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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.

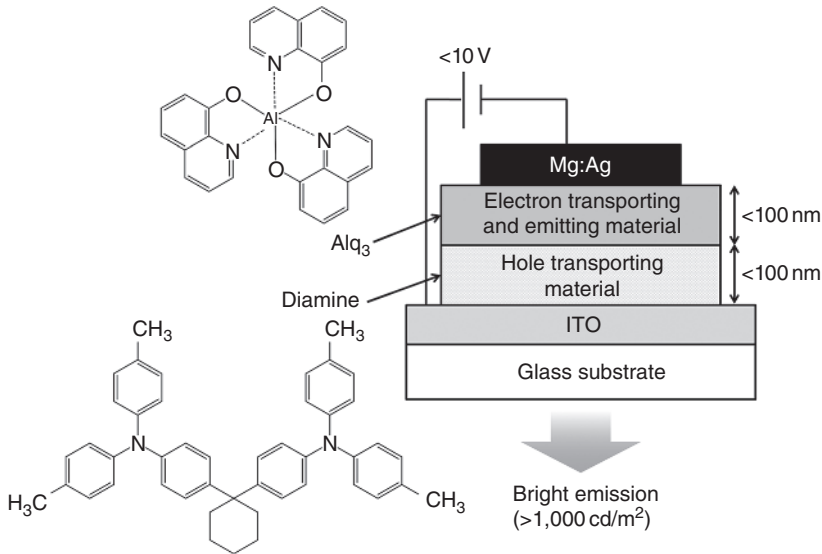


Figure 1.1 The structure and materials of an OLED device reported by Tang et al. [3]

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.

Table 1.1 The history of OLED

1987	Invention of two-layered OLED with a bright emission (Eastman Kodak / Tang and VanSlyke) [3] (Fig. 1.1)
1990	Invention of polymer OLED (Cavendish Lab. / Burroughes et al. of Friend's group) [4]
1994	First report of white OLED (Yamagata Univ. / Kido et al.) [5]
1997	World's first commercial OLED (Pioneer) [6] (Fig. 1.2) (Passive-matrix monochrome OLED display with bottom emission structure and vacuum deposited small molecular fluorescent materials)
1998	Invention of phosphorescent OLED (Princeton Univ./ Baldo et al. of Thompson and Forrest's group) [7]
1999	Prototype of a full-color polymer AM-OLED display fabricated by ink-jet printing (Seiko-Epson) [8]
2001	Prototype 13" full-color AM-OLED display (Sony) [9] (Fig. 1.4)
2002	Invention of multi-photon OLED (Yamagata Univ./Kido et al.) [10] Prototype 17" full-color polymer AM-OLED display fabricated by ink-jet printing (Toshiba) [11]
2003	World's first commercial polymer OLED display (Philips) [12] World's first commercial active-matrix OLED display (SK Display) [13]
2006	Prototype of 3.6" full-color polymer AM-OLED display with the world's highest resolution (202 ppi) fabricated by ink-jet printing (Sharp) [14]
2007	World's first application of AM-OLED displays for main displays of mobile phones (Samsung) [15] World's first commercial AM-OLED-TV (Sony) [16] (Fig. 1.5)
2009	Invention of TADF (thermally activated delayed fluorescence) (Kyushu Univ. / Endo et al. of Adachi's group) [17]
2010	World's largest OLED display with tiling system using passive-matrix OLED display [18] (Fig. 1.3)
2011	World's first commercial OLED lighting (Lumiotec) [19]
2012	Prototype 13" flexible OLED display (Semiconductor Energy Laboratory & Sharp) [20] Prototype of 55" OLED-TV (Samsung) Prototype of 55" OLED-TV (LG Display)
2013	Prototype of 56" OLED-TV (Sony) (Fig. 1.6) Prototype of 56" OLED-TV (Panasonic) World's first commercial flexible OLED lighting with ultra-thin glass (LG Chem) [21] World's first commercial flexible OLED displays (Samsung [22]) World's first commercial flexible OLED displays (LG display [23]) Commercial 55" OLED-TV (LG Display) [24]
2014	Prototype 77" OLED-TV with 4K format (LG Display) [24] Prototype 13.3" AM-OLED display with 8K format (Semiconductor Energy Laboratory & Sharp) [25] (Fig. 1.7) Prototype 65" full-color AM-OLED display fabricated by ink-jet printing (AU Optronics) [26] Commercial flexible OLED lighting using plastic film and roll-to-roll (R2R) production system (Konica Minolta) [27]
2015	Prototype 2.8" AM-OLED display with ultra high definition format (1058 ppi) (Semiconductor Energy Laboratory) [28] (Fig. 8.15) Prototype 13.3" foldable AM-OLED display with 8K format (Semiconductor Energy Laboratory) [29] (Fig. 1.10) Prototype 18" flexible AM-OLED display (LG Display) [30] (Fig. 10.14) Prototype 81" Kawara type multi AM-OLED display with 8K format [31] (Semiconductor Energy Laboratory) (Fig. 10.13)



Figure 1.2 The world's first OLED product (passive-matrix OLED display for car audio) commercialized by Pioneer in 1997 [6]. (provided by Pioneer Corporation)

Display size: 94.7 mm × 21.1 mm

Number of pixels: 16,384 dots (64 × 256)

Color: green (monochrome)

Driving: passive-matrix

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 300cd/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 ($>300 \text{ cd/m}^2$), 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 8 K 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

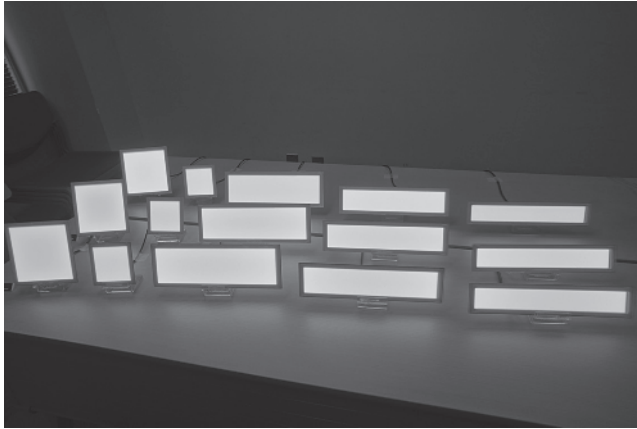


Figure 1.8 Examples of OLED lighting. (provided by Lumiotec Inc.)

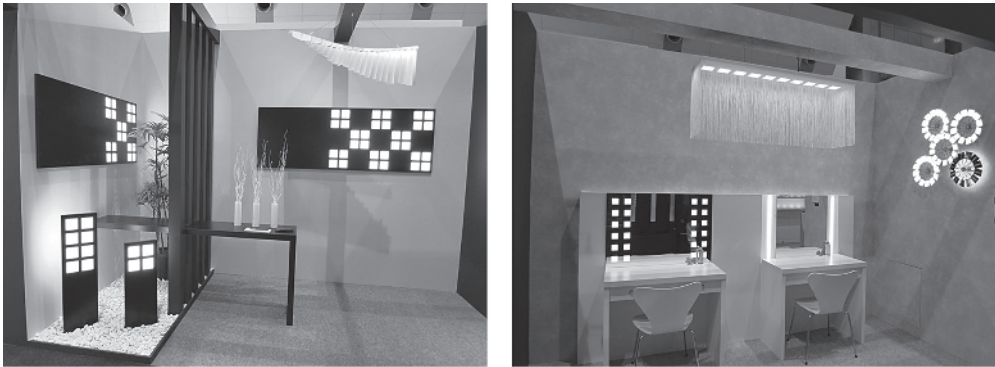


Figure 1.9 Examples of OLED lighting. (provided by Kaneka Corporation)

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 326ppi [32]. SEL and Sharp developed a 13.5" flexible OLED prototype display with 81.4ppi in 2012 [20] and SEL developed a 13.3" flexible OLED prototype display with 8K format (664ppi) in 2015 [29]. Figure 1.10 shows a prototype of 13.3" foldable AM-OLED display with 8K 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 8K 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 (4k8k)
Resolution: 664 ppi
Color: full color
Device structure: white tandem OLED (top emission)+color filter
Driving: active-matrix with CAAC-IGZO TFT

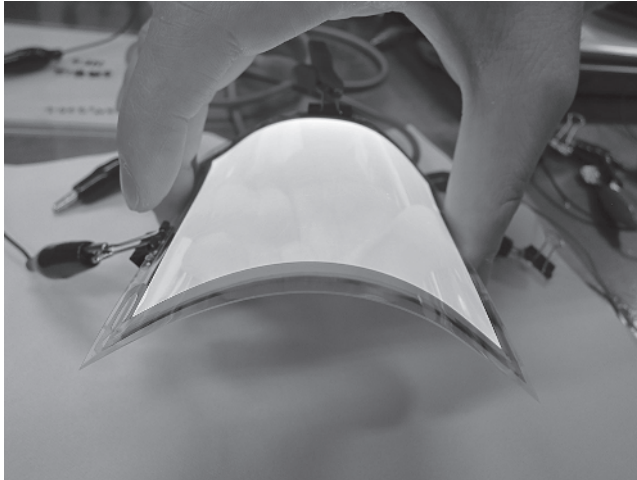


Figure 1.11 A prototype flexible OLED lighting panel [33]. (provided by NEC Lighting, Ltd)
 Panel size: 92 mm × 92 mm
 Emission area: 75 mm × 75 mm

OLED 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.

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