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Active-Matrix Organic Light-Emitting Display Technologies

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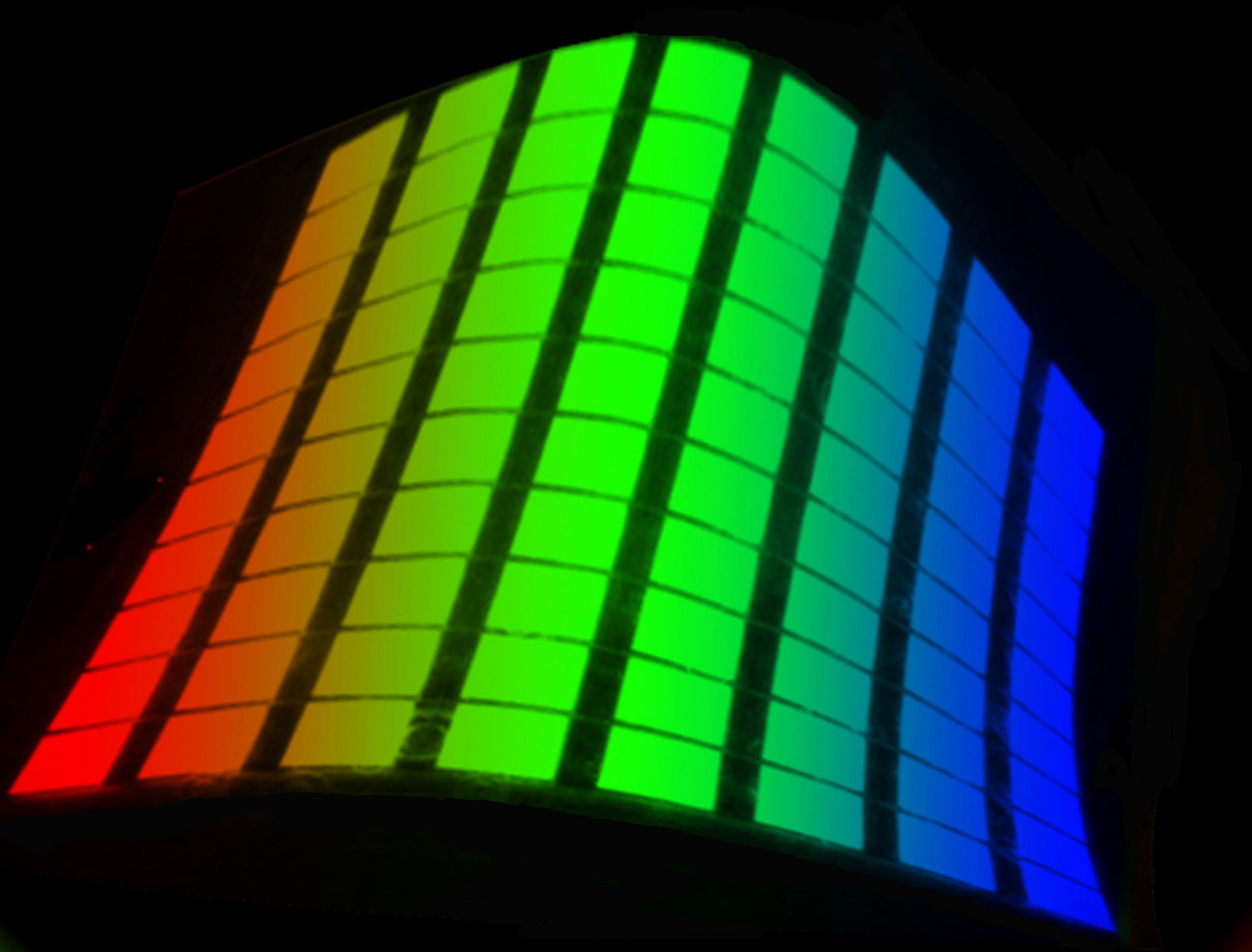

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Vol. 1

Active-Matrix Organic Light-Emitting Display Technologies

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PREFACE

Over the last several decade years, great successes have been achieved in the industrialization of organic light-emitting diode (OLED) technologies. Active-matrix OLED (AMOLED) emerged as an important and low-cost candidate to replace liquid crystal displays due to its attractive advantages like self-emitting, high efficiency, high contrast, vivid color, fast response, and flexible form factor. The purpose of this eBook is to present an introduction to the subject of AMOLED and their related technologies which are generally integrated to the production application, including OLED basic working principles, fabrication and characterization, white OLED technologies, light outcoupling technologies, encapsulation technologies, thin film transistor backplane technologies, driving scheme, circuit and layout design technologies. Although it is impossible to cover completely the vast amount of publications concerning these topics, we will select those key areas in device structures, fabrication techniques and application that we feel are most pertinent to the practical production.

This book will be helpful for young scientists and engineers who work at the development of practical OLED display and OLED lighting. Target readers include researchers in organic electronics field, undergraduate and graduate students who study in OLED display and OLED lighting, and also for the engineers who work in OLED industry. Through reading the eBook, readers can get a comprehensive and insight view of the AMOLED display, including the principles of OLED, the fabrication and characterization techniques of OLED and various related technologies for display system integration, which is benefit for their future academic or industrial career.

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CHAPTER 1

Introduction to Organic Light-Emitting Display Technologies

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Abstract: Organic Light Emitting Diodes (OLEDs) emerged 30 years ago as a very promising flat-panel display technology because of their lots of advantages. OLEDs consist of several nanometer-scale thin films between anode and cathode, which can be integrated on various substrates, especially the ultra-thin and flexible substrates. As a result, OLEDs present advantages of high efficiency, lightweight, fast response time, wide viewing angle, vivid color, high contrast and *etc*. After development of technology improvement over past several decades, enormous progress has been made to promote OLED products to be launched into market. In this chapter, we review the development history of OLEDs, with special emphasis on several key technical innovations which significantly advanced the industrialization. From two main application filed of display and lighting, we describe the working mechanism, technical development, advantages and disadvantages, and production status of OLED technology.

Keywords: Composite cathode layer, Display, Electrical doping, Electroluminescence (EL), Emitter doping, Flexible OLED, ITO surface treatment, Light outcoupling, Lighting, Multilayer structure, Organic light-emitting diode (OLED), Phosphorescent emitter, Thermally activated delayed fluorescence.

INTRODUCTION

Avatar wakes up on a sunny weekend morning. As he washes, the mirror displays today's weather and his agenda. He makes a coffee for himself and sits down at

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the table; today's latest news is already displayed on the table. He rolls up his laptop and puts it into his bag. As he walks down the street, the sun starts charging his bag and his laptop, PDA *etc* inside the bag. Night is coming; the windows shine the light and light up the whole room.

These dream displays/lightings usually appear in fictions or movies. However, they will become a reality in the near future with the help of organic optoelectronics devices like organic light-emitting diodes (OLEDs) [1 - 4], organic photovoltaic cells (OPVs) [5 - 7] and organic thin film transistors (OTFTs) [8, 9]. Being organic-based devices, they can be flexible as cloth or transparent as glass, thus opening a new wide variety of applications. This chapter provides a basic background to OLED technology. After a brief introduction of the OLED history, an overview of the working mechanisms of OLEDs is presented. The fabrication and characterization of OLEDs is then given, followed by outlining their applications.

DEVELOPEMNT HISTORY OF OLEDS

Organic electroluminescence (EL) is emission of light from organic materials in response to electric current, which was found for the first time in a thick (50 μm to 1 mm) anthracene crystal by Pope's group from New York university in 1960s [10]. However, they did not receive too much interest due to their high driving voltage (>100 V) and weak EL emission in those early crystal devices [10, 11]. In 1987, Tang and VanSlyke, who were both from Eastman Kodak, introduced the first double layer thin-film OLED, which consisted of 60 nm Alq_3 and 75 nm diamine sandwiched between a Mg:Ag reflective cathode and an indium-tin-oxide (ITO) transparent anode as shown in Fig. (**1.1**); all are deposited by vacuum thermal sublimation. The resultant device, driven at 10 V, exhibited a luminance of 1000 cd/m^2 with a moderate external quantum efficiency of 1% (luminous efficiency 1.5 lm/W) [1]. Shortly afterwards, in 1990, a research group from Cambridge University announced the first polymer-based LED prepared by spin-coating the conducting conjugated polymer poly(p-phehylene vinylene) (PPV) onto the ITO-coated glass substrate, followed by capping a thermal evaporated Al cathode. The external quantum efficiency of the device is 0.5% mainly due to the poor exciton confinement in such a single layer device [12].

From then on, OLED has attracted considerable research attention due to its potential applications in flat-panel-display and solid-state-lighting. Enormous progress has been made in the past 30 years in the improvement of driving voltage, efficiency, luminance, color saturation and stability. Several key technologies that significantly advance the development of OLEDs are listed below.

1. Emitter doping. In 1989, Tang, VanSlyke and Chen introduced the concept of emitter doping [2]. By doping highly fluorescent molecules into the Alq_3 matrix, a 2~3 folds efficiency improvement has been achieved. Also, it was observed that the reliability of the doped devices was significantly improved due to the elimination of intermolecular hydrogen bonding between the dopant molecules [13, 14]. More importantly, by simply changing the guest dopants, the emission color can be readily tuned. The doping technique is widely used in modern high efficiency devices [21, 27, 28].
2. Multi-layer structure. In 1990, Adachi *et al.* introduced a double-heterojunction structure with a 5 nm emission layer enclosed by an electron-transport layer and a hole-transport layer [15]. With such configuration, the charge carriers and molecular excitons are better confined within the emission layer, thus preventing charge carrier leakage and/or molecular exciton quenching by the electrodes. Inspired by this pioneering work, modern devices typically adopt a multi-layer structure with each layer specially functioning as hole-injection, hole-transport, electron-block, light emission, hole-block, electron-transport or electron-injection.
3. Al/LiF composite cathode layer. In 1996, Huang *et al.* discovered that the presence of an ultra thin (0.5 nm) LiF layer between the organic layer and Al layer significantly enhances electron injection [16]. Also, the Al/LiF has better chemical stability against atmospheric corrosion compared to the MgAg alloy electrode. The improved electron injection probably results from the release of low work function Li atoms and subsequent formation of the Alq_3 radical anions. Today, LiF is a necessity for making efficient bottom-emitting OLEDs.
4. ITO surface treatment. In 1997, Wu *et al.* demonstrated that the chemical composition of ITO surfaces could be substantially modified by O_2 plasma treatment [17]. The work function of the treated ITO surfaces was increased by 100-300 meV compared to the cleaned as-grown ITO surfaces, mainly due to

CHAPTER 2

White Organic Light-Emitting Diodes for Display and Lighting Application

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Abstract: The history of white light organic light-emitting diodes (WOLEDs) can be dated back to 1993 when Kido and coworkers reported the first OLEDs that emit white color, *i.e.*, the emitted light contain wavelengths across the entire visible spectrum [1, 2]. From then on, considerable research efforts have been devoted throughout the world by both academia and industry in developing efficient WOLEDs for next generation high resolution large area displays and solid-state light sources. In this chapter, the applications of WOLEDs in display and lighting will first be presented, followed by introducing the general approaches to achieve white light emission. Finally, challenges and solutions for large area, high efficiency and high CRI WOLEDs will be posed.

Keywords: Color patterning, Color rendering index, Emitting diode (WOLED), Solid-state lighting, White organic light- full color display.

WOLEDs FOR FULL COLOR DISPLAYS

In order to realize a full color display, the OLEDs should emit the red (R), green (G) and blue (B) three primary colors. A simple and straight forward method is to deposit the R, G and B emission layers side by side, as shown in Fig. (**2.1**). The emission layers are patterned by the fine metal shadow masks (FMMs). Organic functional materials are deposited and defined onto the substrate through the openings of the FMMs. The FMMs, with opening as small as 50 μm, typically are made by etching or electroforming the metal sheet [3]. Although FMMs is widely used in the production of full color OLED display currently, they are unsuitable for future high resolution and large area display, because they have some intrinsic

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limitations. For instance, the stainless steel used in FMMs always suffers from shape changing due to heat and/or external force, and when the size becomes larger it is hard to handle [3 - 5]. To circumvent these problems, alternative color patterning methods were proposed such as inkjet printing [6, 7], laser-induced thermal imaging and radiation induced sublimation transferring [8, 9]; however, all these new methods are still under developing and do not ready for commercial production.

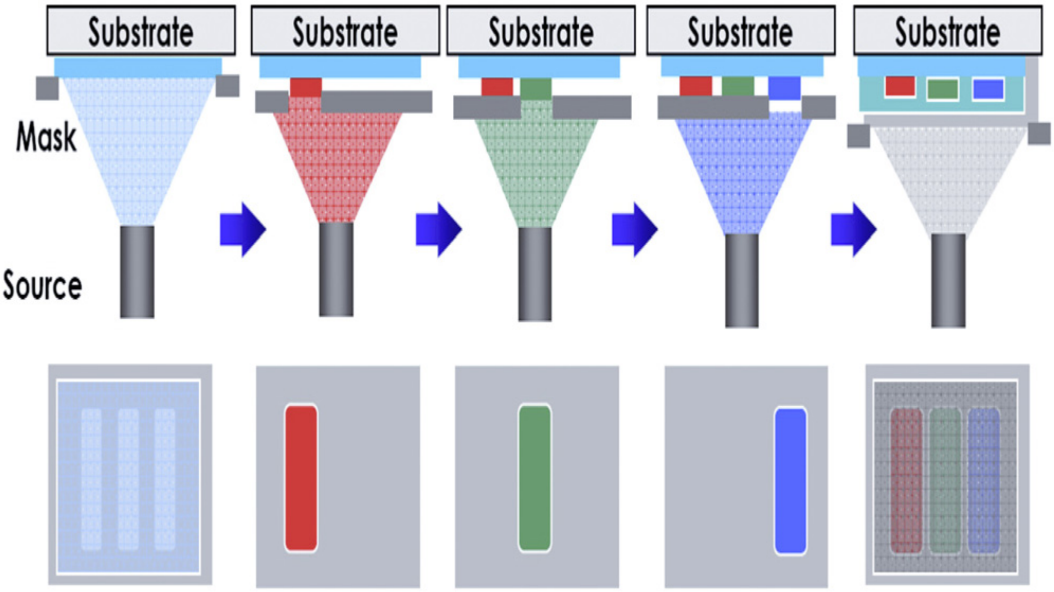

Fig. (2.1). The organic emissive layers are patterned by fine metal masks.

The combination of WOLEDs and color filters was proposed to remedy these deficiencies [5, 10]. As shown in Fig. (**2.2**), in such a scheme, one only needs to pattern the color filters using traditional photolithography technology; thus large area and high resolution can be easily achieved. One of the drawbacks is that most of the white emission (~70%) is absorbed by the color filters, resulting in low panel efficiency. A W-RGBW four primary colors method was proposed to improve the panel efficiency [11 - 14]. It takes the advantage that the W color is used most frequently in practice due to un-saturation of the color of most images, and because the W color is not filtered, the panel efficiency is hence much higher than that of W-RGB method [14]. Assuming the area of each sub-pixel is 1/3, and the transmission of color filters is also 1/3, then the transmitted light in W-RGB scheme is 1/3×1/3(R) + 1/3×1/3(G) + 1/3×1/3(B) =1/3, while for W-RGBW scheme, the transmitted light is ¼×1/3(R) + ¼×1/3(G) + ¼×1/3(B) + ¼×1 (W) =1/2; thus only half of the light is absorbed by the color filters in the W-RGBW scheme. Kodak and LG Display are in favor of this technology. LG Display focuses on making large area OLED-TV by adopting the W-RGBW color patterning scheme; they demonstrated the world's largest 55 inch OLED-TV in Jan 2012 in CES and plan to commercialize it in the second quarter of 2012 in their 8G pilot line [15].

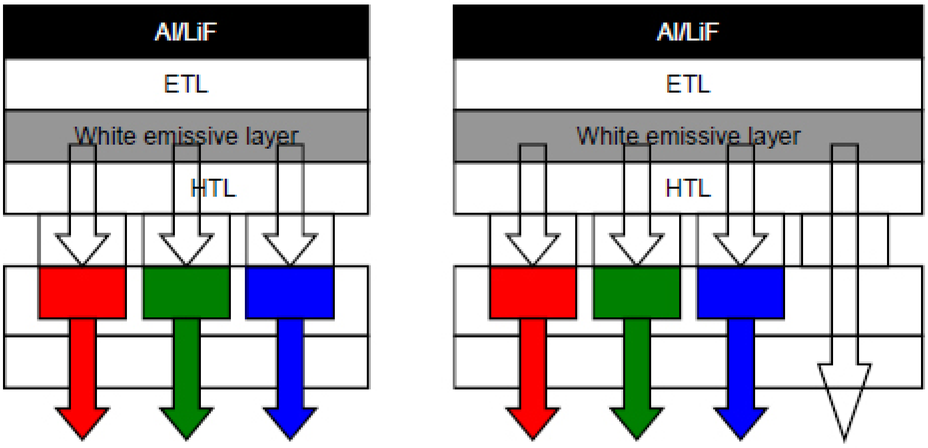

Fig. (2.2). Left: W-RGB, right: W-RGBW color patterning scheme.

A comparison of various color patterning technologies is listed in Table (**2.1**). As can be seen from Table **2.1**, the W-CF patterning method offers highest patterning accuracy/ resolution, largest aperture ratio, fastest TACT and highest yield thus lowest manufacture cost among other color patterning technologies. With the continual improvement of white light efficiency, the shadow-mask-free W-RGBW method is very competitive for low cost, large area and high resolution displays. For example, LG demonstrated the world's largest AMOLED panel by adopting the W-RGB method very recently (shown in Fig. (**2.3**) left) [16]. Again with the W-RGBW technology, e-Magin has commercialized a very high resolution (2128 ppi, 1270×1024×4) microdisplay with pixel size as small as 12 μm in 2008 (shown in Fig. (**2.3**) right) [17].

CHAPTER 3

Light Outcoupling Technologies

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Abstract: This chapter gives comprehensive description of the light outcoupling technologies for organic light-emitting diodes (OLEDs). Some state of art techniques will be introduced in detail. This chapter consists of three parts. The first part analyzes the light distribution in OLED with two models: ray optics model and dipole interference model. The second part introduces the external extraction structures, which can extract the light trapped in the substrate. The last part describes the more effective outcoupling technologies, the internal extraction structures, which can couple out not only the light in the substrate but also the light trapped in the active layers of the device. Finally, a conclusion will be given.

Keywords: Air mode, Dipole interference, External extraction structure, Internal extraction structure, Metal nanoparticles, Microlens array, Nanostructured random scattering layer, Outcoupling, Perforated hole injection layer, Photonic crystal, Ray optics, Scattering film, Substrate mode, Surface plasmon, Total internal reflection, Waveguide mode.

INTRODUCTION

Because of its great potential in flexible flat-display and solid-state lighting applications, organic light-emitting diode (OLED) has attracted intensive attentions from researchers in recent years to improve the efficiency. Theore-tically, 100% internal quantum efficiency (IQE) of OLED can be achieved by applying phosphorescent emitters which make use of both the singlet and triplet excitons. In spite of the high IQE, only ~20% of the internal emission can be extracted out into the air while the remaining ~80% of the internal emission are trapped and guided in the device mainly due to total internal reflection (TIR) at the ITO/glass,

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glass/air interfaces and surface plasmons (SP) at the organic/metal interface [1].

In order to extract the 80% trapped photons, a lot of techniques have been proposed, including roughened substrate [1 - 3], microlens matrix [4, 5], scattering layer [6 - 10], embedded low index grids [11], high refractive index substrate [12, 13], photonic crystal structure [14, 15], and metal nanoparticles [16 - 18]. These extraction techniques can be sorted into two types: external extraction structure (EES) and internal extraction structure (IES) [8]. EES, which is set on the external surface of the substrate as its name shows, can break the TIR at the air/glass interface to extract the substrate waveguide photons. IES, which is fabricated between the device and the internal surface of substrate, is designed to interrupt the TIR at the glass/ITO interface or the SP at the organic/metal interface.

LIGHT DISTRIBUTION IN OLED

A typical OLED is just like a multilayer sandwich consisting of a planar glass substrate (d_{sub}: ~1mm, n_{sub}: ~1.5), a layer of ITO anode (d_{ITO}: ~100nm, n_{ITO}: ~1.9), one or more organic layers (d_{org}: ~100 nm, n_{org}: 1.7~1.8), and a reflecting cathode (*e.g.* Mg:Ag or LiF/Al), where d refers to the layer thickness and n refers to the refractive index. If all surfaces are planar, light emitted out of the backside of the substrate will originate only from the light at the angles less than the organic/air critical angle.

Fig. (**3.1**) shows a schematic ray diagram for a planar OLED. θ_1, given by $\sin^{-2}(n_{air}/n_{org})$, and θ_2, given by $\sin^{-2}(n_{sub}/n_{org})$, represent the critical angles at air/substrate and substrate/ITO interfaces, respectively. The ray diagram indicates that the internal emitted photons can be classified into four modes: (i) the air mode, which can escape from the substrate of the device freely ($0<\theta<\theta_1$); (ii) the substrate mode, which are trapped in the substrate by TIR at glass/air interface and thus guided to the periphery of the substrate ($\theta_1<\theta<\theta_2$); (iii) the ITO/organic mode or waveguide mode, which are confined by TIR at the ITO/substrate interface and will be quickly absorbed by ITO, organic and metal cathode layers ($\theta_2<\theta<\theta_3$); (iv) the surface plasmon (SP) mode, which are due to the coupling between the free electrons of the top metal electrode and the emission wave ($\theta_3<\theta<90°$) [1].

Assuming the cathode is a perfect reflector, and the emission is isotropic in the organic layer, the fraction of the air mode light can be calculated by

$$\eta_{air} = \int_0^{\theta_1} \sin\theta d\theta = 1 - \cos\theta_1 \approx \frac{1}{2n_{org}{}^2}$$

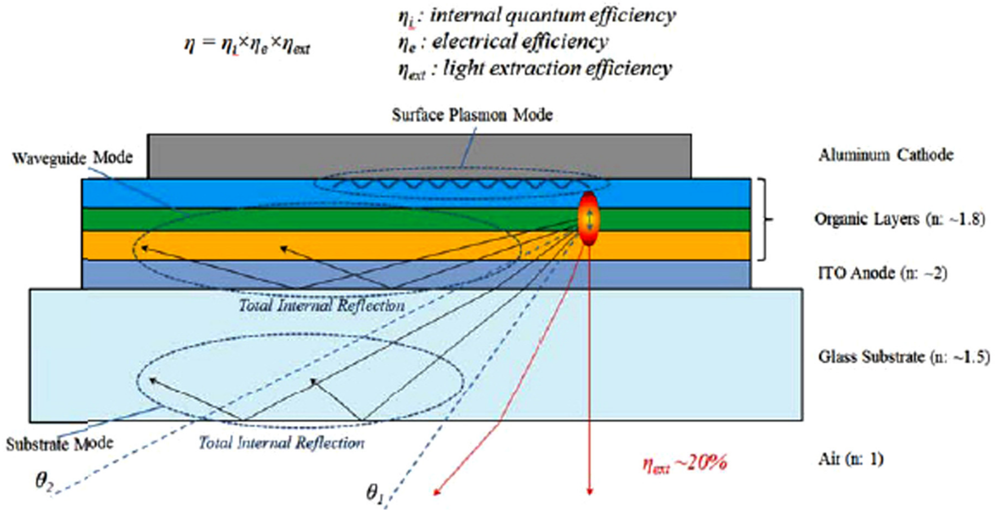

Fig. (3.1). A standard sandwich structure of OLED shows TIR at two interfaces.

The calculation indicates less than 20% light can be extracted from the device as useful lighting. The majority of the internal emitted light is trapped by TIR and waveguided inside the device until it is eventually absorbed and ultimately wasted.

The above ray optics model does not include the effects of interference of the emitted and reflected light and absorption in the various layers that make up the device. A more rigorous approach to modeling the light distribution of OLED is given below, which considers the emitters as radiating dipoles in an optical microcavity.

The general OLED structure consists of a stack of planar films arranged in the xy plane (called the plane of interfaces) as displayed in Fig. (**3.2**). The yz plane is defined as the plane of incidence. The source is considered as electric dipoles with

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CHAPTER 4

Encapsulation Technologies

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Abstract: Flexible organic light emitting diode (OLED) display is an exciting and attractive technology to the consumers and the manufacturers, but there still exists a few challenges before it comes into real application. The biggest challenge is the demanding water and oxygen permeation requirement of the encapsulation, since the lifetime of OLED will drastically decrease when it is exposed to moisture and oxygen. As the barrier performance of polymer is not as good as that of glass, both sides of the OLED device which is deposited on polymer substrate need to be encapsulated by dense thin films. This chapter will provide a summary of the encapsulation technologies, including the traditional encapsulation and the advanced thin film encapsulation. First, the degradation mechanism, the permeation mechanism, and the permeation measurement are introduced as background information. Then thin film encapsulation technologies (Vitex organic/inorganic multilayer and atomic layer deposited film) will be the main topic.

Keywords: Atomic layer deposition, Barrier, Ca test, Dark spots, Degradation, Encapsulation, Flexible display, Getter, Glass or metal lid, Lifetime, Moisture, Multilayer, Nanocomposite film, Oxygen, Permeation, Water vapor transmission rate.

INTRODUCTION

The organic materials, which make up different functional layers of OLEDs, are very sensitive to the oxygen and moisture. Without encapsulation, non-emitting areas which are called "dark spots" will quickly appear once the OLEDs are exposed to atmosphere environment. The dark spots will gradually grow larger and larger, and finally cover the entire device area of the OLEDs and make the device "die" several tens of hours later. Therefore, encapsulation technologies are

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very necessary in order to increase the lifetime of the OLED device, considering the long lifetime requirements in the OLED display and OLED lighting applications.

The existing encapsulation technologies can be classified into two categories: traditional encapsulation and thin film encapsulation. This chapter is divided into three sections. The encapsulation requirements will be discussed firstly. Then the traditional encapsulation technology will be covered. Finally, the state-of-art thin film encapsulation technology will be the theme of the last section.

DARK SPOTS FORMATION MECHANISM

Dark spots formation is a story about the defects in OLED device. Therefore defects should be talked about first. It is well known that the organic material forms continuous film without pinholes, while the inorganic material grows film with pinholes due to the granular structure of the material, the dust particle contamination on the substrate or the protrusions of the substrate. As a result, pinhole defects are formed on top of the organic layers after the metal deposition in OLED [1], as shown in Fig. (**4.1**). It has been found that the distribution of the dark spot area follows a Gauss distribution just as the typical dust size distribution [2]. This indicates that dust contamination may be the major defects sources. Apart from the pinhole defects, there are inherent natural defects which are the device edges defined by the metal electrode due to the device structure.

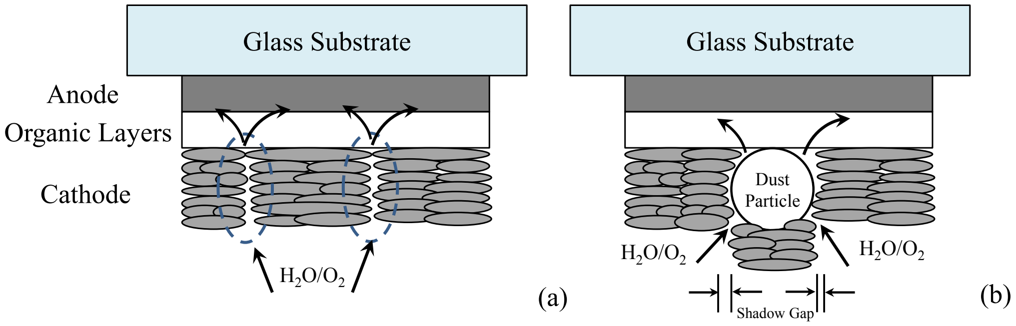

Fig. (4.1). Proposed mechanism of the formation of pinhole defects (**a**) at grain boundaries and (**b**) at contaminant particles.

Water vapor and oxygen can diffused to the organic layers through these defects as shown in Fig. (**4.2**). After the water vapor and oxygen flow down to the bottom of the hole, they begin to diffuse laterally into the interface between the cathode and the organic layers through the boundary of the hole, as indicated by the white arrow. Therefore, the hole perimeter determines the amount of water and oxygen diffusing into the interface at a certain time. As a result, the area and growth rate of the dark spots show a linear relationship with the pinhole diameter.

Under the normal operation of OLEDs, the water on the cathode-organic interface will undergo an electrochemical reduction process because of the electrode field across the organic layers. This electrochemical process leads to hydrogen gas evolution according to: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$.

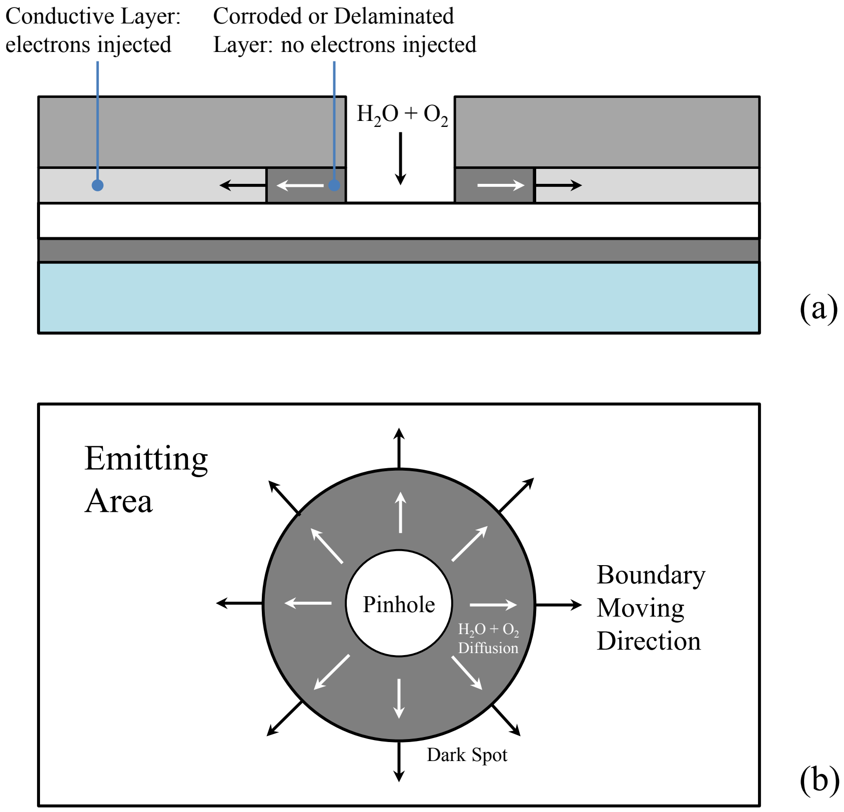

Fig. (4.2). Schematic drawings showing the process and mechanism of (**a**) dark spot formation and (**b**) growth.

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CHAPTER 5

Thin Film Transistor Technology

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Abstract: TFTs with large field-effect mobility, low threshold voltage, sharp sub-threshold swing, small leakage current, good uniformity, high stability and reliability are highly desired for high resolution active matrix OLED application. The three most popular technologies for the TFT backplane are a-Si TFT technology, LTPS technology and metal oxide TFT technology. There also exist some promising compounds TFTs, such as GaN, MoS_2 TFTs, and so on. The main properties of these technologies will be introduced and studied in this chapter.

Keywords: Amorphous silicon, Compound, Excimer laser crystallization, Gallium nitride, Metal induced crystallization, Metal oxide, Polycrystalline silicon, Solid phase crystallization, Thin film transistor.

INTRODUCTION

OLED displays can be classified as passive matrix OLED (PMOLED) and active matrix OLED (AMOLED) display.

PMOLED are particularly suitable for small area and low resolution display applications, such as mobile phones, MP3 players and automotive audio applications. The process for PMOLED is not complicated, which use separators or shadow mask [1]. For the driving scheme of PMOLED, an electric current is adjusted to pass through the selected pixels by scan line and simultaneously applying an electric current source to the corresponding data lines. There is no storage capacitor in the driving scheme of PMOLED, so the pixels are off most of the time during the driving. For the compensation, large current is needed to make OLED brighter. For example, if the display has 10 lines, one scan line that is on

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maybe 10 times brighter. So the efficiency and the lifetime are low for the PMOLED. PM is not a good driving method for high resolution OLED displays.

AM addressing is a better method to realize high resolution, high quality, and large size OLED display, as compared with PM addressing. The OLED works in the best power efficiency region and is driven by simple low voltage signals [2]. The AM TFT backplane acting as an array of switches controls the amplitude of current passing through each OLED pixel. Generally, this driving current is adjusted by at least two TFTs at each OLED pixel. One TFT is to turn on and turn off the charging of a storage capacitor C_S and the second TFT is to provide a constant current flow through the OLED pixel. The schematic of typical pixel circuit in AMOLED is shown in Fig. (**5.1**). This basic pixel circuit has two TFTs and one storage capacitor $C_{S.}$ However, one TFT is required in AMLCD pixel. The switch TFT is acting as a switch while the driving TFT is providing the driving current required to turn on the OLED pixel. During the whole frame period, the driving TFT will still keep on providing current flow through the OLED pixel by the voltage held on the capacitor C_S. The main issue for this basic pixel driving circuit is its sensitivity to the non-uniformity of the TFT electrical performance over the whole backplane, which causes the non-uniformity of the luminance. In order to compensate the threshold voltage variation of TFTs, more complicated pixel circuits with additional TFTs have been designed and fabricated [3, 4].

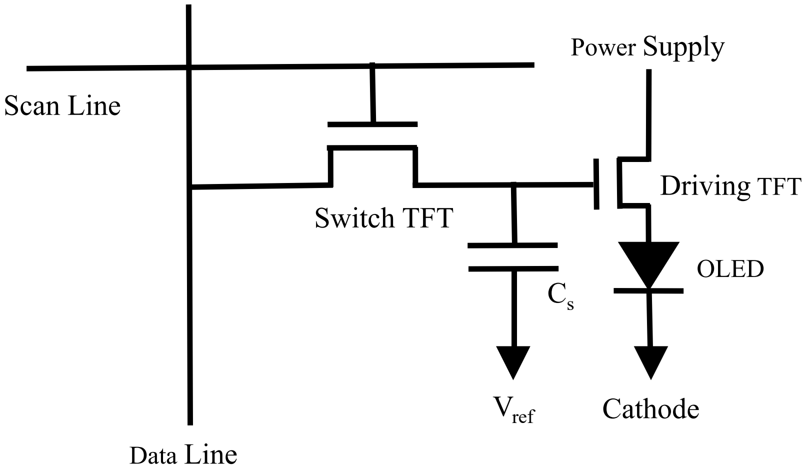

Fig. (5.1). Schematic diagram of the basic 2-TFTs pixel circuit in AMOLED.

For AMOLED, the peripheral circuit, such as control IC, scan driver, data driver, *etc*. are fully integrated and fabricated on the panel substrate and are called system-on-panel (SOP), as shown in Fig. (**5.2**). SOP is the flat panel display trend for high quality and high resolution display in the future. The cost of the display system is reduced dramatically by this technology because the peripheral ICs on silicon substrate can be eliminated. The connection of signal lines between active matrix panel and peripheral circuits become easy and more reliable [5]. The demands on TFT performance for SOP technology are much higher, as compared to that for application in AM driving pixel circuits.

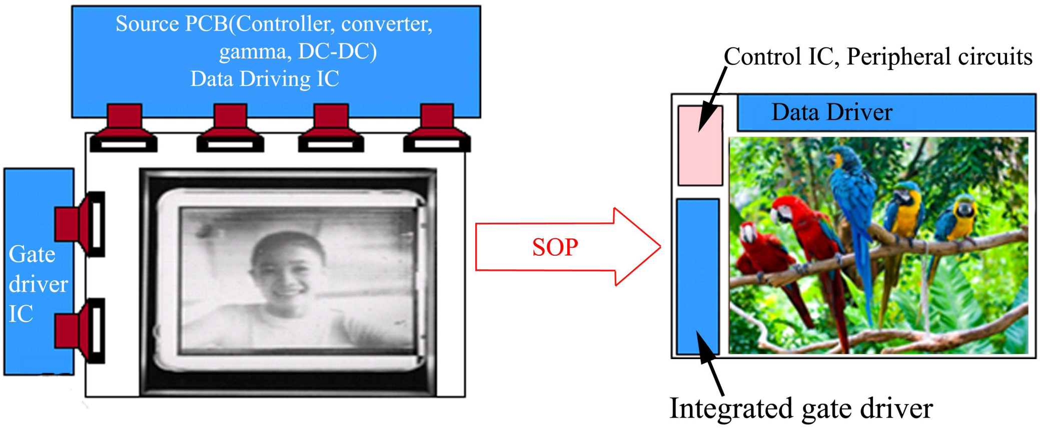

Fig. (5.2). The diagram of system-on-panel for AMOLED.

The TFTs on the glass for AM driving pixel circuits much show excellent electrical performance, such as high field-effect mobility (>20 cm^2/Vs), small subthreshold swing (0.5 V/decade), low threshold voltage, high on/off current ratio, and low leakage current. And the uniformity of the TFTs performance in the whole panel is required to maintain the uniformity brightness of the AMOLED display. The conventional a-Si:H TFTs, which are widely used as switching TFT in AMLCD, have the advantage of good uniformity and low cost. However, their low field-effect mobility (<1 cm^2/Vs) may be not sufficient to drive OLED pixels. The poly-Si TFTs are mainly used as switching and driving devices in the small size AMOLED display, due to their relative high mobility (> 50 cm^2/Vs) and good electrical stability. However, due to the different grain size and grain boundaries

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CHAPTER 6

Driving Schemes and Design Considerations for AMOLED

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Abstract: State of the art thin-film transistor technologies continue to fuel new areas of researches and applications in flat-panel display. However, this does not come without new issues related to device-circuit stability and uniformity over large areas, placing an even greater need for new backplane designs, driving algorithms and compensation techniques in pixel architectures. In this work, we explained design considerations for active matrix backplane. We outline a systematic design approach, including circuit theory, enabling user to design circuits without worrying about the details of device physics.

Keywords: AMOLED, Backplane design, OLED design consideration, OLED driving.

CIRCUIT FUNDAMENTALS

In this chapter, we dedicated to circuit design techniques for thin-film transistor (TFT). In TFT technology, the dynamics of operation of transistors and circuits composed of transistors can be analyzed using approximate equivalent RC circuits. In this section, the RC circuits and the related dynamics are first introduced. Then we will go over the approximation process of transistor circuit in a systematic design approach. Finally, we will cover some special TFT circuit design techniques.

Resistor-Capacitor Circuit

The passive resistor and capacitor are the most fundamental circuit elements. The

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resistance of a resistor, measured in Ohms, is also referred to as impedance. In integrated circuit design, metal thin films can be regarded as resistors. In metal thin films, the free electrons are accelerated when an electric field is applied. However, the accelerating electrons collide with other electrons and positive ions in the metal. The net effect leads to a constant velocity drift in the metal, producing current. By Ohm's Law, the current passing a resistor is directly proportional to the potential difference across the resistor, which are related as

$$V=IR$$

The passive capacitor consists dielectric insulating layer enclosed by two conductive electrodes can be treated as an energy storage device. The dielectric layer is insulating with very high resistivity, and thus charges cannot flow easily even under the driven of an electric field. However, with the present of electric field, positively charged nucleus and negatively charged electron move from their equilibrium position forming dipole, which develops charges stored onto the capacitor

$$Q=CV$$

A RC circuit is formed when these two components are connected in series. The RC circuit, which can be analyzed easily by first order rules, is often exploited to study the behavior of transistor circuit to obtain useful design information.

Charging and Discharging RC Circuit

When a RC circuit is connected to a voltage source, all components connected in series and so they share the same current throughout the process. In charging a capacitor, the initial current is the largest; this is because the initial voltage across the capacitor is zero, while the voltage across the resistor is maximum. As the process goes on, charges store in the capacitor that would develop a potential difference across the capacitor, and so potential across the resistor would decrease and hence the charging current decays. Fig. (**6.1**) shows the rate of change of the stored charges and charging current.

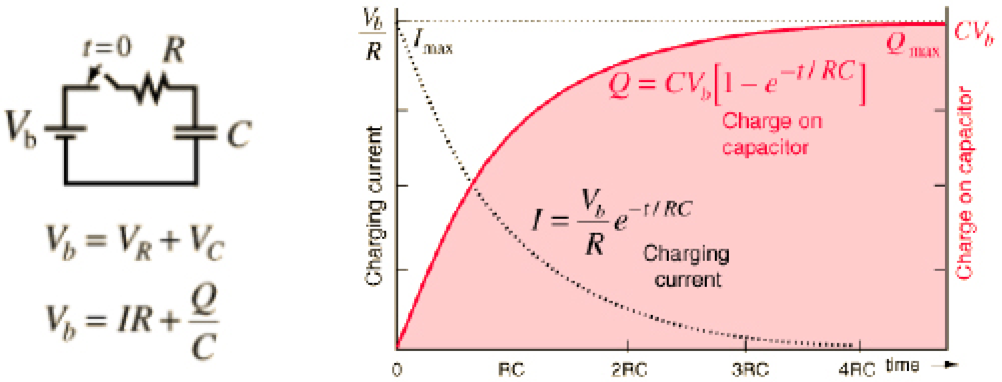

Fig. (6.1). Electrical characteristic in charging capacitor through a resistor [1].

Similarly, in discharging situation, now the capacitor itself acts as a voltage source. The voltage of both the capacitor and the resistor is the same throughout the process. From Fig. (**6.2**), the voltage, the discharging current and the capacitor's charge all follow the same type of decay curve during the process.

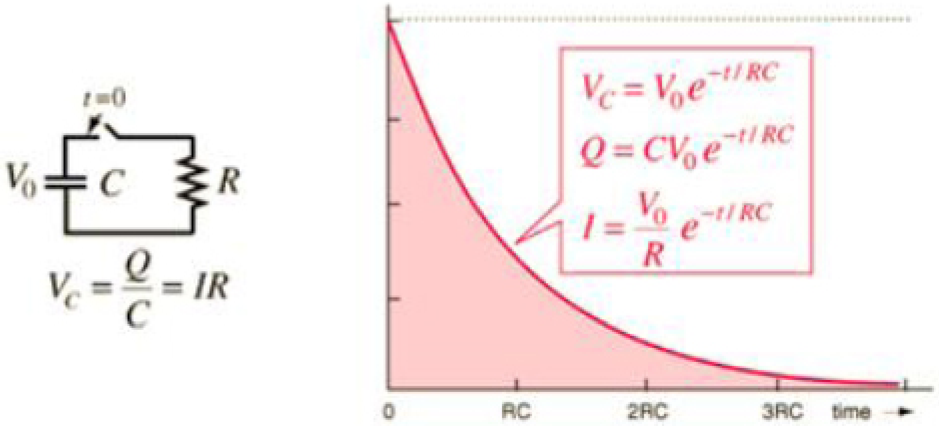

Fig. (6.2). Electrical characteristic in discharging capacitor through a resistor [1].

One important thing to note is the RC time constant, given by the product of the circuit resistance and the circuit capacitance. The rate of change of the above quantities can be described in terms of time constant. Ideally the capacitor takes infinite time to fully charge up, for our consideration, charging 90% of the applied

SUBJECT INDEX

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Dr. Shuming CHEN received his PhD degree in Electronic and Computer Engineering from Hong Kong University of Science and Technology (HKUST) in 2012. From Sep. 2012-May 2013, he was a postdoctoral researcher in Center for Display Research, HKUST and a senior engineer in Sinodisplay Technology Co. Ltd.. In June 2013, he officially joined the Department of Electrical and Electronics Engineering, South University of Science and Technology of China as an Assistant Professor. His current research focuses on OLED and QD-LED for display and lighting applications. He has published over 30 papers on top-tier international journals including Advanced Functional/Optical Materials, Organic Electronics and Applied Physics Letters with more than 800 citations. He was the recipient of 2013 HKIS "Young Scientist Award", 2013 Shenzhen "Overseas High-Caliber Personnel Award" (B-Class) and 2015 Guangdong "Special Support Plan for Young Talent Scholar".