OLED Displays and Lighting

Mitsuhiro Koden

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OLED DISPLAYS
AND LIGHTING
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Since a bright organic light emitting diode (OLED) device was first reported by C. W. Tang and S. A. VanSlyke of Eastman Kodak in 1987, the high technological potential of OLEDs has been recognized in the display and lighting field. This technological potential of OLEDs has been proved and demonstrated by various scientific inventions, technological improvements, prototypes, and commercial products.

Indeed, OLEDs have various attractive features such as colored or white self-emission, planar and solid devices, fast response speed, thin and light weight, and applicability to flexible applications. Therefore, it should be seen that OLEDs are not only an interesting scientific field but also have great potential for major market applications.

In the past 10 years, OLEDs have experienced serious and complicated business competition from liquid crystal displays (LCDs) and light emitting diodes (LEDs) due to the rapid performance improvement and rapid cost reduction of LCDs and LEDs. However, at the time of writing (2016), new major business possibilities for OLED displays and lighting devices seem to be appearing, in particular, being induced by the huge potential of flexible OLEDs, although LCDs and LEDs are still major devices in displays and lighting, respectively. Rapid growth toward huge market size is forecast for OLED displays and OLED lighting by several market analysts.

For about ten years I have been developing practical OLED technologies at Sharp Corporation, after developing LCD technologies there. Since 2013, I have developed practical flexible OLED technologies at Yamagata University, involving collaborations with a number of private companies.

The purpose of this book is to give an overview of fundamental science and practical technologies of OLEDs, accompanied by a review of the developmental history. This book provides a breadth of knowledge on practical OLED devices, describing materials, devices, processes, driving techniques, and applications. In addition, this book covers flexible technologies, which must be key technologies for future OLED business.

I trust that this book will contribute to not only university students but also researchers and engineers who work in the fields of development and production of OLED devices.
1

History of OLEDs

Summary

Active research and development of OLEDs (organic light emitting diodes) started in 1987, when Tang and VanSlyke of Eastman Kodak showed that a bright luminance was obtained in an OLED device with two thin organic layers sandwiched between anode and cathode. Since their report, OLEDs have been an attractive field from scientific and practical points of view because OLEDs have great potentials in practical applications such as displays and lighting. This chapter describes the history of the OLED.

Key words

History, Tang, Kodak, Friend, Forrest, Kido, Adachi

Light emission by organic materials was first discovered in a cellulose film doped with acridine orange by Bernanose et al. in 1953 [1]. Ten years later, in 1963, Pope et al., reported that a single organic crystal of anthracene showed light emission induced by carrier injection in a high electric field [2]. Also, since it became known that a large number of organic materials showed high fluorescent quantum efficiency in the visible spectrum, including the blue region, organic materials have been considered as a candidate for practical light emitting devices. However, early studies did not give any indication of the huge potential of OLEDs because of issues such as very high electric field (e.g. some needing 100V), very low luminance, and very low efficiency. Therefore OLED studies remained as scientific and theoretical fields, not indicating any great motivation towards practical applications.
A major impact was made by C. W. Tang and S. A. VanSlyke of Eastman Kodak in 1987. They reported a bright emission obtained in an OLED device with two thin organic layers sandwiched between anode and cathode, as shown in Fig. 1.1 [3]. They introduced two innovative technologies, which used very low thicknesses (<150 nm) of organic layers and adoption of a bi-layer structure. They reported that light emission was observed from as low as about 2.5 V and that high luminance (>1000 cd/m²) was obtained with a dc voltage of less than 10 V. Although the obtained external quantum efficiency (EQE) was still as low as about 1% and the power efficiency was still as little as 1.5 lm/W, the reported results were enough to draw huge attention from scientists and researchers. Indeed, their report started the age of the OLED not only in the academic field but also in industry.

The history of OLEDs is summarized in Table 1.1.

The device reported by Tang and VanSlyke in 1987 consists of a bottom emission structure and small molecular fluorescent monochrome organic material evaporated on glass substrates, but various other novel technologies have been studied and developed, aiming at a revolution in OLED technologies.

In the academic fields, several novel disruptive technologies giving drastic changes in performance of OLEDs have been discovered or invented. These include polymer OLEDs [4], white OLEDs [5], phosphorescent OLEDs [7], multi-photon OLEDs [10], TADF OLEDs [17].

In 1990, Burroughes et al. of the group led by Friend in the Cavendish Laboratories (Cambridge, UK) reported OLED devices with a light emitting polymer [4]. This invention opened the huge possibility of wet-processed OLED technologies.

The first scientific report of white-emission OLED was published in 1994 by Kido et al. of Yamagata University [5]. This report generated active development, aimed at lighting applications for OLEDs. The report also led to developments of the combination of white OLED emission with color filters, aimed at full-color OLED displays.
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<td>1990</td>
<td>Invention of polymer OLED (Cavendish Lab. / Burroughes et al. of Friend’s group)</td>
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<td>1994</td>
<td>First report of white OLED (Yamagata Univ. / Kido et al.)</td>
<td>[5]</td>
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<td>deposited small molecular fluorescent materials)</td>
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<td>1998</td>
<td>Invention of phosphorescent OLED (Princeton Univ./ Baldo et al. of Thompson and Forrest’s group)</td>
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<td>1999</td>
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<td>2001</td>
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<td>2003</td>
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<td>2006</td>
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<td>2007</td>
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<td>World’s first commercial AM-OLED-TV (Sony)</td>
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<td>2009</td>
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<td>2013</td>
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In 1998, Baldo et al. of Thompson and Forrest’s group at Princeton University reported phosphorescent OLEDs [7], which are theoretically able to realize 100% of internal quantum efficiency. The appearance of phosphorescent OLEDs drastically improved the efficiencies of OLEDs.

In 2002, Kido et al. at Yamagata University reported the multi-photon technology [10], which is able to realize high luminance and long lifetime.

In 2011, Endo et al. of the group led by Adachi in Kyushu University reported thermally activated delayed fluorescence (TADF) [17], which is an alternative technology to phosphorescent OLEDs for realizing high efficiency.

In parallel with such inventions and discoveries, much effort has been devoted to technological development on topics such as performance improvement, analysis of emission mechanism and degradation.

Much effort has also been devoted to practical device development and commercialization.

In 1997, Pioneer commercialized the world’s first OLED display, which was a passive-matrix green monochrome display (Fig. 1.2) [6]. This display had a bottom emitting monochrome device structure fabricated using vacuum evaporation technology with small molecular fluorescent organic materials. This display was applied to car audio.

The world’s first polymer type OLED was commercialized by Philips in 2003 [12]. This was a passive-matrix yellow monochrome display, being applied in shavers.

Currently, passive-matrix OLED displays are widely used in various applications with small to medium information content. In addition, tiling technology with passive-matrix OLED displays has realized very large size display (e.g. 155”) and cubic type displays such as a terrestrial globe display as shown in Fig. 1.3 [18].

Active-matrix OLED (AM-OLED) displays with full-color images have also been actively developed. In 2001, Sony demonstrated a 13” active-matrix full-color OLED display with 800×600 pixels (SVGA), which had a major impact on the display industry (Fig. 1.4) [9]. The OLED display was constructed using several novel technologies: top-emission structure with micro-cavity design for increasing luminance and they achieved excellent color purity, novel
Figure 1.3  The world largest cubic-type terrestrial globe display “Geo-Cosmos” [18]. (provided by Miraikan, the National Museum of Emerging Science and Innovation, Japan)

Figure 1.4  A 13” active-matrix full-color OLED display developed by Sony in 2001 [9]. (provided by Sony Corporation)
Display size: 13” (264 mm × 198 mm)
Number of pixels: 800 × 600 (SVGA)
Color: full color, R(0.66,0.34)  G(0.26,0.65)  B(0.16,0.06)
Luminance: higher than 300 cd/m²
Driving: Active-matrix with LTPS
current-drive LTPS-TFT circuit with four TFTs for attaining uniform luminance over the entire screen, solid encapsulation for enabling thinner structure, etc. In addition, the display was the largest OLED display at that time, and the pictures with beautiful color – R(0.66,0.34), G(0.26,0.65), B(0.16,0.06) – high luminance (>300 cd/m²), high contrast ratio, and wide viewing angle, greatly impressed many scientists and researchers in OLED and display fields.

The world’s first active matrix OLED display was commercialized in 2003 by SK Display (a joint company by Eastman Kodak and Sanyo Electric) [13]. The display was used by Kodak in digital cameras.

Sony commercialized the world’s first OLED-TV in 2007 (Fig. 1.5) [16]. The display size was 11” diagonal. In mobile application, in 2007, Samsung’s full-color AM-OLED displays were applied to main displays of mobile phones [15].

In 2012 and 2013, 55 or 56 inch large size OLED-TVs were demonstrated by Samsung, LG Display, Sony (Fig. 1.6), Panasonic, respectively. LG Display commercialized a 55” OLED-TV [24] in 2013 and developed a 77” OLED-TV prototype in 2014 [24]. In addition, Semiconductor Energy Laboratory (SEL) developed high resolution AM-OLED displays, such as a 13.3” AM-OLED display with 8K format (664 ppi) (Fig. 1.7) in 2014 [25] and a 2.8” AM-OLED display with ultra high definition format (1058 ppi) (see Fig. 8.15) in 2015 [28].

On the other hand, AM-OLEDs using light emitting polymers have also been developed. In 1999, Seiko Epson demonstrated an ink-jet AM-OLED display [8], in 2002, Toshiba showed a 17” prototype polymer AM-OLED fabricated by ink-jet [11], and in 2006, Sharp demonstrated a polymer AM-OLED with the world’s highest resolution (202 ppi), fabricated by ink-jet printing [14]. Moreover, in 2014, AU Optronics presented a 65” AM-OLED prototype display fabricated by ink-jet printing [26].

**Figure 1.5** The world’s first OLED-TV commercialize by Sony in 2007 [16]. (provided by Sony Corporation)
- Display size: 11” (251 mm × 141 mm)
- Number of pixels: 960 × 540 (QHD)
- Color: full color
- Contrast ratio: higher than 1,000,000 : 1
- Driving: active-matrix with LTPS
Figure 1.6 A 56” active-matrix full-color OLED display with 2K4K format developed by Sony in 2013. (provided by Sony Corporation)

Figure 1.7 Prototype of 13.3” AM-OLED display with 8K format (Semiconductor Energy Laboratory & Sharp) [25]. (provided by Semiconductor Energy Laboratory)

Display size: 13.3 inches (165 mm × 294 mm)
Number of pixels: 4320 × 7680 (4K8K)
Resolution: 664 ppi
Color: full color
Device structure: white tandem OLED (top emission)+color filter
Driving: active-matrix with CAAC-IGZO TFT
In the lighting fields, in 2011, Lumiotec, which is a Japanese venture company for OLED lighting, commercialized the world first OLED lighting [19]. At present, active demonstrations have shown new usage images of OLED lighting by several companies, as shown in Figs 1.8 and 1.9.

Recently, flexible OLEDs have also been actively developed. In 2011, Semiconductor Energy Laboratory (SEL) developed a 3.4″ flexible OLED prototype display with 326 ppi [32]. SEL and Sharp developed a 13.5″ flexible OLED prototype display with 81.4 ppi in 2012 [20] and SEL developed a 13.3″ flexible OLED prototype display with 8 K format (664 ppi) in 2015 [29]. Figure 1.10 shows a prototype of 13.3″ foldable AM-OLED display with 8 K format. The world’s first flexible OLED displays were commercialized by Samsung [22] and LG Display [23]. In addition, in 2015, LG Display developed an 18″ prototype flexible display [30] and SEL developed an 81″ Kawara type multi-AM-OLED display with 8 K format (see. Fig. 10.13) [31].

On the other hand, world’s first flexible OLED lighting was commercialized by LG Chem in 2013, using flexible ultra-thin glass [21]. In 2014, Konica Minolta commercialized flexible
Figure 1.10  Prototype of 13.3" foldable AM-OLED display with 8 K format (Semiconductor Energy Laboratory) [29]. (provided by Semiconductor Energy Laboratory)
Display size: 13.3" (165 mm × 294 mm)
Number of pixels: 4320 × 7680 (4 k8 k)
Resolution: 664 ppi
Color: full color
Device structure: white tandem OLED (top emission) + color filter
Driving: active-matrix with CAAC-IGZO TFT
OLED displays and lighting using plastic film and a roll-to-roll (R2R) production system [27]. An example of flexible OLED lighting is shown in Fig. 1.11.

As described above, various OLED technologies have been actively developed since 1987 and OLED products were steadily commercialized in competition with LCDs (liquid crystal displays) or LEDs (light emitting diodes). While the current business situation of OLEDs is not so favorable due to their high cost, etc., OLEDs have huge potential business in combination with further effort on cost reduction. In addition, “flexible” is a very significant key word for OLEDs because flexible OLEDs can realize certain commercial products that LCDs and LEDs cannot. Current active research and development of flat and flexible OLEDs should be understood in the light of this huge potential for future business.

References


2

Fundamentals of OLEDs

Summary

This chapter describes fundamentals of OLEDs, including the principles, the fundamental device structures and some features of OLEDs.

OLED is a carrier injection type electroluminescent device, having a similar emission mechanism to the inorganic light emitting diode (LED). The fundamental device structure of OLEDs is very simple, consisting of an anode, some organic layers and a cathode. The OLED has several attractive features such as low driving voltage, high efficiency, wide color variation, and fast response speed.

Key words

principle, device, structure, feature

2.1 Principle of the OLED

In OLED devices, organic layers are sandwiched between two electrodes, an anode and a cathode as shown in Fig. 2.1. The organic layers usually consist of multiple layers, in which each layer plays an intrinsic role. When a voltage is applied to an OLED device, charge carriers are injected from the electrodes to the organic layers. A hole (positive charge) is injected from the anode and an electron (negative charge) is injected from the cathode. The holes and electrons are transported to an emission site and recombined. Organic materials in the emission site are excited by recombination of holes and electrons. And then emission occurs when the excited state goes back to the ground state.

Such mechanism can also be illustrated by using an energy diagram as shown in Fig. 2.2.