40, fulfilling DOE specifications. It is obvious that the microcavity effect of the device is significantly reduced by scattering effect of the NLE-17 cap layer. This is further confirmed by measuring the CC shifts over viewing angles. As shown in Figure 4a, the NPD device show large CC shifts over viewing angles from 0.55/0.39 at 0° to 0.35/0.46 at 80° due to strong microcavity effect. In contrast, because of alleviated microcavity effect by NLE-17, the NLE-17 sample shows much improved CC shifts with a CC of 0.43/0.41 at 0° and 0.41/0.41 at 80° (Figure 4b).

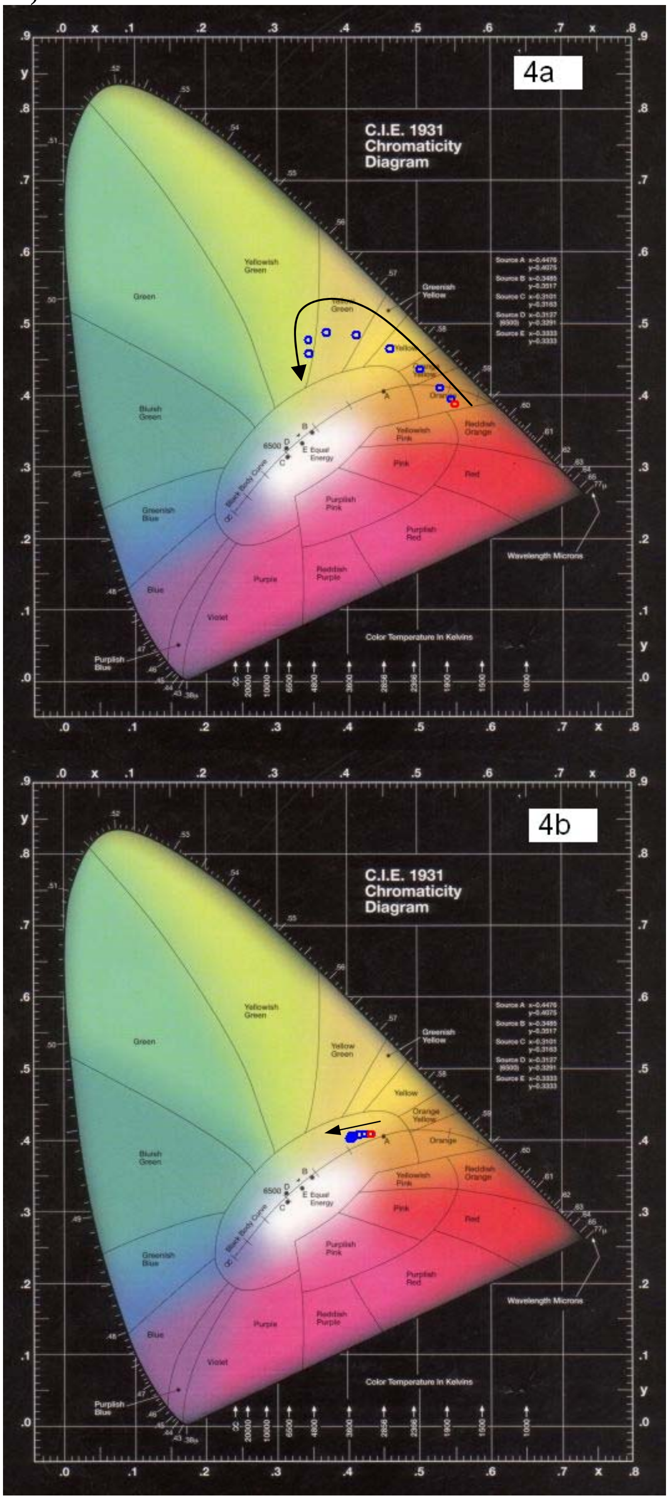

Figure 4. Color coordinates over angle (0°…80°) for the white top-emission OLEDs with (a) 60 nmm NPD and (b) 800 nm NLE-17 cap layer.

The device shown above has only efficiency around 20 lm/W at 1000 cd/m^2 with a CRI ~ 70. Indicated from the spectrum, it is apparently that more green is needed to achieve higher efficiency and better CRI, which is however limited by the emitter stacks themselves. To enhance green emission, additional green emission layers are inserted in both blue and orange unit as shown in Figure 5- A combination of a fluorescent blue/green unit and a phosphorescent red/green unit in a tandem structure using NLE-17 as scattering cap layer for improved outcoupling. With this structure, an efficiency of 36.5 lm/W (28.8 % EQE) at a brightness of 1,000 cd/m² and color coordinates of 0.45/0.41 was achieved. The CRI for this sample is 75, which is already a sufficient level for many commercial lighting applications.

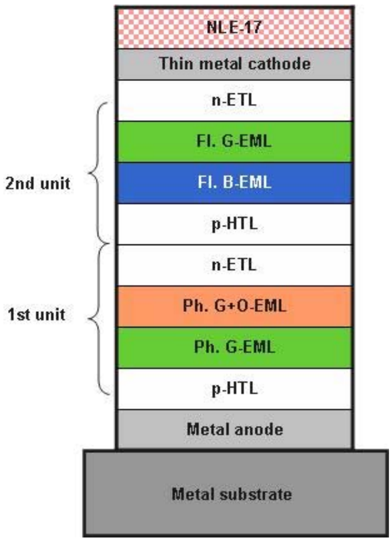

Figure 5. Structure of the white top emitting OLED. A fluorescent blue/green unit and a phosphorescent red/green unit are combined to improve the light quality in combination with the NLE 17 scattering organic cap layer.

2.2. White PIN bottom emission OLEDs

Estimated from ray optics, only ~20% of the light generated inside a standard bottom emission OLED could be coupled out (air mode). The rest is lost in the glass substrate (~30%, the substrate mode) and ITO/organics layer (~50%, the organic mode). To extract light in OLEDs, the so called external outcoupling has already been well developed. In this method, commercially available outcoupling foils consisting of scattering layer, micorlens array or pyramids are used, which is compatible well with OLED process and has the advantage of low cost [3]. However, this kind of external outcoupling method can only extract light trapped in the substrate and hence is limited to the substrate mode. Large part of light is still trapped in the ITO/organics. Internal outcoupling has to be used to converted light from ITO/organic mode into substrate and air modes. To achieve best possible outcoupling, external outcoupling has to be combined with internal outcoupling. During the past, high n glass substrate or substrate/ITO interface modifications have been developed to convert ITO/organics mode into substrate and air modes [4, 5, 6]. However, commercial applications of above internal outcoupling methods are difficult because of their process complexity and high cost. Here it is demonstrated that Novaled organic materials NET-61 for bottom emission offers simple and cost efficient solutions to couple out the ITO/organic mode.
The effect of NET-61 is tested first in a simple white OLED structure. As shown in Figure 6, a single unit 2-color fluorescent OLEDs is used as the reference. Based on the reference structure, part of the electron transport layer is replaced by NET-61 with nominally the same thickness. Electrical characteristics of the two OLEDs are compared in Figure 7. It can be clearly seen the IV curves of the two devices are very similar regarding both the backward currents and the forward currents. This indicates that replacing part of n doped ETL with NET-61 has almost no impact on device electrical properties.

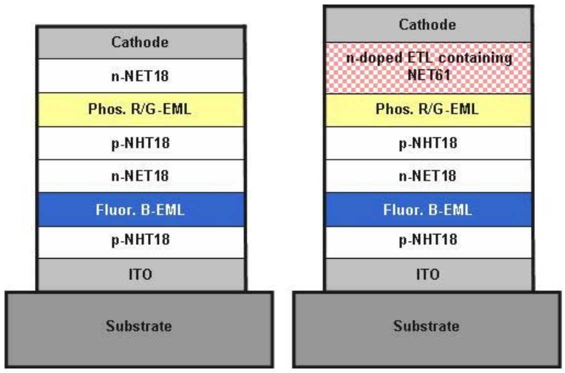

Figure 6. Device structure of a PIN reference OLED (left) and the OLED with improved light extraction with NET-61

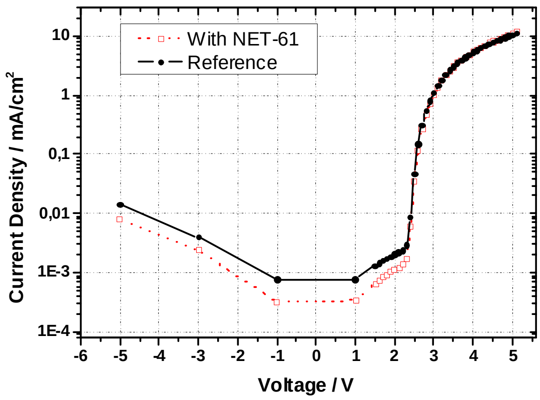

Figure 7. The IV characteristics of the reference device (black solid line) and the device with NET-61 (red dotted line).

Nevertheless, insertion of NET-61 in the n-ETL does change the optical properties of the device. The scattering nature of NET-61 in the device can be nicely seen by checking device off-state appearance. At the offer-state under ambient light, the reference device shows the normal reflective mirror-like appearance. In contrast, the device with NET-61 has a milky or frosted appearance, which is caused by scattering of incident light.
The scattering effect introduced by NET-61 has big positive impact on the device efficiency. Measured in the integrating sphere, the reference device has a high power efficiency of 21.4 lm/W (8.6% EQE) and a color coordinates of 0.49/0.42 at the brightness of 1000 cd/m^2. The efficiency is further increased in the device with NET-61, reaching a power efficiency of 30.9 lm/W (12.6%) with a similar color to the reference. This represents an efficiency increase above 44%.

After simply applying a commercially available outcoupling foil, the efficiency of the NET-61 device is further improved to 36.8 lm/W, which is the best result of fluorescent white OLEDs so far. Therefore, the combination of NET-61 internal outcoupling and an external outcoupling foil increase the power efficiency by 71%.
As in the white top emission case, the NET-61 internal outcoupling method is applied to stacked white OLEDs to reach even higher efficiency. With NET-61, the tandem OLED has already a high efficiency of 38.5 lm/W (31.3% EQE) with a color of 0.43/0.40 at the brightness of 1000 cd/m^2. With an external outcoupling foil, the efficiency rises to 50.1 lm/W (40.5% EQE, CC: 0.46/0.41).

3. Summary

We presented here a simple way to improve the outcoupling efficiency in both top and bottom emission OLEDs by using vacuum-processable organic scattering materials. With a scattering organic cap layer NLE-17, microcavity effect of the top emission OLEDs having thin metal top electrode was suppressed with improved light outcoupling. Using the approach, high performance white top emission OLEDs were demonstrated with a power efficiency of 36 lm/W, CC 0.45/0.41 and CRI of 75. Furthermore, thanks to the scattering cap layer, the device color shifts over viewing angles was significantly reduced as well. Those results are already on a good level ready for commercial applications.
Similarly, scattering layer NET-61 was applied in bottom emission OLEDs, resulting in more than 44% efficiency increase. In combination with external outcoupling foil, a further efficiency increase of more than 70% could be realized. With the approach, a record power efficiency of 36.8 lm/W in a fluorescent white OLED and a high power efficiency of 50.1 lm/W in a hybrid tandem white were reached

4. References

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