

# High-Fidelity Medical Imaging Displays

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## Chapter 5

# Active-Matrix Organic Light-Emitting Displays

*The dream is thus to put electronic circuit properties into single molecules. Arrays of such molecules – possibly connected by conductive-polymer wires – on molecular scaffolds would form molecular wafers. One may speculate that reduced dimensions from 200 nm to, say, 2 Å, and the concomitant shrinkage in circuit size could increase the speed and dynamic memory of computers by a factor of 108. Such progress would correspond to forty years of computer technology development. Conductive polymers may become crucial for the building of such a molecular electronics world.*

—B. Nordé and E. Krutmeijer in the announcement of the 2000 Nobel Prize in Chemistry to A. J. Heeger, A. G. MacDiarmid, and H. Shirakawa, for the discovery and development of electrically conductive polymers

### 5.1 Introduction to OLEDs

Organic light-emitting devices (OLEDs) are one of the most rapidly developing technologies in recent FPD history. Since the first appearance of OLEDs in the market as a monochromatic car stereo display in 1997, tremendous research from academia and industry has been performed to implement OLED-based display for low-cost, small to medium, FPD applications.<sup>120</sup> According to the OLED display industry's 2003 report of Stanford Resources and Strategies Unlimited, the worldwide OLED display market is expected to increase up to \$2 billion (U.S.) by 2006.

OLEDs have several advantages over other FPD technologies: their Lambertian self-emission property<sup>105</sup> produces a wide viewing angle; their fast response time (below microseconds) is a benefit for moving images; their high luminous efficiency and low operation voltage guarantee low power consumption by the display; their

lightweight, very thin structure and robustness against external impacts are desirable characteristics for portable display applications; their simple, low-temperature fabrication process is cost effective; and their thin-film conformability on plastic substrates renders them a promising candidate for flexible display applications.<sup>1, 88</sup> Furthermore, when OLEDs are driven by an AM driving scheme based on TFTs, they can be used in high-resolution, large-size FPD applications such as laptop computers and TV screens. Recently, many companies—Toshiba and Matsushita,<sup>158</sup> Kodak and Sanyo,<sup>101</sup> Sony,<sup>156</sup> Samsung SDI,<sup>145</sup> and Chi Mei Optoelectronics and IBM Japan<sup>159</sup> have reported 15- to 24-in. active-matrix organic light-emitting display (AMOLED) prototypes with wide eXtended graphics array (WXGA) at 1200 × 768 resolution or eXtended graphics array (XGA) at 1024 × 768 resolution. The specifications of these prototypes are summarized in Table 5.1.

Table 5.1 Specifications of AMOLED prototypes.

Specification	Manufacturer				
	Toshiba and Matsushita	Kodak and Sanyo	Sony	Samsung SDI	Chi Mei Optoelectronics and IBM Japan
Screen Size (in.)	17	15	24.2	15.5	20
Resolution	WXGA/ 1280 × 768	WXGA/ 1280 × 720	XGA/ 1024 × 768	WXGA/ 1280 × 768	WXGA/ 1280 × 768
TFT Technology	poly-silicon	poly-silicon	poly-silicon	poly-silicon	amorphous silicon
Peak Brightness	300 cd/m <sup>2</sup>	N/A	> 200 cd/m <sup>2</sup>	N/A	500 cd/m <sup>2</sup>
Emissive Material	polymer	small molecule	small molecule	small molecule	small molecule

### 5.1.1 History of OLEDs

Electroluminescence (EL) is the process of causing light emission from the radiative recombination of electrically created electrons and holes in organic materials. The discovery of EL of organic crystals can be dated back to the 1960s.<sup>136</sup> However, these early EL devices utilizing organic materials required several hundred volts and the light emission was inefficient.

During the late 1970s and early 1980s, the EL of organic thin films was advanced by reducing the operating voltage down to several tens of volts. This was achieved by subliming organic thin-films in a vacuum and using metal oxide electrodes.<sup>139, 163</sup> The efficiency of EL in organic materials was further improved

by new device configurations and new emissive materials. A charge-transport layer was inserted between the electrodes and the emissive material. Tang and Van Slyke observed efficient green light emission from 8-hydroxyquinoline aluminum ( $\text{Alq}_3$ ) by inserting a hole-transporting layer (HTL) of aromatic diamine between the active material and the transparent ITO electrode.<sup>155</sup> In the 1990s, polymeric materials gained wide attention as strong candidates for light-emitting materials. Electroluminescence was observed in a layer of poly (phenylene vinylene) (PPV) sandwiched between two metallic electrodes when the device was sufficiently biased.<sup>36</sup> The EL in polymeric materials is from the radiative recombination of the singlet exciton across the  $\pi$ - $\pi^*$  energy gap. Greenham et al. made a major breakthrough by inserting another polymer layer<sup>69</sup> having a band mismatch with the active polymer layer, causing the injected carriers to be trapped at the interface and resulting in an efficient charge recombination with a 20-fold enhancement of device quantum efficiency.

Overall, significant progress in OLEDs has been achieved in the last decade. Material advancement has enabled fabrication of white light,<sup>98</sup> blue light,<sup>106</sup> variable color,<sup>26</sup> and polarized EL devices.<sup>53</sup> The efficiency of OLEDs has also gained from material engineering. Typical examples include the use of phosphorescent organic material to enhance the internal quantum efficiency and the use of electrostatically self-assembled multilayers to reduce the hole injection barrier height for efficient carrier injection.<sup>17, 81</sup>

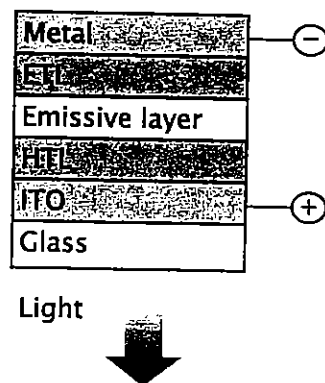
### 5.1.2 OLEDs for displays

After decades of research, OLEDs have exceeded their inorganic counterparts in light-emission performance. The light emission from OLEDs covers the full visible spectrum. They are inexpensive to fabricate and can be patterned on both planar and flexible substrates. Current research on LEDs made from organic semiconductors has shown high brightness and high power-conversion efficiency. Furthermore, displays made using OLEDs overcome many disadvantages associated with traditional LCDs. As discussed in Chapter 4, the disadvantages of LCDs include a narrow viewing angle and a slow response time of the LC molecules. Because OLEDs are emissive devices, components such as the backlight, polarizers, and top glass necessary in LCDs are not needed in OLED displays. OLED displays have a wide viewing angle, high brightness and contrast ratio, high visibility, light weight, and very thin structure. Moreover, the fast electronic response time and high luminescent efficiency associated with light-emitting organic materials allow high scan rates and low-power operation. All of these features make OLED-based displays very attractive.

### 5.1.3 OLED structures

A diode structure, in which the organic semiconductor is sandwiched between two electrodes, is the most commonly used scheme for LEDs (Fig. 5.1). It is speculated that the electrons in this configuration are injected into the organic material from a metal electrode (cathode), and holes are injected from the ITO electrode (anode) because ITO is n-type material. The authors think that electron extraction at the anode electrode is responsible for holes creation within organic layers. The injection of carriers from a metal into an organic material can generally be modeled by two theories: the Fowler-Nordheim (FN) model for tunnelling injection<sup>65</sup> and the Richardson-Schottky (RS) model for thermionic emission.<sup>138, 148</sup> The FN model considers the carrier injection as a process of carrier tunnelling from the metal through a triangular barrier into unbound continuum states, and ignores image charge effects that cause barrier lowering. The RS model assumes that a carrier from the metal can be injected once it has acquired enough thermal energy to surmount the potential maximum that results from the superposition of the external and the image charge potential.

Inelastic scattering of the carriers before travelling through the barrier maximum and tunnelling effects are not considered. However, in a real LED, the maximum of the electrostatic potential is located several nanometers away from the interface.<sup>3</sup> Ignoring this significant barrier lowering at the interface in the FN model makes it problematic. For organic light-emitting solids, the inelastic carrier scattering inside the potential well is important and cannot be ignored. This makes the application of the RS model insufficient to account for the physical process of carrier injection. Due to these deficiencies in the FN and RS models, Arkhipov et al. have come up with a theory that describes injection in similar terms as photo-conduction in organic solids. In the first step, charge and image charge pairs close to the inter-

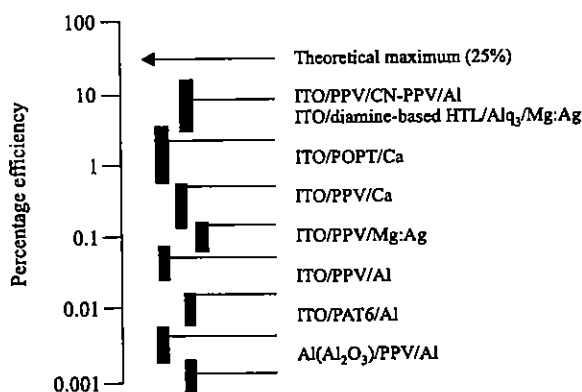


**Figure 5.1** Schematic of an OLED. An ITO electrode is used for hole injection, and a metal electrode is used for electron injection. The emissive organic material is separated from direct contact with the electrodes by a hole-transport layer (HTL) and an electron-transport layer (ETL).

face between the electrode and the organic are generated with the assistance of temperature and electric fields. The pair can fully dissociate in the course of a diffusive process, which is also temperature- and field-assisted. The model calculation generates results in good agreement with experimental results.<sup>3</sup> In order for the carriers to be efficiently injected, the contact between the electrode and the organic are made ohmic, which has a Schottky energy barrier of less than about 0.3 eV.

After the two types of carriers (electrons and holes) are created within the devices, they will drift/diffuse and recombine with each other along their diffusion pathway. The mobility of carriers plays an important role in the light-emission process. If the mobility is very low—much smaller than the  $1 \text{ cm}^2/\text{Vs}$  that is typical for organic semiconductors—the injected carriers pile up near the interface between the electrodes and the organic, and the radiative recombination rate is slow. For an optimized device, the electron and hole creation and transport should be balanced for a maximum recombination current and the highest power-conversion efficiency. A model that takes into account charge injection, transport, recombination, and space charge effects in organic materials has yielded an accurate solution for LEDs, with ohmic contacts for both electron and hole injection and high-mobility materials for balanced carrier transport.<sup>47</sup> In order to overcome the low carrier mobility of organic semiconductor materials, practical LED devices contain an ETL and an HTL that separate the light-emitting layer from direct contact with the electrodes. Figure 5.2 summarizes the typical internal quantum efficiency achieved by selecting electrode and carrier transport materials.<sup>71</sup>

Even though the emission efficiency is enhanced by incorporating electron- and hole-transport layers, other factors such as carrier injection for blue light emission are still problematic due to the large band mismatch between the electrodes and organic materials, especially for hole injection. Efficient electron injection can be achieved by choosing low work function metals, such as Ca. For electron extraction (or hole injection), one of the most suitable candidates is ITO (a high



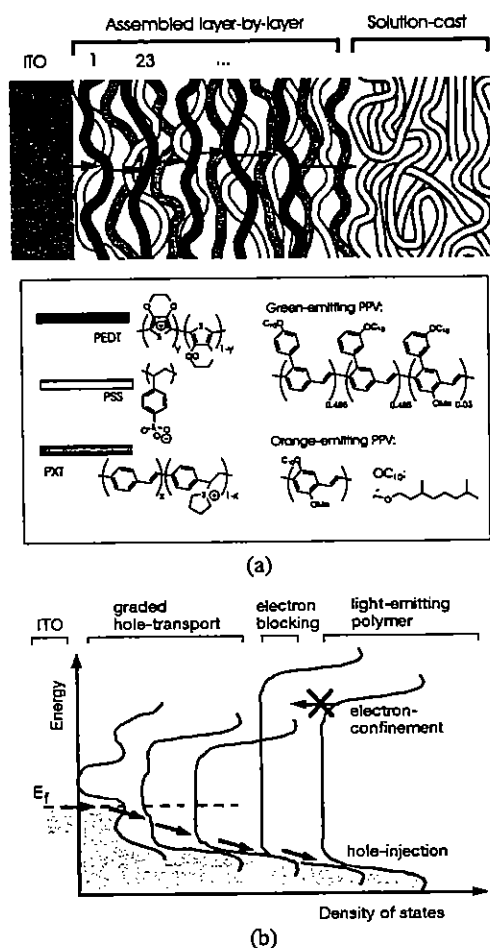
**Figure 5.2** Typical internal quantum efficiencies for OLEDs. Reprinted from Ref. [70] with permission of Elsevier.

work function metal) for better light-emitting devices. However, by novel molecular-scale interface modification through self-assembly, the carrier injection efficiency of ITO can be significantly improved.

In order to grow these electro-statically self-assembled layers, solutions of polymeric ions are needed. The substrate on which the films will be grown is pre-processed to have surface charges. The substrate is alternately dipped into the polycation and the polyanion solutions to form the ionic-attracted polymer layers. Ho et al. have devised a smart design of interface layers to control carrier (especially hole) injection to achieve high EL efficiency in polymer OLEDs.<sup>81</sup> The goal of the ITO surface modification is to form stepped and graded electronic band profiles between the electrode and the light-emitting polymer. It turns out that partially de-doped poly(3,4-ethylenedioxythiophene): poly(4-styrenesulphonate) (PEDT:PSS) composites have different ionization energies. To fabricate the graded profile, PEDT:PSS composites are de-doped by hydrazine ( $N_2H_4$ ) into different levels. The ITO surface normally contains negative charge in solution due to dangling oxygen bonds. By alternately dipping ITO substrate into polycationic poly(p-xylylene- $\alpha$ -tetrahydrothiophenium) (PXT) solution and polyanionic PEDT:PSS solution with various doping levels, an interface HTL forms. The final structure and schematic diagram of the band profile of the interface layer are shown in Fig. 5.3. The abrupt hole-injection (or electron-extraction) barrier between the ITO and the light-emitting polymer are graded into several smaller barrier heights, which permit a much easier carrier extraction from the light-emitting polymer. Such a scheme is expected to be especially useful for blue light-emitting polymers with large ionization energies. A green-emitting LED fabricated using this method yielded a 6% external efficiency at a luminance of 1600  $cd/m^2$  and at a bias of 5 V. Another approach to produce a similar effect is the insertion of the HTL between the ITO/PEDT:PSS interface and the light-emitting layer (LEL). The bandgap of HTL is larger than LEL.

There is another factor that limits the theoretical maximum internal quantum efficiency to 25%. When an organic material becomes excited through the optical energy gap, it returns to ground state by two mechanisms: fluorescence and phosphorescence. These two radiative processes share the same general mechanism but involve different excited states. A singlet state refers to a two-paired electron hole with opposite spins. A triplet state refers to a two-paired electron hole with the same spin. Fluorescence involves the transition from an excited singlet state to a singlet ground state, and phosphorescence is the transition from an excited triplet state to a singlet state.<sup>3, 17</sup>

In OLEDs, the injected carriers have spins, hence their means of recombination determine the spin configuration of the exciton (electron-hole pairs). Only 25% of the generated excitons are in singlet states and can emit light, while the other 75% become triplet excitons and decay through nonradiative pathways. This puts a physical limitation on the internal quantum efficiency that can be achieved in normal OLEDs. Baldo et al. have come up with a solution to harness the triplet excitons to emit light by transferring excitonic energy from a host material to a phosphorescent molecule and then to a fluorescent molecule that emits light.<sup>17</sup>



**Figure 5.3** (a) Schematic of the hole-injection interlayer between the ITO electrode and the light-emitting polymer (top), and the chemical structures of the polymer (below). The interlayer consists of five graded bilayers of PEDT:PSS/PXT films plus one PSS/PXT bilayer formed by electrostatic self-assembly technique. (b) Schematic of electronic density of states across a graded interlayer. Occupied states are shaded. Holes are transported to the light-emitting material through graded lower effective barrier layers. An electron-blocking sublayer fabricated from a lower-electron-affinity polymer is also shown. Reprinted from Ref. [81] with permission of Nature/Macmillan.

There are two primary mechanisms for the energy transfer. One, called Dexter transfer, occurs over short distances and requires contact between the donor and acceptor molecules. During the transition, the exciton retains its spin configuration. Such an energy transfer is useless in terms of improving internal quantum efficiency, since triplet excitons are still forbidden to emit light. The second energy transfer pathway is called Förster transfer and can change the exciton spin configuration. This transfer does not require contact and can occur over a long distance. The different interaction ranges of the two energy transfer processes can be exploited to

minimize Dexter transfer while maximizing Förster transfer. This situation can be realized by placing the phosphorescent and fluorescent molecules in alternating layers of the device. This can give an internal efficiency of fluorescence as high as 100%. The fabricated fluorescent red OLED quadruples the device efficiency. The increased efficiency reduces heating during light emission in the device and extends the lifetime of the device, since high luminance can be achieved at lower current density.

#### 5.1.4 EL organic materials

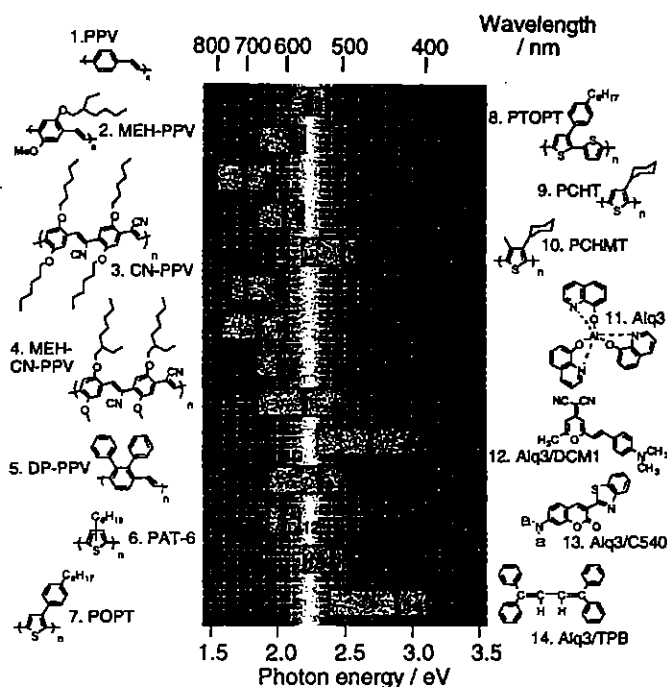
The properties of organic light-emitting materials are different in comparison with the traditional inorganic semiconductors. Table 5.2 offers a comparison of inorganic semiconductors with polymeric light-emitting semiconductors.<sup>71</sup> There are two major categories of EL organic semiconductors: small molecules such as Alq<sub>3</sub>, and polymers such as PPV. The two categories have in common an extended region of alternating single and double bonds in a carbon chain. In these regions, electrons form covalent bonds evenly distributed—an effect known as “conjugation.” Electrons move more freely within the conjugated segments that are flat and rigid. Conjugated materials have distinctively strong coloration because these p-electrons can absorb light in the visible range. Conjugated regions can be affected by extra charge introduced to or removed from the polymer chain by chemical doping or charge injection (or extraction). Charge injection (or extraction) thus gives rise to a change in absorption as the molecule slightly rearranges itself. The color of emission is dependent on the positions of the atoms in the excited molecule, which may be different from the ground state. Some common organic light-emitting materials and their emission wavelengths are shown in Fig. 5.4.

Before the discovery of light-emitting polymers, small molecules such as 8-hydroxyquinoline Al were studied extensively for OLEDs. These materials are easy to purify and can be sublimed directly onto the device in a vacuum. Today, polymers are becoming preferred in device applications since they are expected to be more stable, particularly at high temperatures, and easier to process over large areas. There are two types of polymers used in OLEDs: precursor and soluble. Insoluble polymers, such as PPV, must be deposited in precursor form.<sup>36</sup> PPV precursors are soluble in methanol and water and are readily spin-coated as a thin film onto an ITO-coated substrate. Heating then converts the precursor into the fully conjugated polymer form.

The relative inertness and insolubility of the polymer make it particularly useful for multilayered devices. MEH-PPV is an example of a soluble, conjugated emissive polymer.<sup>169</sup> The large side-groups attached to the phenyl ring cause the polymer to be soluble in common organic solvents such as chloroform, toluene, and xylene. These bulky side-groups also make the polymer more amorphous and affect the color of the films by contributing to the conjugation of the whole molecule. Both precursor and soluble polymers offer advantages for inexpensive large-area, thin-film deposition. Some of their properties such as color, mechanical strength,

Table 5.2 Comparison of traditional and polymeric semiconductors.

Feature	Traditional Semiconductor	Polymeric Semiconductor
Band gaps	Si 1.1 eV Ge 0.67 eV GaAs 1.35 eV  Relatively sharply defined	poly(acetylene) 1.4 eV PPV 2.2 eV MEH-PPV 2.1 eV  Varies with polymeric segments: these are minimum band gaps
Conductivity $\sigma$ $\Omega^{-1} \text{ cm}^{-1}$	Doped silicon 1 Intrinsic Si 0.0001	PPV $10^{-14}$ Doped poly(acetylene) max. $10^4$
Doping	$<10^{20} \text{ cm}^{-3}$ in crystal structure	Up to $<10^{22} \text{ cm}^{-3}$ in interchain sites
Typical dopant	P, As, Sb, B (IV materials) Zn, Si (III-V materials)	$\text{I}_2$ , $\text{AsF}_5$ , $\text{SbCl}_5$ , $\text{FeCl}_3$ , $\text{O}_2$
Mobility $\mu$ ( $\text{cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ )	$>1000$ single crystal $\alpha$ -Si 0.1–10	poly(acetylene) $>10^{-3}$ PPV $<10^{-8}$
Density $\rho$ ( $\text{g cm}^{-3}$ )	Si 2.33 Ge 5.32 GaAs 5.32	PPV 1.24
Preparation	Grown from melt, sawn, and polished	Deposited from solution as thin film (polymer) or vacuum sublimed (small molecule)
Morphology	Single crystal	Disordered with tendency for mole- cules to lie parallel to substrate
Purity	Very high	Polymer: low Sublimed molecules: high
Transport	3D	Quasi-1D with 3D hopping to neighboring chains
Charge	Electrons and holes	Electrons and holes localized as polarons or bipolarons
Temperature dependence	$\sigma \sim e^{-\Delta\epsilon/kT}$	$\sigma \sim e^{-A/T^{1/M}}$ (Mott hopping)
Stability	Good Diffusion of dopants High temperatures	Poor Prone to photo-oxidation Permeable to gases
Surfaces	Dangling bonds	No dangling bonds
Bulk	Covalent bonding	Molecules held by weak Van der Waals forces Atoms held covalently
Refractive index	Si 3.4 GaAs 3.6 In GaAs 3.5	PPV is anisotropic: 2.2 and 1.7



**Figure 5.4** EL emission at full width, half maximum (FWHM) of a typical polymer and small-molecule light-emitting materials. Reprinted from Ref. [71] with permission of Elsevier.

and efficiency can be engineered by chemistry and processing conditions.<sup>35</sup> Polymer blends and copolymers with active side-chains provide a versatile way to modify properties of light-emitting polymers. Unlike PPV or MEH-PPV, which have conjugation extended along the entire polymer backbone, active segments may be incorporated into an inert polymer either in the main chain or attached as side chains.<sup>107, 170</sup> The material will have most of the properties of the parent polymer rather than these active segment molecules. The weakening of the EL effect due to dilution of the active segments can be balanced by an increase in quantum efficiency that arises from an increased separation between active regions.

The biggest hurdle for OLED application in consumer-grade displays lies in the potential instability of the device. Device properties may degrade in a complicated manner as a result of exposure to light, water, and oxygen molecules. The mechanisms of property degradation include the corrosion of contacts, the presence and migration of impurities, and the emissive material degradation. In most cases devices fade with time but maintain the same spectral distribution. On a microscopic level, dark spots and regions often appear, corresponding to pinholes and exposed edges of the cathode electrodes. Higher temperatures promote degradation and catastrophic failure, and are sometimes associated with local "hot spots." More details on device stability and encapsulation will be discussed later in this chapter.

## 5.2 Evaluation of Device Opto-Electronic Performance

Since different OLED materials and device structures affect device performance, it is necessary to characterize the OLED light output properties in order to develop high-performance OLEDs. The most common parameters that are used to describe the device performance are luminance ( $\text{cd}/\text{m}^2$ ), luminous efficiency ( $\text{lumen}/\text{watt}$ ), emission efficiency ( $\text{cd}/\text{A}$ ), quantum efficiency, and lifetime. The brightness of OLEDs determines its application range, and the device luminous efficiency indicates the power conversion ratio and the power consumption of the device.

It is known that the emission from OLEDs is close to a Lambertian emission, especially for small angles from the normal direction to the device surface. During the evaluation of the total luminous flux of the device, it is important to have a very small surface area at the detector and a large separation between the detector and the emissive surface in order to utilize the integration of Lambertian profile to get the total luminous flux. A silicon photodiode can be used as a detector. However, a silicon photodiode cannot resolve spectra, and thus can only be used in measuring the total luminous flux and luminance of the emissive device. In order to obtain the spectral distribution of the radiant power, luminance, luminous flux, and photon emission, a calibrated spectrometer must be used. The resulting spectral curves represent the complete properties of the light emitted from the source, but also provide an accurate description of the physical properties of the device such as the EL external quantum efficiency. It is convenient to use a CCD camera to capture the spectral information of the emitted light.<sup>75</sup> The CCD camera needs to be carefully calibrated because the CCD's spectral response is different at different wavelengths, and this effect needs to be considered during the processing of the acquired spectral response. Once this spectral distribution of energy is obtained, the external quantum efficiency can be calculated using

$$\eta_e = \frac{N_{\text{photon}}}{N_{\text{electron}}} = \frac{\int P(\lambda) sp(\lambda) d\lambda}{J/e}, \quad (5.1)$$

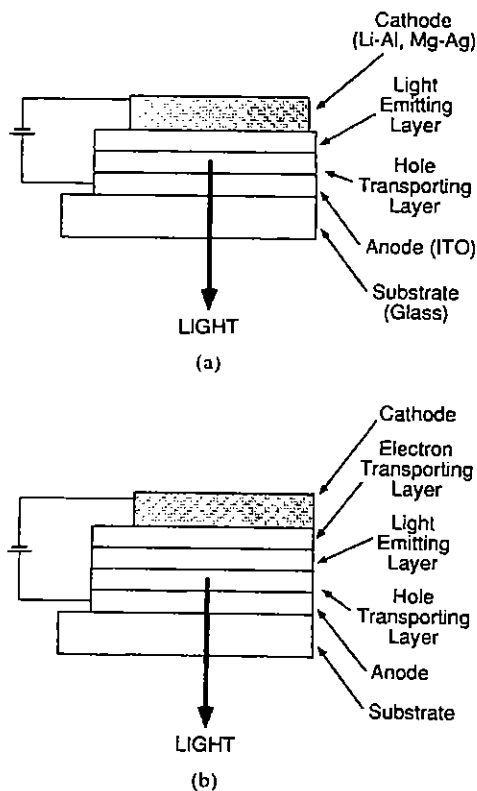
where  $sp(\lambda)$  is the measured spectral response from the CCD,  $P(\lambda)$  is the calibration spectra of the CCD, and  $J$  is the applied current density.

## 5.3 Device Configuration and Display Fabrication

In this section, we discuss some of the OLED pixel and subpixel structures and fabrication processes that have high potential to be used in full-color FPDs. We begin with the basic structure of a conventional OLED and then move to more exotic pixel structures.

### 5.3.1 Conventional OLED

The basic structure of a conventional OLED is shown in Fig. 5.5(a). A minimum of two thin-film organic layers is required. The first layer is the HTL, and the second layer is the electron-transporting, light-emitting layer. In some cases, a third organic thin-film is used, as in Fig. 5.5(b). For this structure, the first layer is the HTL, the second thin-film is the LEL, and the third layer is the ETL. In each case, the bottom, hole-injecting (or electron-extracting) electrode is usually made of conductive ITO sputtered onto the glass substrate. The ITO electrode is transparent to visible light, and therefore, light is emitted through it when the OLED is forward-biased. The top, electron-injecting electrode (cathode) is usually a vacuum-evaporated, low work function metal or metal alloy such as Mg-Ag or Li-Al.<sup>38</sup> The organic layers consist of proper combinations of either small organic molecules or organic polymers. In the case of small molecules, the thin films are deposited by thermal evaporation in a vacuum. For the polymer-based OLEDs, the preferred method of deposition is spin-coating or ink-jet printing. This is a bottom light-emitting device structure. Since most of the organic materials used are sensitive to air,



**Figure 5.5** Conventional OLED structure. Reprinted from Ref. [38] with permission of the IEEE.

some form of encapsulation or passivation is usually required to reduce degradation by the formation and growth of dark-spot defects.<sup>103</sup>

### 5.3.2 Side-by-side subpixels

Figure 5.6(a) shows a side-by-side individual R, G, and B subpixel scheme, which resembles CRT arrangements. In this simple approach, each OLED subpixel requires a different light-emitting organic material. Therefore, arrays of each type of OLED must be deposited and patterned independently. This requirement may give rise to problems; for example, the patterning of one of the organic layers can cause a previous layer to swell due to the organic solvents used in the photolithographic processes, or to deteriorate due to the relatively high processing temperatures used in the etching process.<sup>38</sup> However, by using the side-by-side pixel scheme, 300-dpi displays have been fabricated.<sup>38</sup>

Some fabrication techniques can be used to overcome these limitations. One technique, described by Burrows et al.,<sup>38</sup> uses dielectric “walls” that have been patterned on the substrate to separate each subpixel and to shadow two of the three subpixels from the unwanted thermal deposition of the light-emitting material. By tilting the substrate for each of the three organic layer growths, R, G, and B organic material can be grown in separate areas, thereby providing three distinct subpixels. However, nonuniformity can result from the difficulties of controlling the deposition area. Another technique is the precision shadow-mask method. In this approach, selective deposition of R, G, and B organic materials is done with a thin mask and a high-accuracy mask-moving mechanism. To obtain good patterning and better size control, the mask should be thin and the distance between the mask and the substrate should be as small as possible. Unfortunately, due to the thin mask requirement, difficulties arise because the mask must be kept flat, which leads to a nonuniform gap between the mask and the substrate. This is especially true for large-area substrates. In the side-by-side subpixel technique, the light emission from each subpixel is controlled independently and can be optimized separately to reach higher quantum and power efficiency. In summary, the unevenness of the mask, nonuniform gaps, and nonuniformity caused by oblique deposition hinder this technique from its use for large-area display fabrication.

### 5.3.3 White OLED filtering

Figure 5.6(b) presents another pixel scheme that can be used to realize a full-color display. This color subtraction scheme can be compared to LCDs in that the white OLED serves as a “backlight” and the emitted light is passed through separate R, G, and B filters. The white OLED is fabricated by deposition of two or more organic layers that emit different colors (R, G, and B) onto a prepatterned substrate. The thickness of each organic layer is such that the superposition of the light emit-

