

# Organic Optoelectronic Devices: Organic Light-Emitting Diodes (OLED)

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**Abstract**—A brief induction of organic light-emitting diodes is provided, including the materials, device structure, electronic energy structure, electronic transport properties, and their applications.

**Index Terms**—Organic light-emitting diodes, polymer light-emitting diodes, ionization potential, electron affinity, space charge limited currents.

## I. INTRODUCTION

An organic light-emitting diode (OLED) is a special type of light-emitting diode (LED). An OLED is composed of at least one undoped organic layer that is put between two electrodes. Electrons and holes are injected from either side of the electrode, respectively. After applying a voltage, both carriers will drift towards the other side in the applied electrical field. When both electrons and holes meet at the bulk or the interface, they then recombine to form excitons, which will decay to produce light emission.

In 1987, Tang et al. reported OLEDs based on small organic molecules by thermal vacuum deposition [1] and in 1990, at Cambridge University, Friend et al. reported OLEDs based on solution-processed semiconducting polymers [2]. These two pioneering works made a breakthrough in the OLED areas, and since then lots of papers on this subject were published. According to the materials used for OLEDs, OLEDs can be divided into two types: small-molecular OLEDs and polymer light-emitting diodes (PLEDs). Generally, an OLED refers to small-molecular OLED.

## II. SMALL-MOLECULAR ORGANIC LIGHT-EMITTING DIODES

### A. Device structure

A small-molecular OLED consists of one organic layer or multiple organic layers between two electrodes. The one organic layer device is called a single layer device. Thus, the organic material must serve all the three main functions: electron transport, hole transport and emission. In this case, the injection rates of both carriers should be almost equal for high efficiency. Otherwise, the surplus electrons or holes will not recombine, which results in low operation efficiency [3].

We can overcome this disadvantage by employing multiple organic layers in the OLED structure. The basic device structure with three layers is shown in Figure 1. This structure employs an electron transport layer (ETL), a hole transport

layer (HTL) and an emissive layer. The emitter material can be either a layer between ETL and HTL or a dopant in one of these layers, close to the recombination zone. The dopant with a lower exciton energy than its matrix will yield a high luminescent efficiency.

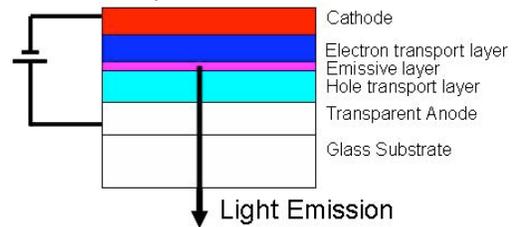


Figure 1. Configuration of OLED.

### B. Materials

The typically used n-type materials for ETL are Alq3, PBD, etc. And the generally used p-type materials for HTL are NPB and TPD, etc. The chemical structures are shown in Figure 2. The commonly used emitters are fluorescent dye and phosphorescent dye, etc.

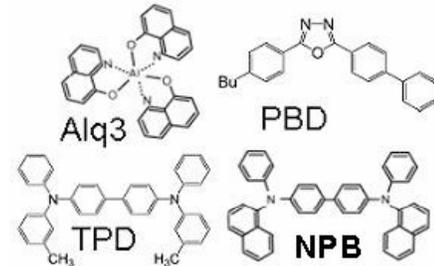


Figure 2. Chemical structures of the small molecules.

### C. Electrodes

The performance of the diode also strongly depends on the materials of electrodes that they employ. Generally, the work function of the cathode should be sufficiently low and the work function of the anode should be sufficiently high in order to have good injection of both carriers, respectively. Furthermore, for the application of the OLEDs, one electrode should be transparent to allow the emission of light from the device.

So far, the most commonly used transparent anode is indium-tin-oxide (ITO), which has a relatively high work function of 4.5-5.1 eV [3]. Since the work function of the cathode should be low enough, the generally used materials for anodes are Al, Mg, Ca, etc. However, these metals will oxidize or corrode in the air. Thus, alloyed electrodes were made for higher stability with relatively low work functions. For example, Mg and Ag alloys are more stable than Mg [3].

### D. Fabrication

Vacuum thermal evaporation is most commonly used for depositing small organic molecules. The process is the sublimation of the materials, including organic semiconductors and metals, from a heated cell in bottom in vacuum onto a substrate on the top, shown in Figure 3 [4]. The general vacuum is about  $10^{-5}$ - $10^{-7}$  torr.

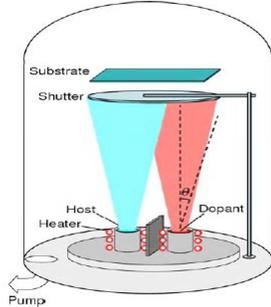


Figure 3. Schematics of the vacuum thermal evaporation process [4].

## III. POLYMER LIGHT-EMITTING DIODES

### A. Device structure

The polymers used in PLEDs are generally conjugated polymers because this kind of structure will lead to high conductance. Polymers are composed of a large amount of repeated similar molecules with a huge molecular weight. The first reported polymer used in PLEDs was poly(*para*-phenylene vinylene) (PPV) [2]. The chemical structure is shown in Figure 5. The device structure of this polymer LED is shown in Figure 4, which is almost the same as that of small molecular OLED. PPV has an energy gap of about 2.7eV which emits green light in the region of the spectrum. In forward bias, the injected electrons and holes recombine in the polymer layer and emit light. The polymer layer is about 100nm, to allow efficient charge injection and carriers transport through the layer. The device structure can be also bilayer with an additional conducting polymer layer between the ITO and emissive layer. The conducting polymer layer will improve the hole injection and electron blocking.

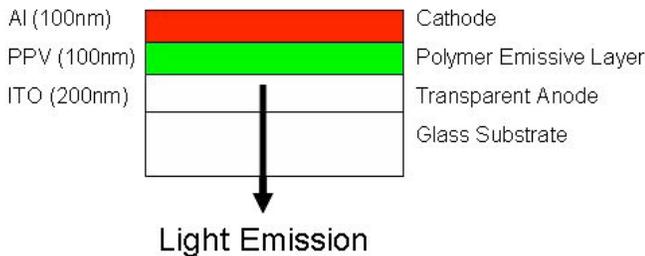


Figure 4. Configuration of PLED.

### B. Materials

Among conjugated polymers, the most used conducting polymers are PANI:PSS and PDOT:PSS, and emissive polymers are R-PPV and PFO. The chemical structures of these polymers are shown in Figure 5.

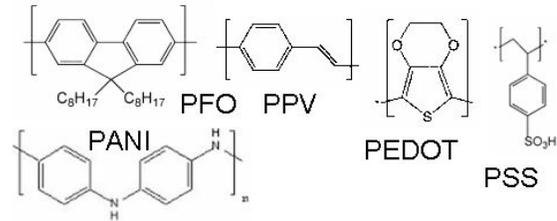


Figure 5. Chemical structures of the polymers.

### C. Fabrications

Polymers cannot use the same method as the small molecules employ because polymers have very large molecular weight. Therefore, polymers are usually deposited by dissolving an organic solvent followed by spin-coating, drop-casting, ink-jet printing or roll-to-roll web coating.

## IV. ELECTRONIC ENERGY STRUCTURE

Charge injection from the electrodes into the organic layers is an important process in the OLED's operation. This process can be understood by considering the electronic energy structure of the organic layers with the work function of the electrodes. To begin, we need some definitions. The ionization potential ( $E_v$ ) [3] is the energy required to remove an electron from the highest occupied state to the vacuum. The electron affinity ( $E_c$ ) [3] is the energy gained when adding an electron to the lowest unoccupied energy state. The energy gap is the difference between these two energies, ( $E_v - E_c$ ). In the case of PPV [3], the ionization potential of PPV is about 5.2 eV, and the electron affinity is 2.5 eV. Thus the energy gap is about 2.7 eV. The ideal barrier height of the semiconductor contact can be applied by the ideal Schottky model [5]. In this model, the energy barrier to electron (hole) injection is

$$\Phi_{e(h)} = |E_{c(v)} - W|$$

(1)

where  $W$  is the work function of the metal contact.

Therefore, to inject electrons into PPV, a metal electrode should have a work function close to or less than 2.5 eV; and to inject holes, the metal should have a work function closer to or greater than 5.2 eV. This is the basic requirements for the use of high work function metals as anodes and low work function metals as cathodes.

## V. ELECTRONIC TRANSPORT PROPERTIES

Currents in the organic semiconductors can be described by Space Charge Limited (SCL) currents [6]. The steady-state SCL currents without trapping can be described by,

$$J = \frac{9}{8} \epsilon \epsilon_0 \mu \frac{V^2}{L^3}$$

(2)

Where  $\epsilon$  is the permittivity of the semiconductor,  $\epsilon_0$  is the permittivity of free space,  $\mu$  is the charge carrier mobility,  $V$  is the applied voltage, and  $L$  is the thickness of the semiconductor.

This important equation is commonly called Child's law for the trap-free insulator. The situation becomes more complicated if trapping is presented. In general, the steady-state SCL currents becomes

$$J = \frac{9}{8} \epsilon \epsilon_0 \mu \theta \frac{V^2}{L^3} \quad (3)$$

Where  $\theta$  may be a complicated function of  $V$ ,  $L$ , and other parameters.

For the more complicated conditions, here we do not put more details on that.

Charge carrier mobility in organic materials is usually measured with the photoinduced time-of-flight technique [7]. Recently, another technique used to measure the mobilities in OLED device has been developed, which is based on the optical detection of the charge carrier concentration [8]. With the mobility, we can calculate the currents by employing the SCL currents equation from above.

Because most organic semiconductors are low-conductance materials, the hole mobilities of the p-type organic materials are typically  $10^{-7}$ - $10^{-3}$   $\text{cm}^2/\text{Vs}$ , and the electron mobilities of n-type organic materials are typically lower by a factor of 10-100. The low mobility is due to the disorder in the amorphous or polycrystalline materials. High mobilities are obtained only in the highly ordered materials. Indeed, the higher mobility is obtained in the rubrene single crystal transistor with a value of  $15 \text{ cm}^2/\text{Vs}$  [9].

## VI. APPLICATIONS AND CHALLENGES

### A. Applications of OLEDs in Flat-Panel Displays

OLED displays offer higher contrast, truer colors, higher brightness, wider viewing angles, better temperature tolerance, and faster response times than LC displays, which make it have the potential to be the next-generation of the display device. By far, OLED technology has been used in the real-life applications such as small screens for mobile telephones and portable digital music players (MP3 players), digital cameras and personal digital assistants (PDA). Since OLED based displays do not have to be back-lit, they have the potential to be thinner, lighter and more flexible than conventional LC displays. It can be also used in large screens and flexible paper-like screens. Currently, the largest OLED display prototype with the size of 40 inches was produced by Samsung in 2005, shown in figure 6 [11]. Flexible screen can also be rolled into the tube for the special usage.



Figure 6. The largest OLED display prototype at 40 inches by Samsung.

### B. Application of OLEDs in Solid-State Lighting

White OLEDs, which emits white light, could also be used as solid state light sources. The total power efficiency of a typical incandescent light bulb is about 12-17  $\text{lm/W}$ , whereas the power efficiency of an OLED has already achieved 30-60  $\text{lm/W}$  in the laboratory [10]. Therefore, OLED will be a good candidate for the new generation of the solid-state lighting.

### C. Challenges

Despite the success of the OLEDs, they still have several challenges: How to improve the power efficiency of the device? How to obtain the purest red, green and blue and tunable white? How to increase the lifetime of the OLEDs?

## VII. CONCLUSION

OLED technology has the potential to be the next generation of displays and lighting. Both small molecular and polymer OLEDs will have their own position in the market. Now the most important issues are to improve the efficiency and lifetime of the OLEDs. In the near future, the flexible OLED display will appear in your laptop or home video applications.

## REFERENCES

- [1] C. W. Tang and S. A. Van Slyke, "Organic electroluminescent diodes," *Appl. Phys. Lett.* 51, 913-915, 1987.
- [2] J. H. Burroughes, D. D. C. Bradely, A. R. Brown, R. N. Marks, K. Mackay, R. H. Friend, P. L. Burns, and A. B. Holmes, "Light-emitting diodes on conjugated polymers," *Nature* 347, 539-541, 1990.
- [3] J. C. Scott and G. G. Malliaras. *Semiconducting Polymers*, ED. G. Hadziioannou, P. F. van Hutten, (Wiley, 2000), Chap. 13.
- [4] P. Peumans, *Organic thin-film photodiodes*, Thesis, University of Princeton
- [5] E. H. Rhoederick and W. R. Frensley, M. P. Shaw, *Handbook on Semiconductors*, Vol. 4, ED. C. Hilsum, (North-Hollans, 1993), p.1.
- [6] W. Helfrich, *Physics and chemistry of the organic solid state*, Vol. III, E.D. D. Fox, M. M. Labes, E. Weissberger, (Wiley, 1967), Chap. 1.8-16.
- [7] P. M. Borsenberger and D. S. Weiss, *Organic photoreceptors for electrophotography*, Marcel Dekker, New York 1998.
- [8] M. redecker, H. Bässler, and H. H. Hörhold, "Determination of the Hole Mobility in Organic Light-Emitting Diodes via Transient Absorption," *J. Phys. Chem. B*, 101, 7398-7403, 1997
- [9] R. W. I. de Boer, M. E. Gershenson, A. F. Morpurgo, and V. Podzorov, "Organic single-crystal field-effect transistors", *Phys. Stat. Sol. (a)* 201, 1302-1331, 2004.
- [10] B. W. D'Andrade and S. R. Forrest, "White organic light-emitting devices for solid-state lighting," *J. Adv. Mater.* 16, 1585-1595, 2004.
- [11] Wikipedia, the free encyclopedia [web]. [http://en.wikipedia.org/wiki/Organic\\_light-emitting\\_diode](http://en.wikipedia.org/wiki/Organic_light-emitting_diode)