

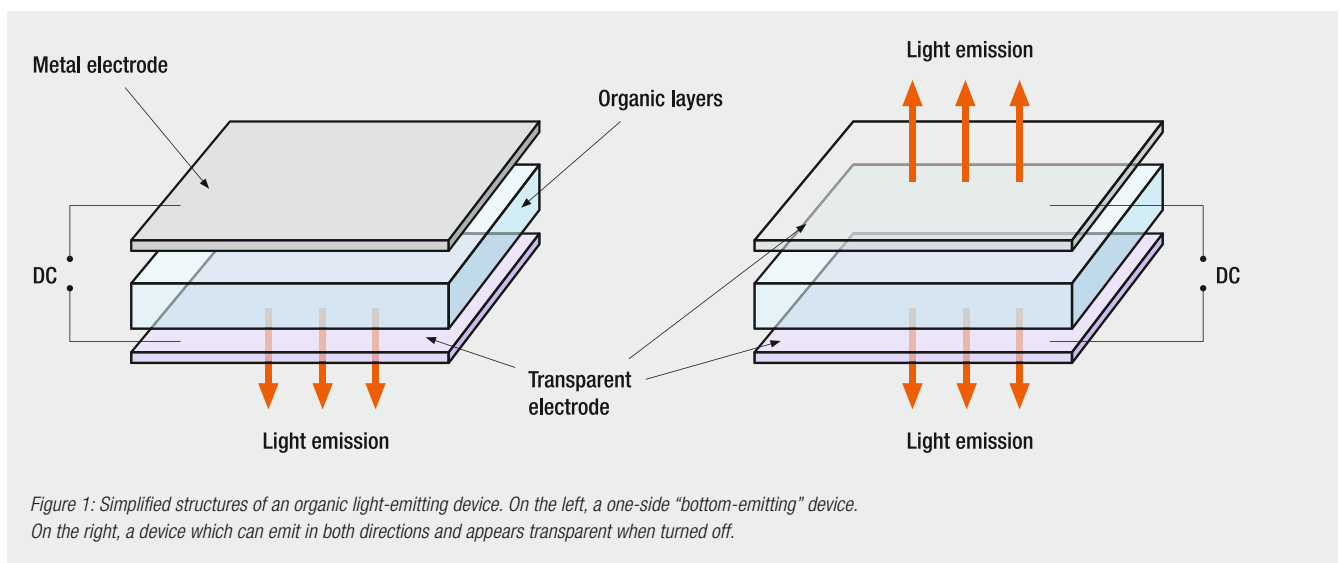
Introduction to OLED technology.

1. General characteristics

1.1. Structure

An organic light-emitting diode (OLED) consists of several semiconducting organic layers sandwiched between two electrodes, at least one of them being transparent. Two simplified device structures are shown in figure 1: a one-side-emitting device (left) and a transparent one which emits light both upwards and downwards (right). The device is fabricated by sequentially depositing organic layers on a conducting substrate followed by another conducting electrode. A common device structure comprises a glass substrate coated with indium tin oxide (ITO) as transparent anode and a thin, opaque metal film as cathode.

The organic stack including the electrodes is usually thinner than 1 μm . Two classes of organic materials are commonly used for 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 optoelectronics is the possibility to use simple screen printing or wet deposition techniques for cost-effective fabrication of large-area devices. Nowadays, this applies only to polymeric organics, whereas evaporating techniques still have to be applied for small molecules.



1.2. Hopping transport and recombination

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 certain color 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. Furthermore, the concept of energetic bands with highly delocalized wave functions is not applicable to organic electronics. Instead of “valence band” and “conduction band”, the relevant terms are “HOMO level” (highest occupied molecular orbital level) and “LUMO level” (lowest

unoccupied molecular orbital level). Before actually decaying radiatively, an electron-hole pair will form an exciton in an intermediate step, which will eventually emit light when it decays. 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. In the former, however, three quarters of all excitons – the triplet excitons – do not emit any light. Fluorescent emitters therefore have a maximum intrinsic efficiency of only 25% and their application is avoided if possible. However, up to now, the lifetimes of phosphorescent emitters, especially at a short wavelength (blue), are inferior to those of fluorescent ones.

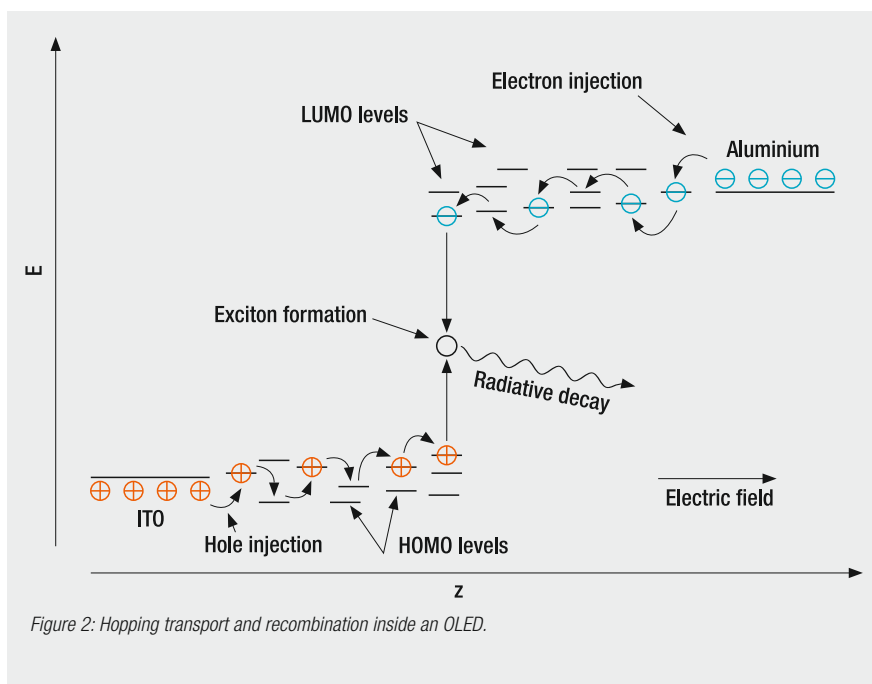


Figure 2: Hopping transport and recombination inside an OLED.

1.3. Emission spectrum

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

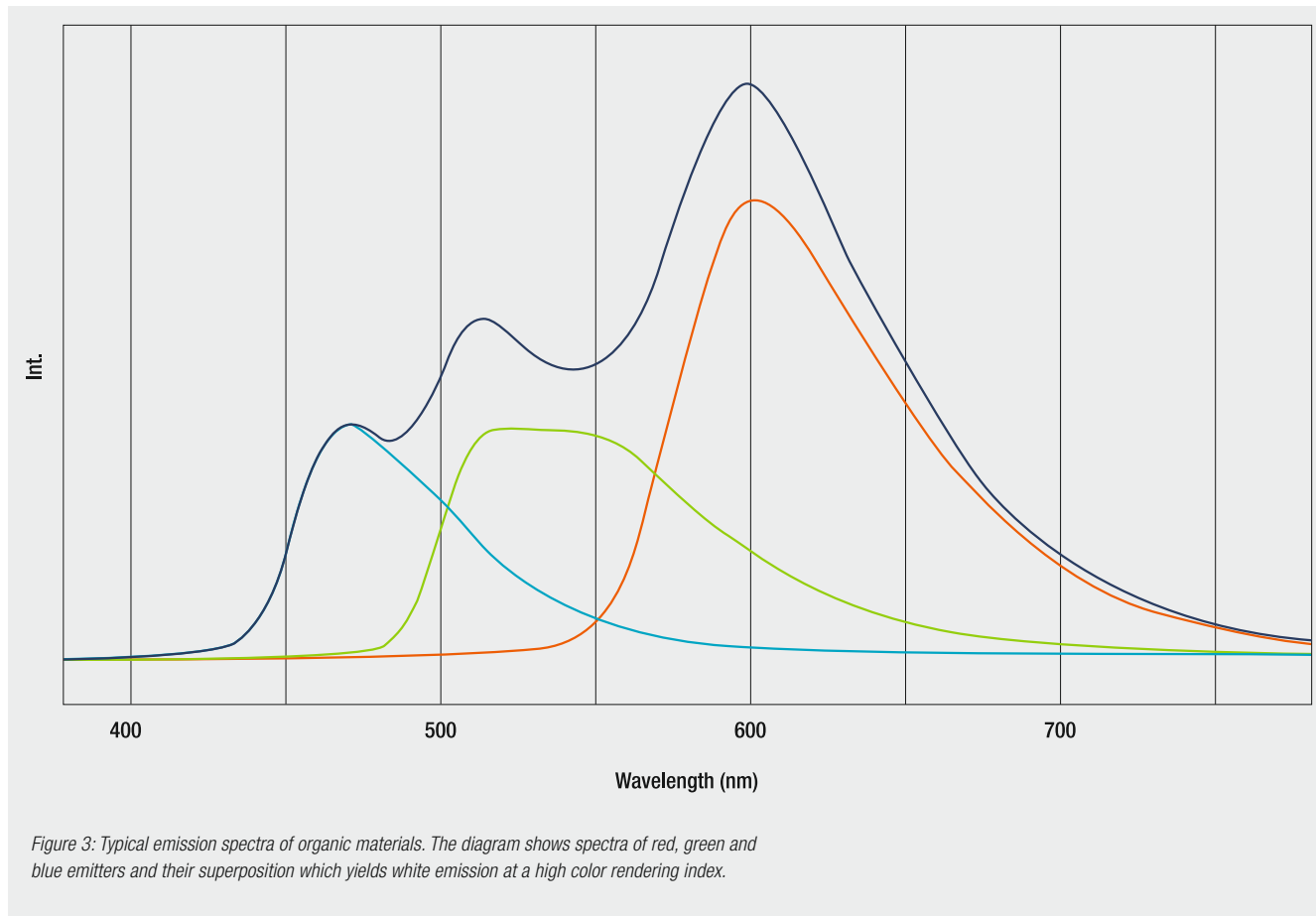


Figure 3: Typical emission spectra of organic materials. The diagram shows spectra of red, green and blue emitters and their superposition which yields white emission at a high color rendering index.

1.4. Doping

In organic semiconductor technology, electrical doping is used to increase the conductivity of the material and to enhance the carrier injection from the electrodes into the organic materials. This allows for the design of devices with intrinsically undoped active layers embedded in p-type and n-type-doped layers, which are therefore referred to as “PIN diodes”. In addition to an improved electrical performance, such a design also provides the opportunity to increase the thickness of the device while maintaining the operating voltage almost constant. The overall thickness of the device between the electrodes should amount to some hundred nanometers to provide sufficient protection against electrical short-circuits. These are often caused by the presence of particles on the substrate during evaporation of the organic layers or by the roughness of the substrate.

Doping also enables a series connection of several active layers in a higher-stacked structure (figure 4). An intermediate PN junction operated in reverse direction behaves like a tunnel contact: the carriers can directly pass from the HOMO level of one layer to the LUMO level of the adjacent layer. In the OLED community, these junctions are often called “charge generation layers (CGLs)” because electron-hole pairs are created at the interface and separated by the field.

A device structure with immanent series connection is referred to as “stacking”. A twofold white stacked device, for example, can basically achieve the same luminance levels as a simple device – at half the current, since there are two emitting units, but at twice the voltage. Compared with simple PIN devices, stacked device architectures offer several advantages in terms of lifetime, optical performance etc. These will be discussed later.

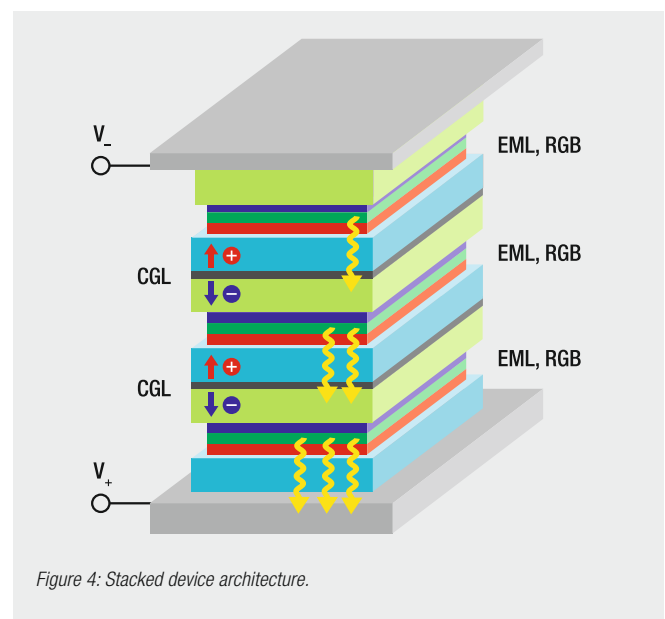
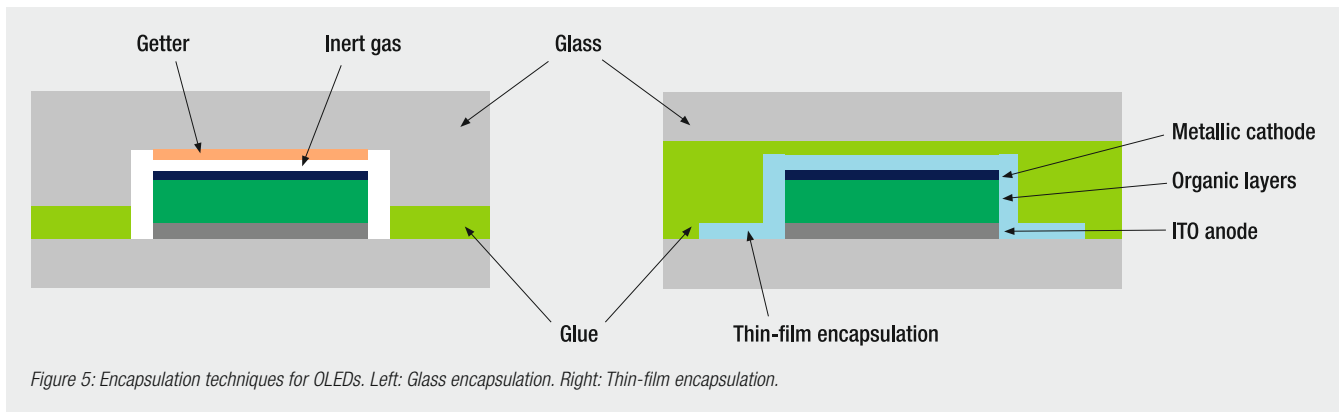


Figure 4: Stacked device architecture.

1.5. Encapsulation

The organic layers have to be protected against air as they are sensitive to moisture and oxygen and decompose when exposed. Possible encapsulation techniques are shown in figure 5. On the left, a glass cap is glued onto the back of the OLED. In order to enhance the stability of the permeation barrier, the void space between the glass cap and the device is filled with an inert gas and a getter material is applied to absorb pene-

trating moisture and oxygen. On the right, a thin but dense amorphous oxide layer is deposited onto the cathode, which provides a similar permeation barrier as the glass encapsulation shown on the left. Due to its thinness, this thin-film encapsulation (TFE) has to be protected from mechanical damage, for example by laminating an additional glass layer onto it, by applying a lacquer coating etc.



1.6. Optical cavity

The thin layer system of an OLED represents an optical cavity in the 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 because only the metal cathode acts as a real mirror. Depending on its thickness and the refractive indices of the materials therein, the cavity shows one or more shallow resonances for light at a certain wavelength. For light rays that leave the device at an angle higher than the normal angle, this resonance condition is shifted to larger wavelengths.

Consequently, the emission color of an OLED may display a pronounced angular dependency which can be minimized by clever engineering of the layer thicknesses and the positions of the emitters with respect to the reflecting cathode. Furthermore, this means that when generating light within a cavity, there is always an optimal position that provides maximum efficiency for a layer that emits light at a certain wavelength. The optimal position of an emitter can be achieved by tuning the layer thicknesses of the non-emitting layers.

1.7. Wave-guiding properties

In addition to forming a microcavity, 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, which is defined by the condition of the 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 as well as the substrate glass and is lost for illumination purposes. One way to overcome this limitation is to add an index-matched layer containing scattering particles to the substrate glass, i.e.

a diffuser film. Light traveling in the substrate will enter the diffuser film, alter its direction when hitting a particle and eventually leave the diffuser film at a higher angle. The benefit is a higher extraction efficiency and therefore a higher overall device performance and good color mixing due to statistical scattering of all wavelengths, which results in a much lower angular dependency of the emission color. The only drawback of applying a diffuser film is the loss of the mirror-like appearance when the device is turned off.

1.8. Conductivity

A major issue of large-area OLEDs is the limited conductivity of the electrode material, in particular that of the transparent conducting oxides (TCOs), e.g. indium tin oxide (ITO), which is about two orders of magnitude lower than that of aluminium, for example. 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. Consequently, the emission intensity decreases from the periphery of the device towards its center. 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 and thus yielding a more uniform luminance pattern. The equivalent circuit of a large-area device is a series connection of three resistors, representing the anode, the organic layers and the cathode. The higher the differential resistivity of the organic layers at the operating point, the lower is the voltage drop across the electrodes which results in an enhanced uniformity. As stacked device architectures have a much higher differential resistivity, stacking is a way to improve the uniformity of large-area devices without having to apply bus lines.

1.9. Lifetime

During the lifetime of an OLED, the luminance will decrease monotonically at constant current. The resistivity and thus the operating voltage will increase accordingly. The lifetime scales super-linearly with both the emitted radiation intensity (or current density) and the temperature. The temperature, in particular, has to be considered when designing OLED-based luminaires. At high luminance levels, large-area devices

may have considerably elevated temperatures during operation and the possibility of heat exchange with the surroundings should be provided in order to ensure a long lifetime of the device. In this case, stacked device architectures once again offer the possibility to lower the individual emission of each unit, thus slowing down their aging mechanisms, while keeping the overall emission constant.

1.10. Special features

OLEDs offer several unique features:

- They can be very thin, mainly limited by the thickness of the substrate and encapsulation, and therefore very lightweight.
- They are glare-free area light sources which can be transparent or have either a mirror-like or milky appearance when turned off.
- They offer high color quality and turn on instantly when current is applied.
- They have the potential to be equally or more efficient and long-living than fluorescent lamps, while being 100 % mercury-free.
- They emit neither UV nor IR radiation.
- Future products based on OLED technology may even be shapeable or flexible.

2. Electro-optical characteristics

2.1. Emission

In good approximation, OLEDs are Lambertian surface emitters, which means that they have the same apparent radiance when viewed from any angle. This characteristic can be modified to some extent by changing the composition of the micro-cavity. Effective beam shaping is only possible by means of additional external optical elements such as microlens arrays. As described before, the emission color 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 color in CIE space can be reduced by more than one order of magnitude by means of a diffuser, while enhancing the outcoupling efficiency up to 50% at the same time.

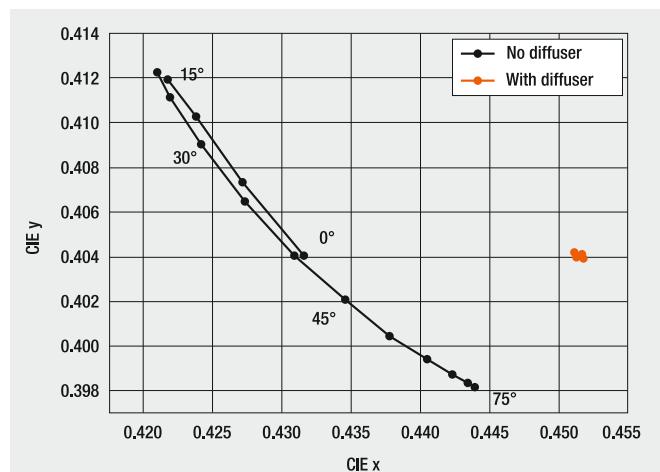


Figure 6: Color coordinates of the OLED emission at different viewing angles from 0° to 75° without and with diffuser film on the surface.

2.2. Emission intensity

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 traveling in a given direction. The unit for luminance is cd/m^2 , often also called “nit”. Typical luminance values range from $300\text{cd}/\text{m}^2$ for mood lighting up to a few thousand cd/m^2 for general illumination. This translates into a luminous flux between 10 and 100 lumen for a device area of

100cm^2 . The efficacy of OLEDs and other light sources is measured in lumen per watt and is called “luminous efficacy”. Sometimes, specifications also include the external quantum efficiency, which relates the number of generated photons to the number of injected electron-hole pairs. Performance data published in technical information usually refer to an operation at $1,000\text{cd}/\text{m}^2$.

2.3. I-V and I-L characteristics

Typical relative current-voltage and current-luminance characteristics are shown in figure 7. In good approximation, the luminance is directly proportional to the operating current. Stacked devices are driven at a multiple of the operating voltage of a simple device at the same luminance, depending on the number of emitting units. At the same time, the operating 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 1.4.).

2.4. Color rendering index

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 < 5,000 K) or daylight (CCT > 5,000 K). Any value below 100 indicates a deficiency in some spectral region. As mentioned in section 1.3., the emission spectrum of an organic molecule is naturally broad and it is easy to achieve a 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 becomes apparent that OLEDs emit neither UV nor IR radiation.

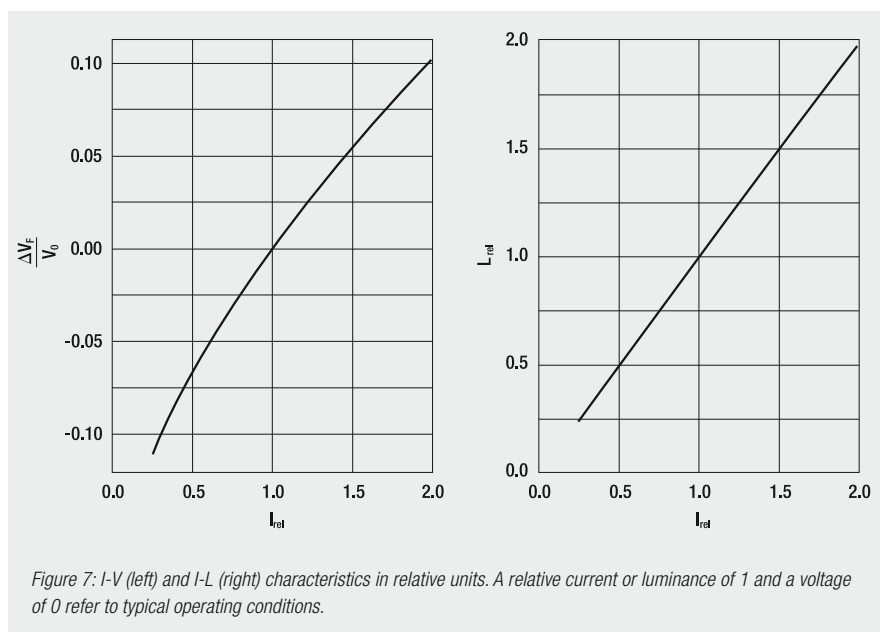


Figure 7: I-V (left) and I-L (right) characteristics in relative units. A relative current or luminance of 1 and a voltage of 0 refer to typical operating conditions.

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