PIN OLEDs – Enhanced Performance and Lifetime by improved Structures and Materials

Tobias W. Canzler, Philipp Wellmann, Michael Hofmann, Jan Birnstock,
Ansgar Werner, and Jan Blochwitz-Nimoth
Novaled AG, Tatzberg 49, 01307 Dresden, Germany

ABSTRACT

One key to achieve highest power efficiency for OLEDs is the introduction of conductivity-doped transport layers. Therefore, Novaled developed its proprietary PIN technology based on molecular P- and N-type dopants. Additionally, Novaled PIN OLED^{TM} technology allows for flexibility concerning electrode materials, tolerates high substrate roughness, and improves quality yield.

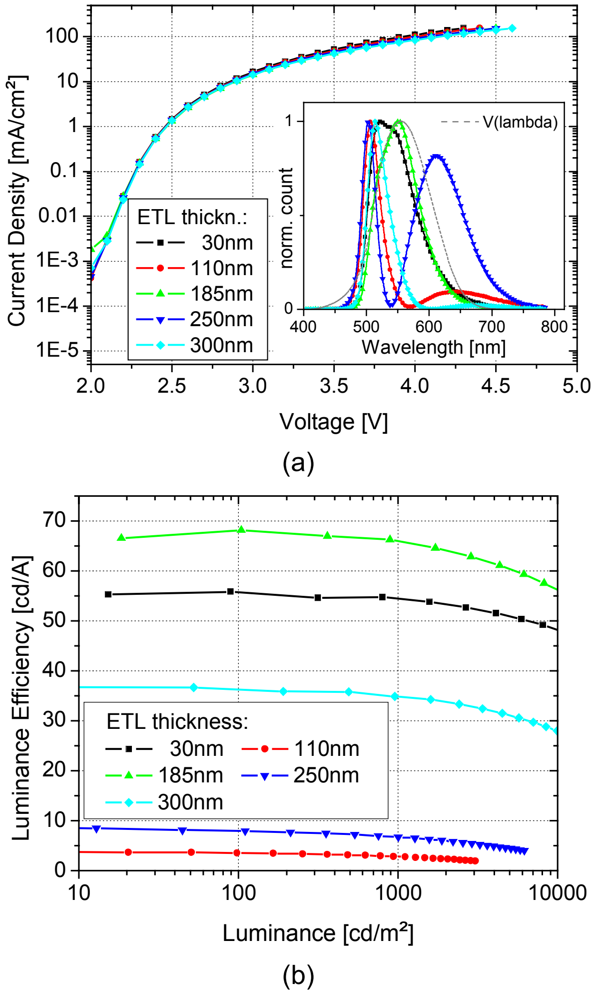
Here, we report that this concept also delivers the world longest lifetimes: In collaboration with UDC green and red phosphorescent PIN OLEDs were achieved with half lifetimes for a starting brightness of 1,000 cd/m² of >200,000 and >150,000 hours, respectively. For fluorescent blue PIN OLEDs half lifetimes up to 13,000 hours at 1,000 cd/m² are reported.

I. INTRODUCTION

The origins of conductivity-doped OLEDs, so called PIN OLEDs, date back to the early nineties. In parallel, phosphorescent OLED (PHOLED™) technology was developed, which has the ability to achieve 100% internal quantum efficiency [1]. However, it took about a decade until a power efficiency as high as 64 lm/W for a green PIN PHOLED was achieved [2]. The next breakthrough in the development of PIN OLEDs was certainly the increase of lifetime above 100,000 hours at an initial brightness of 500 cd/m² [3]. After that, the development of PIN technology was broadened to cover aspects like white emission, stacked architecture [4], thermal stability, top-emitting and inverted architecture as well as simplification of the OLED stack to ensure cost-efficient mass production. In parallel, both efficiency and lifetime were further enhanced. Today, PIN OLEDs outperform standard OLEDs both in efficiency and lifetime in most cases.

II. PIN OLEDs FOR MAXIMUM POWER EFFICIENCY

A standard bottom-emission PIN OLED consists of a transparent anode (ITO) / p-type doped hole-transport layer (HTL) / interlayer on hole side / emission layer / interlayer on electron side / n-type doped electron-transport layer (ETL) / metal cathode (Al).



(a)

(b)

Fig. 1. (a) I-V curves of PIN OLEDs with different ETL thickness. All other layers are kept constant; the emitter is $Ir(ppy)_3$. The I-V curves are identical. Inset shows corresponding emission spectra. (b) Corresponding luminance efficiencies. The drastic differences in EL spectra and current efficiency are due to micro-cavity effects.

The interlayers confine the charge carriers in the emission layer and prevent exciplex formation, thus assuring high luminance efficiency. Neither injection layers between the electrodes and the organic stack nor ITO pre-treatment are necessary. The conductivity of the transport layers is in the range of 1E-5 S/cm, which translates into a voltage drop over a 100 nm thick transport layer of only 0.1 V at high current density of 100 mA/cm².

In the given examples, NDP-2 was used as p-dopant and NDN-1 as n-dopant. Recently, a new n-dopant NDN-26 was developed. In contrast to NDN-1, NDN-26 can be handled under normal atmosphere during loading and unloading of the material in the production tools. Usually, architectures developed for NDN-1 can directly be applied to NDN-26 regardless of the emission layer structure. That means efficiencies as well as operational stability for the various RGB and white structures remain unchanged by replacing NDN-1 with NDN-26 [5].

The layer thickness of the transport layers can be chosen freely while the electrical properties and charge carrier balance of the OLED remain unaffected. Figure 1(a) shows the I-V curves for a set of green-emitting PIN OLEDs based on Tris[2-(2-pyridinyl)phenyl-C,N]-iridium, short Ir(ppy)$_3$, with varying ETL thickness between 30 nm and 300 nm. However, there is a huge effect on the emitted spectrum and luminance efficiency. Inset of Fig. 1(a) shows the corresponding emission spectra for the different ETL thickness. The emission colour can be shifted drastically. In Figure 1(b), the luminance efficiency for the devices is depicted which can be reduced by a factor of 20, just by choosing an inappropriate cavity. Two effects complement one another: (I) The OLED acts as a micro cavity and modulates out-coupling efficiency with ETL thickness. Here, for 185 nm ETL the cavity is optimized for the Ir(ppy)$_3$ spectrum. (II) The eye sensitivity V(λ) has its maximum close to the Ir(ppy)$_3$ emission peak. Therefore, a cavity optimized for a wavelength off the peak of V(λ) will suffer from reduced luminance efficiency.

III. OPERATIONAL STABILITY

Significant increase in lifetime of PIN OLEDs can be reported, which outperform best devices known from literature. Going from a standard OLED structure, i.e. without conductivity doping, to a PIN structure usually changes the charge carrier balance. In a corresponding PIN structure the emission layer is "flooded" with a much higher number of electrons as compared to standard OLED structures in which poor electron supply limits devices. Some emitting systems are in favor of this electron excess [4]. However, for emission layers which are purely electron transporting, a pile-up of electrons at the electron blocker leads to more stress at this interface accompanied by a decrease of efficiency and lifetime. In these cases, modification of the architecture is needed to adjust the charge-carrier balance.

Operational stability of OLEDs is usually described solely by the 50% luminance decay from a given starting brightness. The associated voltage increase is a commonly neglected parameter. Lifetime and voltage increase are usually, but not necessarily, correlated. Voltage increase strongly depends on photon energy of emitted light and is strongest for blue OLEDs.

Here, we give some examples of fluorescent and phosphorescent PIN OLEDs in bottom and top emission architecture and discuss voltage increase exemplarily for blue OLEDs.

Top Emission based on Phosphor Ir(ppy)$_3$

The highest lifetimes for green OLEDs based on the phosphorescent emitter Ir(ppy)$_3$ known from literature are in the range of 20,000 to 50,000 hours at a starting brightness of 500 cd/m² [3,6,7]. Novaled recently developed a top-emitting architecture allowing for a 50% lifetime of more than 100,000 hours at the same initial luminance based on this emitter. Keys for this development are a bilayer metal bottom contact and the out-coupling layer above the top cathode. The structure is highly efficient; it reaches 1,000 cd/m^2 at 2.6 V with 61 cd/A. Figure 2 shows the operational stability of the device. Noticeable is the low voltage increase.

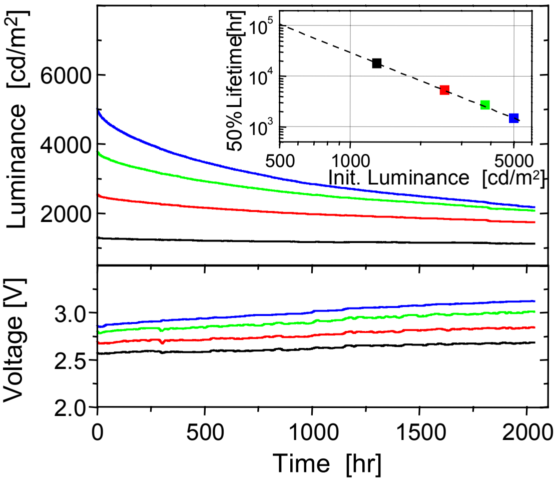


Fig. 2. Operational stability of green phosphorescent top-emitting PIN OLED based on Ir(ppy)$_3$. Luminance decay and voltage increase at different starting brightness are shown. The insert shows 50% lifetime extrapolation.

Bottom Emission based on UDC Emitters

The first demonstration of high efficiency OLED combining PIN doping approach and phosphorescence was reported in 2002 [8]. The successful combination of Novaled's PIN OLED™ technology with Universal Display's phosphorescent OLED (PHOLED™) technology was reported recently [4]. Now, a saturated green PIN PHOLED device is demonstrated with a CIE of (0.36, 0.61), an external quantum efficiency of 11%, and a drive voltage of 3.6 V, all at 1,000 cd/m^2. These characteristics correspond to a luminous efficiency of 41 cd/A and a power efficiency of 36 lm/W, at 1,000 cd/m^2. Quantum and power efficiencies are derived from forward emission assuming Lambertian emission. The green PHOLED device also has an excellent projected operational lifetime of >200,000 hours at an initial brightness of 1,000 cd/m^2. Further improvements, especially in lowering the operating voltage below 3V, are expected upon prolonged device optimization.

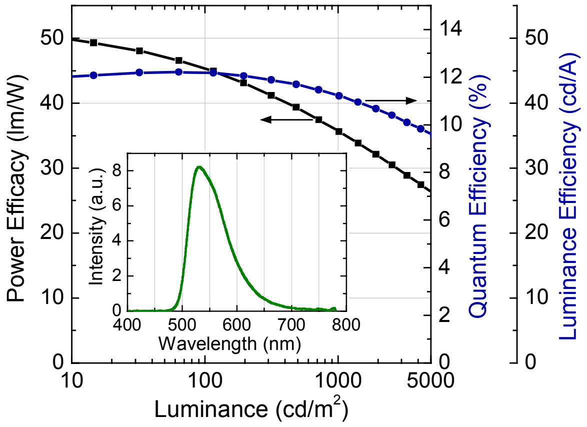


Fig. 3. Efficiencies of a green bottom-emitting PIN PHOLED. The insert shows the corresponding EL spectrum based on Universal Display's green emitting material.

Additionally, an orange-red PIN PHOLED device is demonstrated with a CIE of (0.63, 0.36), an external quantum efficiency of 19%, and a drive voltage of 3.5 V, all at 1,000 cd/m^2. These characteristics correspond to a luminous efficiency of 29 cd/A and a power efficiency of 26 lm/W, at 1,000 cd/m^2. The green PHOLED device also has an excellent projected operational lifetime of >150,000 hours at an initial brightness of 1,000 cd/m^2.

For both emitters the driving voltage for 1,000cd/m^2 was reduced from >7V for a standard structure using NPB for the HTL and Alq_3 for the ETL to ~3.5 V for PIN structure. In general, the combination of UDC's emission layers and Novaled's conductivity-doped transport layers results in well-balanced PIN PHOLEDs for red and green with doubled power efficiency while lifetime remains comparable.

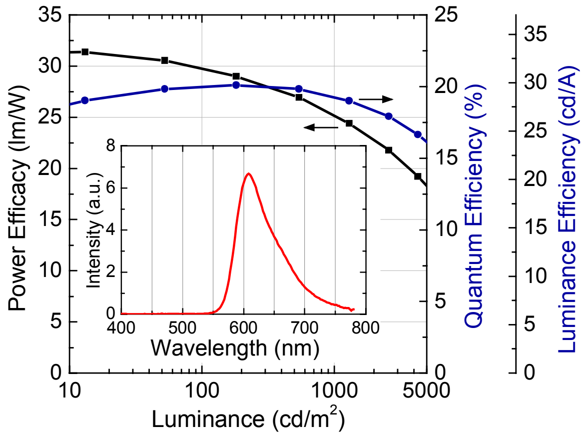


Fig. 4. Efficiencies of an orange-red bottom-emitting PIN PHOLED. The insert shows the corresponding EL spectrum based on Universal Display's orange-red emitting material.

Bottom Emission based on fluorescent Blue

The lifetime of saturated-blue emitting OLEDs is crucial for the commercial success of OLEDs in full-color AM displays. However, not only lifetime for blue OLEDs is lower than for red and green but also voltage increase is significantly higher. Thus, display electronics needs to be designed to compensate for expected voltage increase.

So far, highest lifetimes reported for OLEDs with saturated blue color coordinates of $x \leq 0.14$, $y \leq 0.22$ are about 20,000 hours at 1000 cd/m² with a driving voltage of ~7 V at 10 mA/cm^2 [9]. Unfortunately, corresponding voltage increase is not given.

Currently, most blue-fluorescent emitter systems are purely electron transporting. Therefore, the introduction of PIN doping technology drastically changes the charge-carrier balance: Improved electron supply into the emission layer results in a pile-up of electrons at the electron blocker accompanied by a decrease lifetime. Nowadays, best saturated-blue PIN OLED offers a lifetime of 13,000 hours at 1,000 cd/m^2. This structure features a luminance efficiency of 8 cd/A at color coordinates of (0.13, 0.18) and a driving voltage of 4.4V, all at 1,000 cd/m^2. However, further structural optimization reveals a clear trend: Reduction of driving voltage by modifications in OLED architecture is accompanied by shorter lifetime: e.g. for a driving voltage at 3.2 V the lifetime is reduced to 8,300 hours. For this structure, the voltage increase over lifetime at 1,000 cd/m^2 is only 0.5 V. Interestingly, the voltage increase is independent from starting brightness in the measured range of 1,500 – 5,000 cd/m^2.

Figure 4 shows best lifetimes for different blue fluorescent OLEDs. Lifetime values are given at 10 mA/cm^2 to allow for comparability of different emitters with different color coordinates. Lifetimes from [9,10] are derived using suggested acceleration factor of n = 1.5. The plot features very recent data for a low voltage structure from [10]. It becomes obvious that Novaled PIN technology gives state-of-the-art lifetimes at lowest operating voltages. From the independent BD-1 data, it can be seen again that a reduction in driving voltage results in lower operational stability – independent from PIN technology.

For further improvement of power efficiency and lifetime of blue fluorescent OLEDs, it seems unavoidably to modify the emission layer in order to allow for sufficient hole injection and transport inside the emission layer.

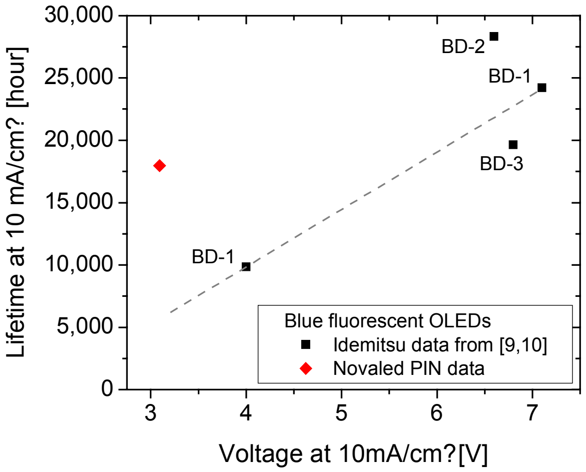


Fig. 5. Best lifetimes for blue fluorescent OLEDs driven at 10 mA/cm^2. Only emission layers with saturated blue color coordinates of $x \leq 0.14$, $y \leq 0.22$ are considered.

CONCLUSIONS

Transition from electrically undoped to PIN OLEDs requires in particular cases – depending on the emitter layer – modifications of the architecture to achieve optimum efficiencies and lifetime. Here, we have shown exemplarily for several phosphorescent and fluorescent systems in bottom- and top-emission architecture that these adaptations can be successfully implemented. For UDC's phosphorescent green and red emitting systems power efficiency is on highest level while lifetimes remain unchanged. In top-emission architecture, for the green phosphor Ir(ppy)$_3$, lifetime is significantly improved to a record value of >100,000 hours for a starting brightness of 500 cd/m². For most blue fluorescent emitters, lifetimes can not be fully conserved in low voltage structures. Nevertheless, at a drive voltage of 3.2 V for 1,000 cd/m2, a lifetime of 8,300 hours and a voltage increase of only 0.5 V for a blue PIN OLED were achieved.

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