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OLED Technology Introduction

An organic light emitting diode (OLED) consists of several semiconducting organic layers sandwiched between two electrodes at least one of them being transparent. A simplified device structure is shown in Figure 1, on the left a one-side emitting device and on the right a transparent one which emits light in both top and bottom direction. The device is fabricated by sequentially depositing organic layers on a conducting substrate followed by another conducting electrode. A common device structure comprises an indium tin oxide (ITO) coated glass substrate as transparent anode and a thin opaque metal film as cathode. The organic stack including the electrodes is usually thinner than 1µm. Two classes of organic materials are commonly used in organic light emitting devices: polymeric substances and so called small molecule materials which do not exhibit any orientating property and therefore form amorphous films. One interesting aspect of organics based opto-electronics is the possibility to use simple screen printing or wet deposition techniques for cost-effective large area fabrication. Nowadays this holds only for polymeric organics whereas for small molecules evaporating techniques still have to be applied.

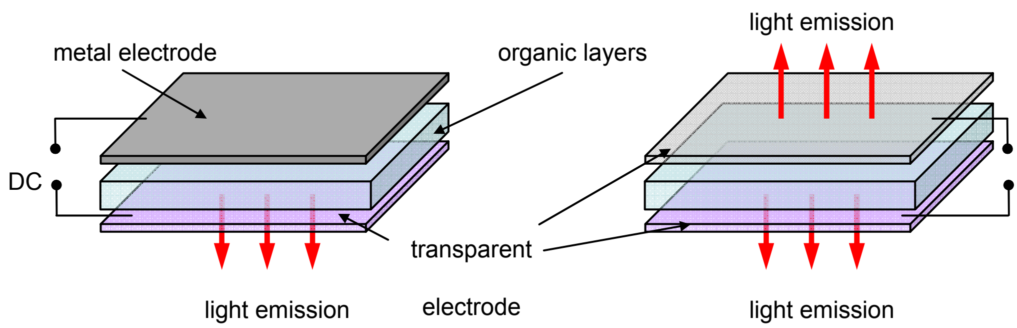

Figure 1: Simplified structre of an organic light emitting device. On the left a one-sided "bottom emitting" device, on the right a transparent device which can emit in both directions and appears transparent when turned-off.

When a DC bias is applied to the electrodes the injected electrons and holes can recombine in the organic layers and emit light of a colour depending on the properties of the organic material. Since charge carrier transport in organic semiconductors relies on individual hopping processes between more or less isolated molecules or along polymer chains (Figure 2), the conductivity of organic semiconductors is several orders of magnitude lower than that of their inorganic counterparts. Also the concept of energetic bands with highly delocalised wave functions is not applicable to organic electronics. Instead of valence and conduction band, highest occupied and lowest unoccupied molecular orbital levels (HOMO, LUMO) are the relevant terms. Before actually decaying radiatively, an electron-hole pair will form an exciton in an intermediate step which, when decaying, will eventually emit light. Depending on its chemical structure, a dye molecule can be either a fluorescent or a phosphorescent emitter. Only in the latter all excitons, singlets and triplets, are allowed to decay radiatively, whereas in the former three quarters of all excitons, the triplet excitons, will not emit any radiation. Therefore fluorescent emitters have a maximum intrinsic efficiency of only 25% and their application is avoided when possible. However, up to now, the lifetimes of phosphorescent emitters, especially for short wavelength (blue) are inferior to that of the fluorescent ones.

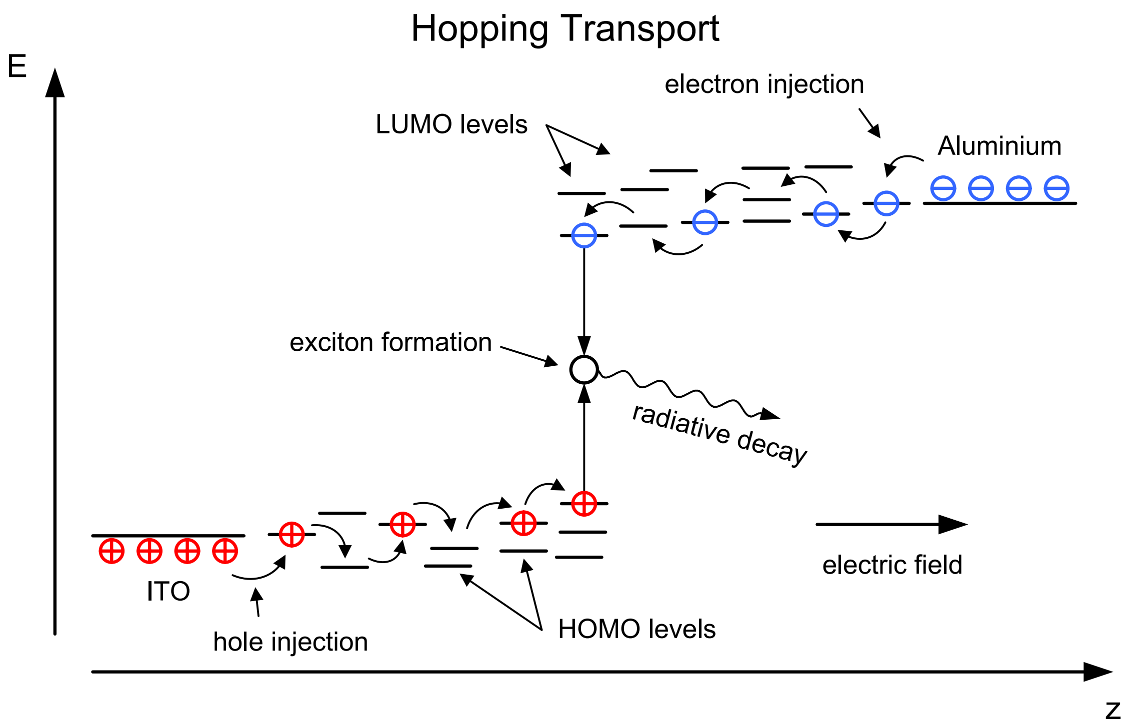

Figure 2: Hopping transport and recombination inside the OLED

Typical emission spectra of organic molecules are broad as shown in Figure 3. As stated before, the emission colour is a material property. Thus, by stacking several different emitting layers in a single device the total emission can be tuned to virtually every colour including white at any colour temperature. This is possible since the organic layers are almost transparent in the visible spectral range. Most white OLEDs contain a red, green and blue emission layer to create high quality white light.

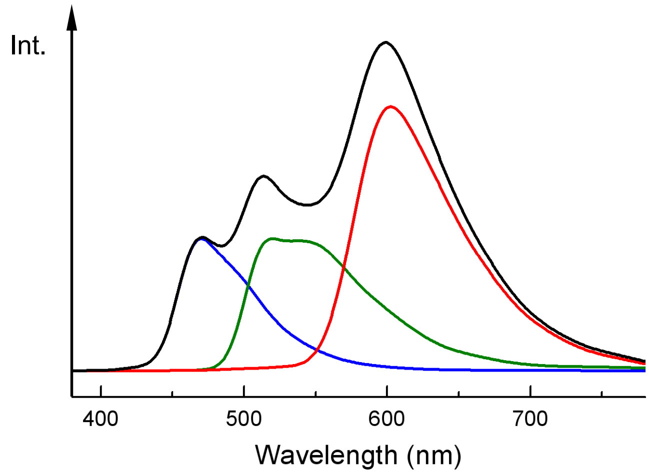

Figure 3: Typical emission spectra of organic materials. Shown are spectra of red, green and blue emitters and their superposition which yields white emission at a high colour rendering index.

As in inorganic semiconductor technology electrical doping is used to increase the material conductivity and to enhance the carrier injection from the electrodes into the organic materials. This allows for designing devices with intrinsic, un-doped active layers embedded in p- and n-type doped layers therefore referred to as PIN diode. One advantage besides an improved electrical performance is the possibility to increase the device thickness while maintaining the operation voltage almost constant. The overall device thickness between the electrodes should amount some hundred nanometers to provide sufficient protection against electrical shorts. They are often caused by the presence of particles on the substrate during evaporation of the organic layers or by the substrate roughness. If the organic layers are sufficiently thick to completely cover the particles, a good shorts protection is to be expected. Doping also enables a series connection of several active layers in a higher stacked structure (Figure 4). An intermediate NP junction operated in reverse direction behaves like a tunnel contact, where carriers can directly pass from the HOMO-level of one layer to the LUMO of the adjacent layer. In the OLED community those junction are often called charge generation layers (CGL) since electron-hole pairs are created at the interface and separated by the field and this kind of device immanent series connection is referred to as "stacking". A two fold white stacked device e.g. can be basically operated at the same luminance as a simple device at half the current, since there are two emitting units, but at twice the voltage. Stacked device architectures provide several advantages compared to simple PIN devices regarding lifetime, optical performance, etc. which will be discussed later.

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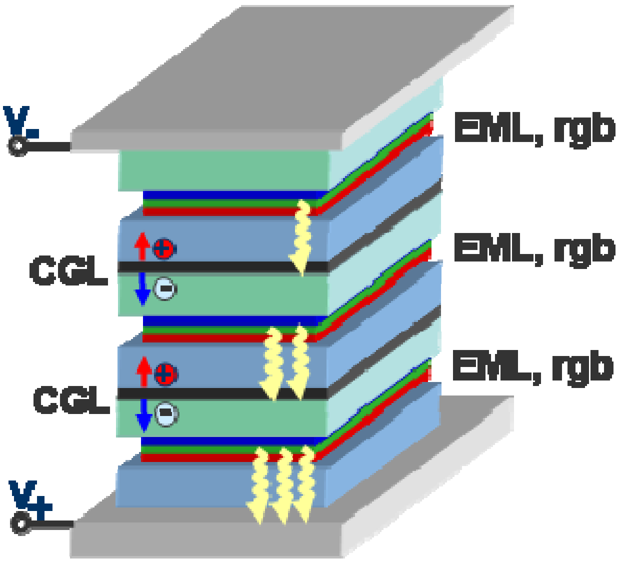


Figure 4: Stacked device architecture

The organic layers have to be protected against air as they are sensitive to moisture and oxygen and decompose when exposed. Possible encapsulation concepts are shown in Figure 5. On the right the OLED is capped by a glass layer glued on top of the cathode. Since the permeation barrier of the glue is not sufficient, the void space between the cap glass and the device is filled with an inert gas and a getter material is enclosed which will absorb penetrating moisture and oxygen. Another encapsulation concept is shown on the left. A thin but dense amorphous oxide layer is deposited onto the cathode which provides a similar permeation barrier as the glass encapsulation shown before. Due to its thinness, this thin film encapsulation (TFE) has to be protected from mechanical damage by e.g. laminating an additional glass layer, applying a lacquer coating, etc.

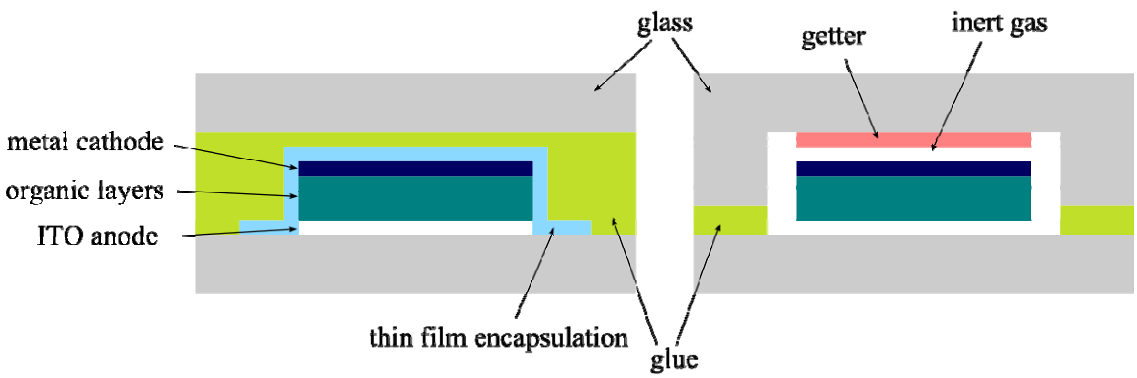


Figure 5: Encapsulation techniques for OLEDs. Left: thin film encapsulation. Right: glass encapsulation.

The thin layer system of an OLED represents an optical cavity in direction of the surface normal, i.e. an optical system with a total thickness of some wavelengths of the emitted light and a mirror at each end. Strictly speaking the OLED is a half-cavity since only the metal cathode acts as real mirror. Dependent on its thickness and the refractive indices of the materials therein, the cavity reveals one or more shallow resonances for light at a certain wavelength. For light rays leaving the device at an angle higher than the normal angle, this resonance condition is shifted to larger wavelengths. Consequently the emission colour of an OLED may display a pronounced angular dependency which can be minimized by clever engineering of the layer thicknesses and positions of the emitters with respect to the reflecting cathode. Furthermore, when generating light within a cavity, this means that there is always an optimal position providing maximum efficiency for a layer emitting at a certain wavelength. By tuning the layer thicknesses of the non-emitting layers it is possible to place the emitters at an optimal position.

In addition to forming a micro cavity the layer stack also has wave-guiding properties. Light generation in the active layers occurs isotropically, but only a small part, i.e. light with a direction of propagation within the escape cone, defined by the condition of total internal reflection at the interfaces, is actually able to leave the device. A large fraction (about 85 %) is wave-guided in the organic layers and in the substrate glass and is lost for illumination purposes. One way to overcome this limitation is to add an index matched layer to the substrate glass which contains scattering particles - a scattering or diffuser film. Light travelling in the substrate will enter the scattering layer, alter its direction when hitting a particle and eventually leave the scattering layer at a higher angle. The benefit is a higher extraction efficiency and therefore a higher overall device performance and good colour mixing since the scattering occurs statistically for all wavelengths which results in a much lower angular dependency of the emission colour. The only drawback of applying a scattering film is the loss of the mirror-like appearance when the device is turned off.

A major issue of large area OLEDs is the limited conductivity of the electrode material, above all that of the transparent conducting oxides (TCO), e.g. indium tin oxide (ITO), which is about two orders of magnitude lower than that of e.g. aluminum. This leads to a significant voltage drop across the transparent electrode and causes variations in the local driving voltage of the active layers depending on the distance to the electrical contacts. In consequence the emission intensity decreases from the borders of the device towards its centre. In order to lower the lateral voltage drop thin metal bus lines can be deposited on top of the ITO anode which increases the mean conductivity of the anode while shadowing only a minor fraction of the active area thus yielding a more uniform luminance pattern. The equivalent circuit of a large area device is a series connection of three resistors, representing anode, organic layers and cathode. The higher the differential resistivity of the organic layers at the operation point, the lower is the voltage drop across the electrodes which results in an enhanced uniformity. As stacked device architectures reveal a much higher differential resistivity, stacking is a way to improve the uniformity of large area devices without having to apply bus lines.

During lifetime of the OLED the luminance at constant current will decrease monotonously, the resistivity and thus the operation voltage will increase accordingly. The lifetime scales super-linearly with both emitted radiation intensity or current density and temperature. Especially the latter one has to be considered when designing OLED based luminaires. Large area devices at high luminance levels may reveal considerably elevated temperatures during operation and the possibility of heat exchange with the surroundings should be provided in order to preserve the device lifetime. Here again, stacked device architectures offer the possibility to lower the emission of each unit thus slowing down their ageing mechanisms, while keeping the overall emission constant.

OLEDs offer several unique features which distinguishes them from conventional light sources. They can be very thin, mainly limited by the thickness of substrate and encapsulation and thus very light weight. They are a non-glaring area light source which can be transparent or have either mirror-like or milky appearance when turned off. They offer high colour quality and turn on instantly when a current is applied. They have potential to be as efficient and long living or better than fluorescent lamps while 100% mercury-free. They do not contain UV radiation which means they do not bear any risk for eye safety. Future products based on OLED technology may even be shapable or flexible.

Electro-optical device characteristics

OLEDs are in good approximation Lambertian surface emitter, which means that when viewed from any angle, they have the same apparent radiance. This characteristic can be modified to some extent by changing the composition of the micro cavity. Significant beam shaping is only possible by means of additional external optical elements like e.g. mircolens arrays. As described in the previous section, the emission colour of an OLED displays a notable angular dependency which can be minimized by applying a diffuser film on the emitting surface. As shown in Figure 6, the angular shift of the colour in CIE space can be reduced by more than one order of magnitude by means of a diffuser while enhancing the out-coupling efficiency at the same time up to 50%.

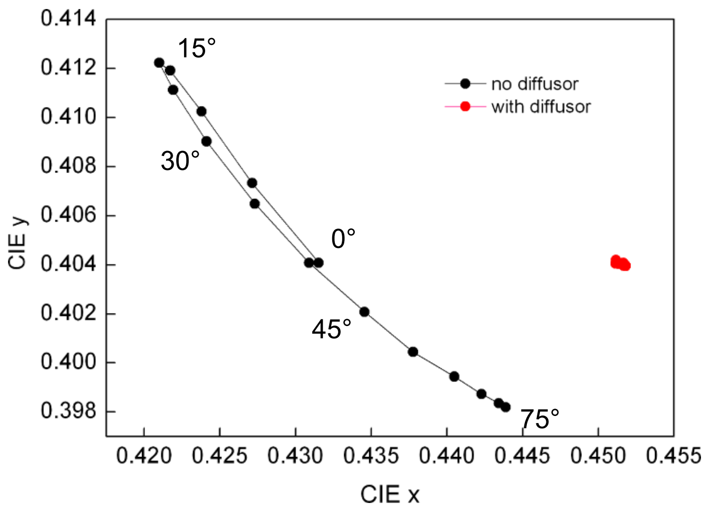
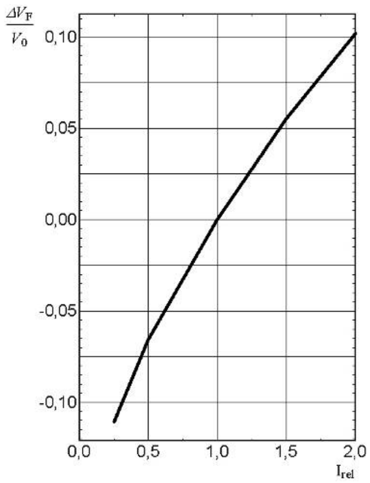


Figure 6: Colour coordinates of the OLED emission under different viewing angles from 0° to 75° without (black) and with (red) diffusor film on the surface.

The emission intensity of an OLED is usually characterized by its luminance which is a measure of the luminous intensity per unit area of light in a given direction. The unit is given in cd/m^2 also often named 'nits'. Typical numbers are in the range between 300 cd/m^2 for mood lighting up to a few thousand cd/m^2 for general illumination. This translates to a luminous flux between 10 and 100 lumen for a device area of 100 cm^2. The efficacy of light sources and so of OLEDs is measured in lumen per Watt, named luminous efficacy. Sometimes also the external quantum efficiency is specified, which relates the number of photons generated to the number of injected electron-hole pairs. Performance data published in technical information usually refers to operation at 1000 cd/m^2.

Typical relative current-voltage and current-luminance characteristics are shown in Figure 7. The luminance is directly proportional to the operation current in good approximation. Stacked devices are driven at a multiple of the operation voltage of a simple device at the same luminance, depending on the number of emitting units. At the same time the operation current is lower so that the luminous efficacy is about the same for both device architectures. However, the differential resistivity, i.e. the slope of the voltage-luminance characteristics is reduced which makes stacked architectures favorable for the fabrication of large area devices (see section 1).



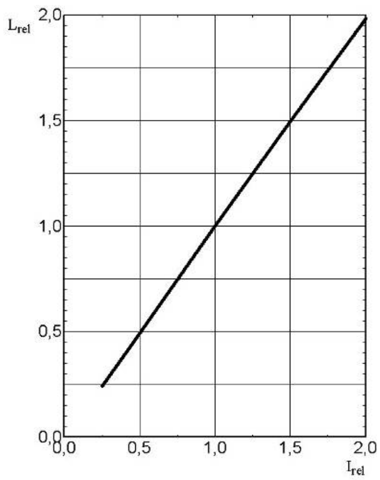


Figure 7: I-V (left) and I-L (right) characteristics in relative units. A relative current or luminance of 1and voltage of 0 refer to typical operation conditions.

The color rendering index (CRI) is a quantitative measure of the ability of a light source to reproduce the colors of various objects similarly to a natural light source. A CRI of 100 means that the light source has the same illuminating properties as incandescent light (CCT <5000K) or daylight (CCT >5000K), any value below that indicates a deficiency in some spectral region. As mentioned in section 0, the emission spectrum of an organic molecule is naturally broad and it is easy to achieve CRI above 80 by combining a red, a green and a blue emitter as shown in Figure 1. In addition, when looking at the spectrum, it is apparent that OLEDs reveal neither UV nor IR radiation.

Excursion: Photobiological Safety

In fact OLED emission is harmless in terms of eye safety. Lamps are rated according to a norm for general illumination IEC 62471 (Photobiological safety of lamps and lamp systems). This norm distinguishes between four risk groups:

1. Exempt group → no risk
2. Low risk group → no hazard because of eyelid closure reflex
3. Moderate risk group → (relating to devices in the visible spectrum with an exposure time of 0.25s). Under real circumstances (for exposure time, eye pupils, observation distance), it is assumed that no endangerment to the eye exists from these devices.
4. High risk group

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These groups are not fully compliant with the IEC 60825 (laser classification) because – as an example – photochemical effects are weighed differently than thermal effects. Comparing the blue light and thermal retinal exposure levels derived from typical and maximum operation conditions of a warm white OLED with the exposure limits given by IEC 6247 (see Table below) OLED emission is far away from hazardous exposure limits.

		Exposure*		Emission limits			
	Symbol	2000 cd/m^2	5000 cd/m^2	Exempt	Low risk	Mod risk	Units
Blue	L_B	0.39	0.95	100	10000	4000000	W m^{-2} sr^{-1}
Thermal retinal**	L_R	8.3	20.3	28000/α	28000/α	71000/α	W m^{-2} sr^{-1}

* Radiance derived from warm white OLED emission at 2000 cd/m^2 corresponds to 5.5 W m^{-2} sr^{-1} (13.5 W m^{-2} sr^{-1} for 5000 cd/m^2)

** Maximum angular subtense of the source in radians is $\alpha_{max} = 0.1$

Table 1: Typical exposure caused by OLED emission and exposure limits according to IEC 62471.