

# Organic light emitting devices

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*The purpose of this paper is to provide general information about basic physical processes involved in organic electroluminescence and to present the main parameters and advantages of organic light emitting devices (OLEDs).*

**Keywords:** organic materials, electroluminescence, injection, recombination, organic light emitting diodes (OLEDs), organic electroluminescence devices.

## 1. Introduction

Electroluminescence (EL) of organic materials is a phenomenon that has been examined since the 1960's [1]. Promising results of these early studies established that the process of electroluminescence in organic materials can be utilized in practical device applications. Moreover, other impulses for further investigations of organic light emitted diodes (OLEDs) were high values of electroluminescence yield, favourable physical and technological properties and very cheap manufacture. It should be noted that fabrication of electroluminescence devices based on organic materials and then their introduction into market was long-range and rather complicated problem, which required among other things the new technology of material production.

Since the beginning of the 1980's, the organic thin-film electroluminescence devices have developed rapidly. First research efforts on organic materials have led to their use in electrophotography (or xerography) [2] and in active-matrix liquid crystal displays [3]. Since the 1990's, LEDs are routinely fabricated with molecular materials [4] and polymers [5] and now are developed to be viable technologies for large-area flexible electronics [6].

The purpose of this paper is to present basic information concerning the principles of operation of electroluminescence devices and promises of their realization based on organic materials.

## 2. Physics of organic electroluminescence

Electroluminescence can be simply defined as the emission of light by a substance when acted upon by an electric field [7–10]. Electroluminescence can be produced by different factors resulting from external electric field applied to the sample. Among them the most important is the recombination of charge carriers with opposite signs [11–14].

To obtain electroluminescence process in the sample, the carriers of opposite sign can be injected and recombination should take place in the bulk [11,15,16]. Two-carrier (double) injection can be realized in a system of an organic layer supplied with two electrodes. As a result of charge carriers recombination process, visible, ultraviolet and infrared radiation can be produced. In Fig. 1, the diagram of electroluminescence device structure (a) and simplified scheme of the electroluminescence process (b) are presented.

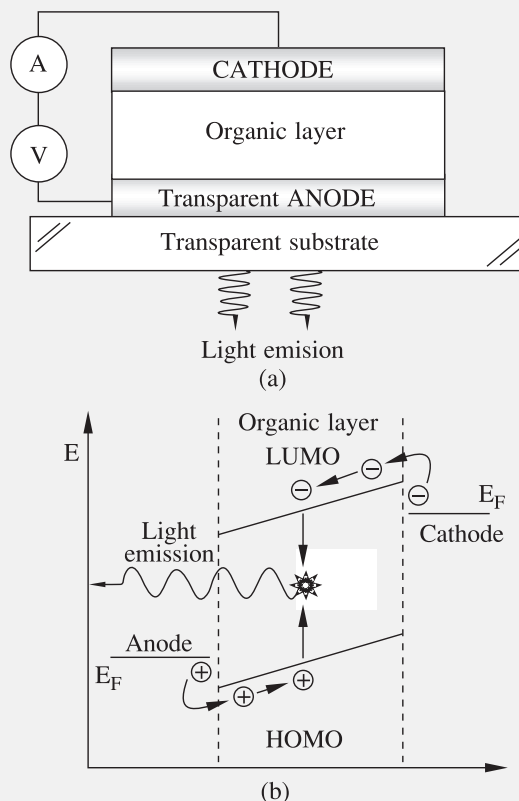


Fig. 1. Schematic diagram of OLED device structure (a) and simplified scheme of the electroluminescence process (b).

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It follows from Fig. 1 that effective double injection is possible when the work function of metal electrodes is close to the lowest unoccupied molecular orbital (LUMO) and the highest occupied molecular orbital (HOMO) levels for organic material.

As it has been mentioned above, one of the factors determining the electroluminescence efficiency is the probability for the e-h recombination represented by the recombination time  $\tau_{rec}$  to the transit time  $\tau_t$  ratio as [11].

$$P_R = \frac{1}{1 + \tau_{rec}/\tau_t}, \quad (1)$$

where

$$\tau_{rec} = \frac{1}{\gamma_{eh}n} \quad \text{and} \quad \tau_t = \frac{d}{\mu F},$$

and  $\gamma_{eh}$  is the recombination rate constant,  $n$  is the free charge carrier density,  $d$  is the thickness of the sample, and  $\mu$  is the charge carrier mobility. For organic materials electron-hole pair recombination is bimolecular taking the Langevin form Ref. 17. Recently, an alternative formula of the bimolecular recombination rate constant as a function of charge carrier concentration and external electric field has been proposed [18].

It follows from Eq. (1) that  $P_R$  is tending to 1 when  $\tau_{rec} \ll \tau_t$ , that is for a high concentration of charge carriers. It can be pointed out that the average charge carrier concentration in the sample does not exceed the value obtained for space charge limited currents (SCLC) conditions [15,16]. In such a situation, the recombination time is close to the transit time and the recombination probability is relatively high.

The final products of recombination are the excited states. Their decay in organic materials produces not only photons but also phonons. The phonons production is unfavourable from practical application of electroluminescence phenomena, because it leads only to the increase in a sample temperature. Thus, the most important seems to obtain, from the recombination process, the excited states which decay lead to efficient radiation in a visible region of electromagnetic wave. It should be noted that the carrier recombination can produce singlet and triplet excitons in the ratio 1:3 (expected from spin statistics) [15,16]. Although the singlet excitons decay radiatively producing EL, whereas the triplet excitons in most organic materials decay nonradiatively. Therefore maximal value of EL efficiency defined as the ratio between photons and the number of pairs recombining in the sample can reach only 25% [15]. However, the last value can be improved by the light emission from the triplet charge transfer states.

### 3. Conditions leading to high efficiency of electroluminescence

The process responsible for electroluminescence requires the existence of oppositely charged carriers, the capture of oppositely charged carriers (the recombination), and the ra-

dioactive decay of the excited state (exciton) produced by this recombination process. Schematic diagram of the processes leading to electroluminescence is presented in Fig. 1.

The oppositely charged carriers can be injected into the layer from electrodes or they can be generated due to different physical processes [15]. The most common process which is used to obtain electroluminescence from an organic material is thermionic injection. According to relatively high values of ionisation energy of organic materials, for thermionic injection to occur, the anode material should have the large work function  $\phi$  (e.g., ITO, Au, Ag). As the cathode, for thermionic injection to be efficient, low- $\phi$  material is required (e.g., Ca, Mg, Al). It is worth to notice that one of the electrodes must be transparent to let emitted light leave the diode. Therefore as a convenient transparent anode, the ITO layer on a glass is used.

It is desirable, to obtain efficient charge carrier injection from electrodes, to ensure SCLC conditions in the sample. However, to achieve SCLC conditions is rather complicated from technological and physical point of view. Therefore the methods leading to increase in charge carrier time of flight are still looking for.

One of them is application of two or more organic layers [19]. There is then an organic-organic interface within the diode, which may work as a barrier for one carrier or both, so the recombination predominantly takes place near the interface. It follows from the fact that heterojunction causes a build up in charge density. The schematic diagram of a two-layer diode is presented in Fig. 2.

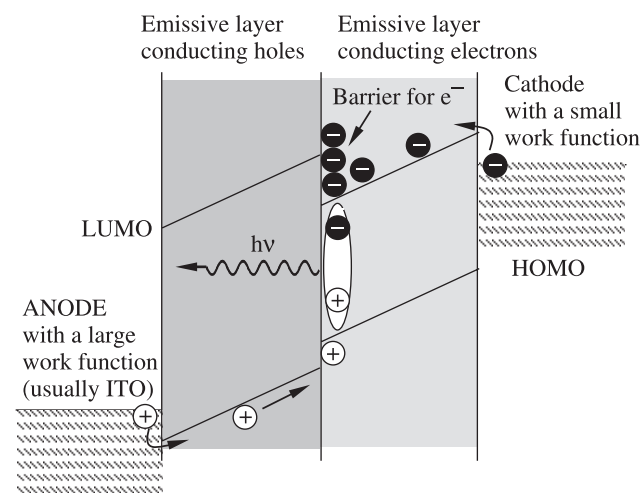


Fig. 2. The simplest model of a two-layer organic diode under forward bias.

For a bilayer diode consisted of NPB (N, N'-di(naphthalene-1-yl)-N, N'-diphenylbenzidine) and Alq<sub>3</sub> (tris(8-hydroxyquinoline) aluminum) layers, the electroluminescence and luminescence spectra are shown in Fig. 3.

In Fig. 4, typical technical parameters of organic light-emitting diodes with double-emission layers are shown.

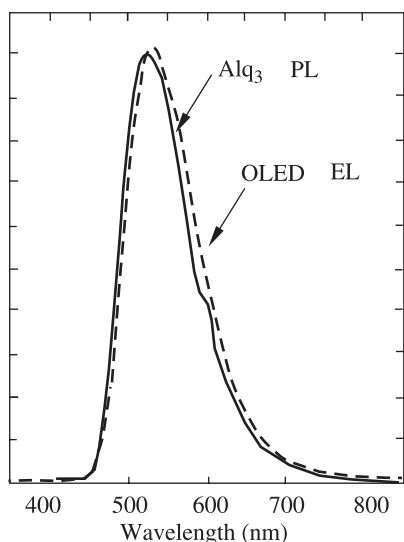


Fig. 3. Electroluminescence (EL) and photoluminescence spectra of Alq<sub>3</sub> layer (after Ref. 20).

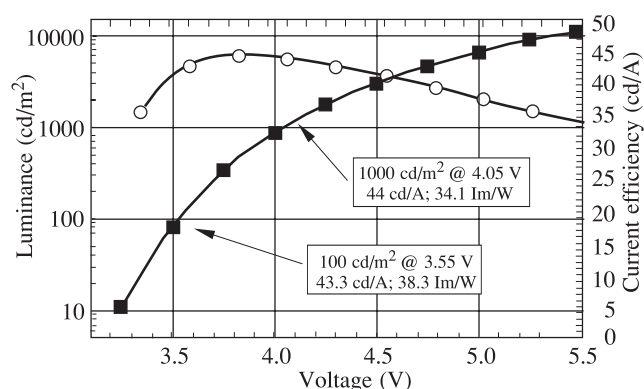


Fig. 4. The luminance and the current efficiency vs. voltage for an optimised double-emission layer OLED [21].

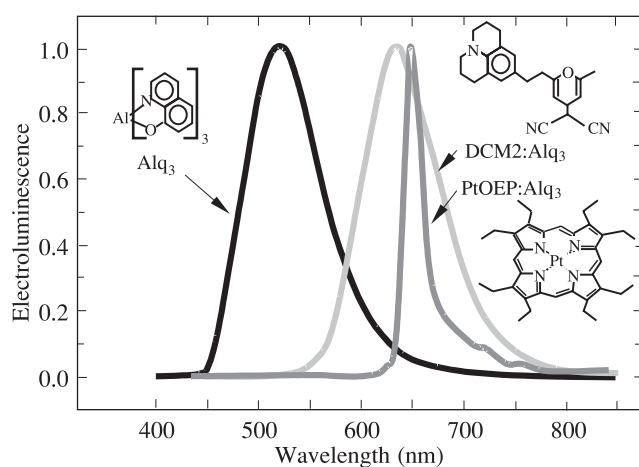


Fig. 5. The electroluminescence spectra of pure Alq<sub>3</sub>, DCM2 and PtOEP doped into Alq<sub>3</sub> (after Ref. 22).

The important feature of electroluminescence spectra is the possibility of their optical modification. In Fig. 5, the electroluminescence spectra of pure Alq<sub>3</sub> and DCM2 ([2-methyl-6-[2-(2,3,6,7-tetrahydro-1*H*,5*H*-benzo[*ij*]quinolizin-9-yl)ethenyl]-4*H*-pyran-4-ylidene] propane-dinitrile) and PtOEP (2,3,7,8,12,13,17,18-octaethyl-21*H*,23*H*-porphine platinum (II)) doped into Alq<sub>3</sub> are presented.

#### 4. OLED efficiency

Quantities of practical significance for OLED are the quantum efficiency, luminous efficiency, and luminance.

The device quantum efficiency consists of two parts, namely internal and external quantum efficiency. The internal quantum efficiency, defined as the ratio of the number of photons  $\phi$  produced within the device to the number of electrons flowing in the external circuit  $j/e$  is given by

$$\eta = \frac{\phi}{j/e}. \quad (2)$$

However, the external quantum efficiency refers to the number of photons that are emitted from the device. It should be noted that the quantum efficiency depends on the device structure and its operating conditions, particularly on the applied voltage. To the best of our knowledge, values of the internal quantum efficiency for experimental OLEDs are close to those obtained for LEDs based on inorganic materials and reach about 30% [23].

The luminous efficiency (lumen per watt) is the total luminous flux emitted, divided by the total diode power input. What is important from practical point of view, experimental OLEDs are already more energy-efficient than incandescent lamps. The luminous efficiency of light bulbs is about 13–20 lm/W and the latest experimental OLEDs already have luminous efficiency of about 100 lm/W [24]. It shows that OLEDs can effectively compete with fluorescent lamps, which have the luminous efficiency of 50–100 lm/W.

The luminance (cd per square meter) is defined as luminous intensity of any surface in a given direction per unit of a projected area of the surface viewed from that direction. It can be found that the luminance of OLEDs is of the order of  $10^6$  cd/m<sup>2</sup> [25].

The values of the luminance and the current efficiency as a function of the applied voltage for OLED with double-emission layer are shown in Fig. 4.

#### 5. Selected advantages of OLEDs

OLEDs are thin film multi-layer devices which can find different practical applications. Among them the most prospective are: monochrome and full-colour display for electronic devices, large screen computer and TV monitors and lighting panels. Presently, the main effort in the development of OLEDs is focused on the full-colour flat panel display application.

Organic light emitting devices have got a number of advantages in comparison to the existing light sources. First, they can operate at very low voltages of the order of 3–5 V. Second, they are current-driven devices, where brightness can be varied over a very wide dynamic range.

Another advantage of OLEDs is that they have the ability to change the colour of light emission to any desired. It can be done by selecting an appropriate emitter or mixture of emitters with proper emission spectra. By mixing light from two or more sources, OLEDs can produce white light.

Furthermore, OLEDs could be deposited on any substrates such as glass, metal, thin plastic sheets and flexible and conformable substrates, therefore they could be fabricated in any shape and design.

Except the advantages mentioned above, the fabrication of OLEDs is inexpensive and its lifetime (an average number of hours of operation in which the initial light intensity drops to 50%) is long. Recent studies of the market show that the cost of producing one square meter of OLED is of the order of 50\$ [26], however, lifetimes of the latest OLEDs are nearly 20.000 hours [27].

This qualitative comparison shows that the OLEDs may soon capture and dominate the lighting market. According to the latest studies, the full-colour flat panel display based on OLEDs achieved better optical properties than the others. Table 1 shows qualitative comparison of panel displays.

Table 1. Qualitative comparison of displays (after Ref. 28).

Performance	CRT	PDP	LCD	OLED
High resolution	○	●	☺	☺
Luminescence	☺	●	●	☺
Contrast	Bright condition	☺	●	○
	Dark condition	○	☺	○
Viewing angle	○	○	○	☺
Power consumption	●	○	○	○
Weight	●	○	☺	☺☺
Thickness	●	○	☺	☺☺

☺☺ Excellent ☺ Very Good, ○ Acceptable, ● Poor

CRT = cathode ray tube; PDP = plasma display panel; LCD = liquid crystal display

## 6. Conclusions

The presented results referring the electroluminescence in organic materials show that it is generally believed that OLEDs have all the attributes to effectively compete with conventional light sources. However, it should be pointed out that the prospects of wide application require deeper understanding of OLED operation. Further investigation of the processes like injection or problems specific for high fields should be done. It should be noticed that though

OLEDs have already reached the level required for practical application, they are still far below their physical potential.

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