OLED DISPLAY FUNDAMENTALS AND APPLICATIONS

SECOND EDITION

Takatoshi Tsujimura

WILEY SID Series in **Display Technology**

OLED Display Fundamentals and Applications

Wiley-SID Series in Display Technology

A complete list of the titles in this series appears at the end of this volume.

OLED Display Fundamentals and Applications

Second Edition

Takatoshi Tsujimura

WILEY

This edition first published 2017

Registered Office
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA

Editorial Office
111 River Street, Hoboken, NJ 07030, USA

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

Library of Congress Cataloguing-in-Publication Data

Names: Tsujimura, Takatoshi.
Title: OLED display fundamentals and applications / Takatoshi Tsujimura.
Description: Second edition. | Hoboken, New Jersey : John Wiley & Sons Inc., 2017. | Series: Wiley series in display technology | Includes bibliographical references and index.
Identifiers: LCCN 2016042831| ISBN 9781119187318 (hardback) | ISBN 9781119187486 (epub) | ISBN 9781119187325 (epdf)
Subjects: LCSH: Flat panel displays. | Electrtoluminescent devices. | Organic semiconductors. | Light emitting diodes. | BISAC: TECHNOLOGY & ENGINEERING / Electronics / General.
Classification: LCC TK7882.I6 T84 2017 | DDC 621.3815/422–dc23 LC record available at https://lccn.loc.gov/2016042831

Cover image: © Blend Images - Colin Anderson/ Gettyimages
Cover design by Wiley

Set in 10/12pt Warnock by SPi Global, Chennai, India

Printed in United States of America

10 9 8 7 6 5 4 3 2 1

Contents

About the Author *xi*
Preface *xiii*
Series Editor's Foreword to the Second Edition *xv*

1 Introduction *1*
References *5*

2 OLED Devices *7*
2.1 OLED Definition *7*
2.1.1 History of OLED Research and Development *7*
2.1.2 Luminescent Effects in Nature *8*
2.1.3 Difference Between OLED, LED, and Inorganic ELs *11*
2.1.3.1 Inorganic EL *11*
2.1.3.2 LED *11*
2.2 Basic Device Structure *12*
2.3 Basic Light Emission Mechanism *14*
2.3.1 Potential Energy of Molecules *14*
2.3.2 Highest Occupied and Lowest Unoccupied Molecular Orbitals (HOMO and LUMO) *15*
2.3.3 Configuration of Two Electrons *17*
2.3.4 Spin Function *20*
2.3.5 Singlet and Triplet Excitons *20*
2.3.6 Charge Injection from Electrodes *24*
2.3.6.1 Charge Injection by Schottky Thermionic Emission *25*
2.3.6.2 Tunneling Injection *28*
2.3.6.3 Vacuum-Level Shift *28*
2.3.7 Charge Transfer and Recombination *29*
2.3.7.1 Charge Transfer Behavior *29*
2.3.7.2 Space-Charge-Limited Current *29*
2.3.7.3 Poole–Frenkel conduction *32*
2.3.7.4 Recombination and Generation of Excitons *33*

2.4 Emission Efficiency *36*
2.4.1 Internal/External Quantum Efficiency *36*
2.4.2 Energy Conversion and Quenching *37*
2.4.2.1 Internal Conversion *37*
2.4.2.2 Intersystem Crossing *37*
2.4.2.3 Doping *38*
2.4.2.4 Quenching *40*
2.4.3 Outcoupling Efficiency of OLED Display *42*
2.4.3.1 Light Output Distribution *42*
2.4.3.2 Snell's Law and Critical Angle *43*
2.4.3.3 Loss Due to Light Extraction *44*
2.4.3.4 Performance Enhancement by Molecular Alignment *45*
2.5 Lifetime and Image Burning *46*
2.5.1 Lifetime Definitions *46*
2.5.2 Degradation Analysis and Design Optimization *47*
2.5.3 Degradation Measurement and Mechanisms *50*
2.5.3.1 Acceleration Factor and Temperature Contribution *50*
2.5.3.2 Degradation Mechanism Variation *50*
2.6 Technologies to Enhance the Device Performance *51*
2.6.1 Thermally Activated Delayed Fluorescence *51*
2.6.2 Other Types of Excited States *53*
2.6.2.1 Excimer and Exciplex *53*
2.6.2.2 Charge-Transfer Complex *53*
2.6.3 Charge Generation Layer *54*
References *56*

3 OLED Manufacturing Process *61*
3.1 Material Preparation *61*
3.1.1 Basic Material Properties *61*
3.1.1.1 Hole Injection Material *61*
3.1.1.2 Hole Transportation Material *62*
3.1.1.3 Emission Layer Material *62*
3.1.1.4 Electron Transportation Material and Charge Blocking Material *63*
3.1.2 Purification Process *67*
3.2 Evaporation Process *68*
3.2.1 Principle *68*
3.2.2 Evaporation Sources *72*
3.2.2.1 Resistive Heating Method *72*
3.2.2.2 Electron Beam Evaporation *75*
3.2.2.3 Monitoring Thickness Using a Quartz Oscillator *76*
3.3 Encapsulation *79*
3.3.1 Dark Spot and Edge Growth Defects *79*

3.3.2 Light Emission from the Bottom and Top of the OLED Device *80*
3.3.3 Bottom Emission and perimeter sealing *81*
3.3.4 Top Emission *82*
3.3.5 Encapsulation Technologies and Measurement *83*
3.3.5.1 Thin-Film Encapsulation *84*
3.3.5.2 Face Sealing Encapsulation *87*
3.3.5.3 Frit Encapsulation *88*
3.3.5.4 WVTR Measurement *88*
3.4 Problem Analysis *91*
3.4.1 Ionization Potential Measurement *91*
3.4.2 Electron Affinity Measurement *92*
3.4.3 HPLC Analysis *93*
3.4.4 Cyclic Voltammetry *94*
References *96*

4 OLED Display Module *99*
4.1 Comparison Between OLED and LCD Modules *99*
4.2 Basic Display Design and Related Characteristics *101*
4.2.1 Luminous Intensity, Luminance, and Illuminance *101*
4.2.1.1 Luminous Intensity *101*
4.2.1.2 Luminance *102*
4.2.1.3 Illuminance *103*
4.2.1.4 Metrics Summary *104*
4.2.1.5 Helmholtz–Kohlrausch Effect *106*
4.2.2 OLED Current Efficiencies and Power Efficacies *106*
4.2.3 Color Reproduction *109*
4.2.4 Uniform Color Space *115*
4.2.5 White Point Determination *116*
4.2.6 Color Boost *119*
4.2.7 Viewing Condition *120*
4.3 Passive-Matrix OLED Display *121*
4.3.1 Structure *121*
4.3.2 Pixel Driving *122*
4.4 Active-Matrix OLED Display *125*
4.4.1 OLED Module Components *125*
4.4.2 Two-Transistor One-Capacitor (2T1C) Driving Circuit *127*
4.4.3 Ambient Performance *136*
4.4.3.1 Living Room Contrast Ratio *136*
4.4.3.2 Chroma Reduction Due to Ambient Light *137*
4.4.4 Subpixel Rendering *138*
References *139*

5 OLED Color Patterning Technologies *143*
5.1 Color-Patterning Technologies *143*
5.1.1 Shadow Mask Patterning *143*
5.1.1.1 Shadow Mask Process *143*
5.1.1.2 Blue Common Layer *146*
5.1.1.3 Polychromatic Pixel *147*
5.1.2 White + Color Filter Patterning *148*
5.1.3 Color Conversion Medium (CCM) Patterning *149*
5.1.4 Laser-Induced Thermal Imaging (LITI) Method *149*
5.1.5 Radiation-Induced Sublimation Transfer (RIST) Method *151*
5.1.6 Dual-Plate OLED Display (DOD) Method *152*
5.1.7 Other Methods *153*
5.2 Solution-Processed Materials and Technologies *153*
5.3 Next-Generation OLED Manufacturing Tools *158*
5.3.1 Vapor Injection Source Technology (VIST) Deposition *158*
5.3.2 Hot-Wall Method *163*
5.3.3 Organic Vapor-Phase Deposition (OVPD) Method *164*
References *165*

6 TFT and Driving for Active-Matrix Display *167*
6.1 TFT Structure *167*
6.2 TFT Process *169*
6.2.1 Low-Temperature Polysilicon Process Overview *169*
6.2.2 Thin-Film Formation *172*
6.2.3 Patterning Technique *173*
6.2.4 Excimer Laser Crystallization *177*
6.3 MOSFET Basics *180*
6.4 LTPS-TFT-Driven OLED Display Design *183*
6.4.1 OFF Current *183*
6.4.2 Driver TFT Size Restriction *184*
6.4.3 Restriction Due to Voltage Drop *185*
6.4.4 LTPS-TFT Pixel Compensation Circuit *190*
6.4.4.1 Voltage Programming *190*
6.4.4.2 Current Programming *192*
6.4.4.3 External Compensation Method *193*
6.4.4.4 Digital Driving *194*
6.4.5 Circuit Integration by LTPS-TFT *197*
6.5 TFT Technologies for OLED Displays *200*
6.5.1 Selective Annealing Method *200*
6.5.1.1 Sequential Lateral Solidification (SLS) Method *200*
6.5.1.2 Selective Annealing by Microlens Array *200*
6.5.2 Microcrystalline and Superamorphous Silicon *202*
6.5.3 Solid-Phase Crystallization *205*

6.5.3.1 MIC and MILC Methods *205*
6.5.3.2 AMFC Method *205*
6.5.4 Oxide Semiconductors *207*
References *210*

7 OLED Television Applications *215*
7.1 Performance Target *215*
7.2 Scalability Concept *217*
7.2.1 Relationship between Defect Density and Production Yield *217*
7.2.1.1 Purpose of Yield Simulation *217*
7.2.1.2 Defective Pixel Number Estimation Using the Poisson Equation *217*
7.2.2 Scalable Technology *217*
7.2.2.1 Scalability *218*
7.3 Murdoch's Algorithm to Achieve Low Power and Wide Color Gamut *219*
7.3.1 A Method for Achieving Both Low Power and Wide Color Gamut *219*
7.3.2 RGBW Driving Algorithm *221*
7.4 An Approach to Achieve 100% NTSC Color Gamut With Low Power Consumption Using White + Color Filter *224*
7.4.1 Consideration of Performance Difference between W-RGB and W-RGBW Method *224*
7.4.1.1 Issues of White + Color Filter Method for Large Displays *224*
7.4.1.2 Analysis of W-RGBW Approach to Circumvent Its Trade-off Situation *224*
7.4.1.3 Design of a Prototype to Demonstrate That Low Power Consumption Can Be Achieved with Large Color Gamut *229*
7.4.1.4 Product-Level Performance Demonstration by the Combination of Scalable Technologies *230*
References *233*

8 New OLED Applications *235*
8.1 Flexible Display/Wearable Displays *235*
8.1.1 Flexible Display Applications *235*
8.1.2 Flexible Display Substrates *235*
8.1.3 Laser Liftoff Process *236*
8.1.4 Barrier Technology for Flexible Displays *240*
8.1.5 Organic TFTs for Flexible Displays *241*
8.1.5.1 Organic Semiconductor Materials *242*
8.1.5.2 Organic TFT Device Structure and Processing *243*
8.1.5.3 Organic TFT Characteristics *245*
8.2 Transparent Displays *245*

8.3 Tiled Display *247*
8.3.1 Passive-Matrix Tiling *247*
8.3.2 Active-Matrix Tiling *248*
References *252*

9 OLED Lighting *255*
9.1 Performance Improvement of OLED Lighting *255*
9.2 Color Rendering Index *257*
9.3 OLED Lighting Requirement *259*
9.3.1 Correlated Color Temperature (CCT) *260*
9.3.2 Other Requirements *262*
9.4 Light Extraction Enhancement of OLED Lighting *262*
9.4.1 Various Light Absorption Mechanisms *262*
9.4.2 Microlens Array Structure *266*
9.4.3 Diffusion Structure *266*
9.4.4 Diffraction Structure *268*
9.4.5 Reduction of Plasmon Absorption *268*
9.4.5.1 Plasmonic Loss Mechanism *268*
9.5 Color Tunable OLED Lighting *269*
9.6 OLED Lighting Design *272*
9.6.1 Resistance Reduction *272*
9.6.2 Current Reduction *272*
9.7 Roll-to-Roll OLED Lighting Manufacturing *273*
References *275*

Appendix *277*

Index *281*

About the Author

Takatoshi Tsujimura joined IBM Japan for TFT-LCD development and was selected as one of the "10 best engineers/researchers in the 10 best Japanese companies" by Nikkei Electronics Magazine. He demonstrated OLED's capability to be applied to large television by the world's largest 20-in. demonstration and received SID Special Recognition Award in 2008. He moved to Kodak as a director and developed 100% NTSC white + color filter OLED display with less power consumption than LCDs, which has become industry-standard technology for OLED TV over 50 in. He is currently general manager of OLED business unit, Konica Minolta Inc. He received SID Fellow Award in 2013. He is an SID executive and is a former SID Japan chapter chair. He received PhD in materials science and engineering.

Dr. Tsujimura holds 144 worldwide registered patents and 7 publications including the following:

T. Tsujimura, *OLED Display Fundamentals and Application*, SID-Wiley Series in Display Science, ISBN: 978-1-118-14051-2 (2012)
T. Tsujimura, *OLED Overview (Japanese),* Sangyo Tosho, ISBN: 978–4782855560 (2010)
T. Tsujimura, *OLED display overview (Korean)*, Hantee Media, ISBN: 8964211766 (2013)
T. Tsujimura, *OLED display overview (Chinese)*, Publication House of Electronics Industry, ISBN: 9787121262814 (2015)
T. Tsujimura, *Technology and Material Development,* CMC Technical Library (2010)
T. Tsujimura, *OLED Material Technology,* CMC Publishing (2004)
T. Tsujimura, *OLED Handbook,* Realize Science and Engineering (2004).

Preface

In the 30 years that have passed since the release of the "first OLED paper," there have been many publications promoting organic light-emitting diode (OLED) displays as a superior technology. Although many aspects of OLED performance are excellent, such as the ultimate high contrast provided by its self-emissive mechanism, it has not been an easy path to achieve wide acceptance in the industry. A decade ago, I was often told by my customers that they totally agree with the beauty of OLED screens, but they are not affordable for common display applications. It is always the case that emerging technology faces difficulty in the wide-scale adoption, in spite of its inherent advantages. The well-established liquid-crystal display (LCD) has been manufactured for a very long time, so it has already been progressively engineered to improve its shortcomings, such as viewing angle, response time, and cost. It was not easy for OLED to overcome such a situation.

What triggered OLED to become so popular was the rapid growth of smart phones. The touchscreen interface paired very well with the OLED screen, as OLED did not show any "touch mura," a smear-like contrast reduction caused by flow-induced liquid crystal deformation. LCD, in a short time, improved the touch mura, but OLED makers utilized this momentary advantage to obtain a chance of growth. From this penetration of OLED display screens, end customers had a chance to recognize the superior display image quality of OLED, especially the beauty of its high contrast. This fortunate circumstance was a major benefit to OLED technology.

More recently, OLED has also penetrated the large television market, taking advantage of the high color gamut white + color filter method we developed, which promises high-yield manufacturing. OLED technology offers many important features for good television, so we expect it will gradually become more popular as the manufacturing cost goes down.

It is still a very important phase for OLED technology to become more widely used. The purpose of this book is to provide necessary information for everyone

who is involved with this great technology, so that such knowledge can lead to further improvements. I also hope the contents will help readers to hit upon new great applications, taking advantage of the features of OLED devices.

Takatoshi Tsujimura

Series Editor's Foreword to the Second Edition

In the 4 years since the first edition of Dr Tsujimura's book was published, the status of OLED displays has undergone a transformation. Their development can be exemplified by two products; the introduction of OLED televisions with diagonal screen sizes and resolution fully matching those of LCD sets but with curved screens represented a striking innovation which at that time could not be provided by LCD panels. Many commentators were surprised by the speed with which LCD manufacturers responded to this challenge. On the other hand, OLED panels on flexible substrates provide thin, conformable displays offering excellent compatibility with touchscreen technologies, which many users regard as a benchmark for display performance on mobile electronic devices.

OLED devices are therefore showing their ability to drive customer expectations for display performance. OLED displays provide a performance lead in terms of thin profile, response speed, and black level dominated dark room contrast, which appear difficult to challenge, while brightness, stability, and manufacturing cost are relatively weaker points. Meanwhile, competition between OLED and LCD manufacturers has stimulated innovation in both technologies, driving improvement in key areas such as power efficiency, color gamut, and resolution. As self-emissive devices, OLEDs are also generating widespread interest for lighting applications where their ability to offer a large area source and to achieve high-quality color rendering and tunable color temperature promises an excellent quality of illumination.

This second edition of Dr Tsujimura's book recognizes all these advances through updating and revision of his earlier material, and the addition of extensive new sections covering advances in the technological exploitation of OLEDs. Some of the most prominent of these include approaches to improved power efficiency and color gamut for OLED television, and how to combine both of these key advances; materials and manufacturing methods for flexible OLED displays; roll-to-roll manufacture of OLED lighting panels; and structures of transparent OLED panels. The treatment of a number of the underlying scientific principles involved in device operation and efficiency is

also expanded, with new material on luminescence mechanisms, light trapping and extraction, the behavior of various pixel driver circuits, and numerous other topics. It is our hope that these changes will both maintain the currency of the volume and increase its value to a broad range of users.

Dr Tsujimura brings to his subject, the experience and background knowledge gained through his long career researching and developing active matrix technologies, liquid crystal displays, and OLEDs. His knowledge and enthusiasm for his subject are clear in this book, which I believe will continue to provide a most valuable resource both for those working on OLED technologies and their applications, and for scientists and engineers who wish to increase their knowledge of this important field.

Malvern, UK *Ian Sage, Series Editor*

1

Introduction

The basic structure of organic light-emitting diodes (OLEDs) was reported by Tang and Van Slyke at Eastman Kodak in 1987 [1]. This was a groundbreaking study and was later referred to as the "first OLED paper." Now, almost 30 years later, there is a large market for OLED devices. The first OLED product was developed by Pioneer for car audio. Then the first mass production of AMOLED by SK display (a joint manufacturing venture by Eastman Kodak and Sanyo Electric) for Kodak's LS633 digital camera (Figure 1.1) accelerated the use of OLED for display applications.

This was followed by the widescale development of many other OLED-based products, including cellular phones (Figure 1.2), smart watches (Figure 1.3), audio players (Figure 1.4), and portable global positioning satellite (GPS) devices, which now provide high-resolution displays in brilliant, multitone colors.

Larger-display products have also been introduced on the market, such as those shown in Figure 1.5. Much larger prototypes have also been developed (Figure 1.6). Because of their superior features such as slim flat-screen design and aesthetically pleasing screen image, and due to high-contrast image signal emission and very good response time, the current state of the art of OLED television technology that has debuted in the marketplace is indeed groundbreaking [2].

The main objective of this book is to explain the basics and application of this promising technology from various perspectives.

OLED Display Fundamentals and Applications, Second Edition. Takatoshi Tsujimura.

Figure 1.1 The first active-matrix OLED display product on the market (Kodak LS633 digital camera).

Figure 1.2 Example of a cellular phone using active-matrix OLED (AMOLED) (Galaxy S7 smartphone by Samsung).

Figure 1.3 Example of a smart watch using active-matrix OLED (AMOLED) (Apple Watch Series 2 by Apple).

Figure 1.4 Example of an audio player using active-matrix OLED (AMOLED) (Sony Walkman NW-X-1050).

Figure 1.5 Example of a large television using active-matrix OLED (AMOLED) (65-in. curved OLED TV demonstrated in SID2015 by LG display).

Figure 1.6 111-in. dual-sided flexible OLED television prototype (LG Display at IMID2016).

References

1 C. W. Tang and S. A. Van Slyke, Organic electroluminescent diodes, *Appl. Phys. Lett.* **51**(12):913–915 (1987).
2 T. Tsujimura, W. Zhu, S. Mizukoshi, N. Mori, M. Yamaguchi, K. Miwa, S. Ono, Y. Maekawa, K. Kawabe, M. Kohno, and K. Onomura, Advancements and outlook of high performance active-matrix OLED displays, *SID 2007 Digest*, 2007, p. 84.

2

OLED Devices

2.1 OLED DEFINITION

2.1.1 History of OLED Research and Development

Before any in-depth discussion of OLED display structure, let us consider the initial origins of OLED technology, which are based on early observations of electroluminescence (EL). In the early 1950s, a group of investigators at Nancy University in France applied high-voltage alternating-polarity fields in air to thin films of cellulose or cellophane containing deposited or dissolved acridine orange and quinacrine, and observed light emission [1]. One mechanism identified in these reaction processes involved excitation of electrons. Then in 1960, a team of investigators at New York University (NYU) made ohmic (a nonrectifying charge injection, which shows linear current–voltage relationship) dark-injecting electrode contacts to organic crystals and described the necessary workfunctions (energy requirements) for hole and electron-injecting electrode contacts [2]. These contacts are the source of charge injection in all present-day OLED devices. The same NYU group also studied direct-current (DC) EL in vacuo on a single pure anthracene crystal and tetracene-doped anthracene crystals in the presence of a small-area silver electrode at 400 V [3]. The proposed mechanism for this reaction was termed *field-accelerated electron excitation of molecular fluorescence*. The NYU group later observed that in the absence of an external electric field, the EL in anthracene crystals results from recombination of electron and hole and that the conducting-level energy of anthracene is higher than the exciton energy level [4].

Because of the association between EL and later OLED development on the basis of these and other early EL studies, the term *organic EL* gradually emerged and is still used today. EL includes two basic phenomena:

1. Light emission due to the presence of excited molecules caused by accelerated electrons (i.e., electrons that are accelerated to higher energy levels)
2. Light emission due to electron–hole recombination, as in all light-emitting diodes (LEDs).

OLED Display Fundamentals and Applications, Second Edition. Takatoshi Tsujimura.

Table 2.1 Differences between Liquid Crystal and OLED Displays

Parameter	LCD	OLED
Response time	Slow	Fast
Luminance boost	Difficult	Possible
Viewing angle	Narrower high contrast angle region	Lambertian distribution[a)]
Number of components	More	Fewer
Differential aging[b)]	Small	Larger
Susceptibility to water and O_2		Larger

a) Outgoing light distribution whose luminance is proportional to $\cos\theta$. To be discussed in Section 4.2.1.4.
b) Luminance reduction in terms of use of a particular pixel and between colors. To be discussed in Section 2.5.

Phenomenon 1 is the narrower definition. Current OLED devices, after Tang and Van Slyke's "first OLED paper," utilize exclusively LED-like emission mechanisms, that is, phenomenon 2.

Table 2.1 lists the differences between a liquid crystal display (LCD) and an OLED display. The OLED has a very short response time and is capable of using "punching" (an imaging technique for enhancing the local luminance to emphasize the highlighted region of an image). The punching technique is used in cathode ray tubes (CRTs), which can have much higher luminance of a dot than the screen luminance. An OLED can use a similar operation, while a normal LCD display cannot.

Table 2.2 outlines the chronological history of OLED technology development.

The chronological sequence of development listed in Table 2.2 reflects the emergence of some general terms of classification of OLED technologies, including the following:

- Small-molecule OLED (SMOLED) and polymer OLED (PLED)
- Passive-matrix OLED (PMOLED) and active-matrix OLED (AMOLED) displays
- Fluorescent emission and phosphorescent emission.

The developments listed here and in Table 2.2 indicate that the rapid advances in OLED technologies resulted from extensive experimental trial and error. Each technology is discussed in further detail later in the book.

2.1.2 Luminescent Effects in Nature

There are several kinds of "luminescence" in nature, which can be explained by a mechanism similar to that of an OLED.

Table 2.2 Timeline for OLED Technology Development

Year	Event[a)]	Company/Institute
1960–mid–1970s	D OLED crystal molecule, anthracene, etc.[b)]	NRC (Canada), RCA
1983	D First observation of electroluminescence from polymer film	National Physical Laboratory
1987	P OLED diode structure paper in *Appl. Phys. Lett*.[b)]	Eastman Kodak
1988	P Double heterojunction[c)]	Kyushu University
1990	P First PLED paper in *Nature*[b)]	Cambridge University
1994	P White OLED demonstration[c)]	Yamagata University
1996	P first AMOLED demonstration (QVGA)[b)]	TDK
1998	D first phosphorescence OLED[b)]	Princeton University
1999	D first passive OLED product	Pioneer
1999	D Color OLED display by white + color filter method[c)]	TDK
2001	D 0.72-in. headmount display by AMOLED on silicon[b)]	eMagin
2001	D 13-in. SVGA AMOLED prototype[b)]	Sony
2001	D 2.1-in. 130-ppi AMOLED prototype[b)]	Seiko Epson/CDT
2002	D 15-in. 1280×720 OLED prototype[b)]	Eastman Kodak/Sanyo
2002	P Tandem OLED device demonstration[c)]	Yamagata University
2003	D digital camera with 2.2-in. AMOLED display[b)]	Eastman Kodak
2003	D Tiled 24-in. AMOLED prototype with by 12-in. display[b)]	Sony
2003	D 20-in. phosphorescence AMOLED prototype by a-Si backplane[b)]	ChiMei/IDT/IBM
2006	P White OLED with phosphorescent emitter[c)]	UDC
2007	D 11-in. OLED Television product[c)]	Sony
2007	P White OLED by all phosphorescent emitters[c)]	Konica Minolta
2008	P 12-in. Transparent OLED prototype[c)]	Samsung
2008	P 4-in. Flexible OLED prototype[c)]	Samsung
2008	P 100% NTSC low power OLED by white + color filter method[c)]	Kodak
2009	D OLED lighting product[c)]	Philips
2009	P TADF OLED device[c)]	Kyushu University

Table 2.2 (Continued)

Year	Event[a)]	Company/Institute
2010	P White OLED over 100 lm/W	UDC
2011	D OLED lighting product by all phosphorescent emitters[c)]	Konica Minolta/Philips
2013	D 55-in. OLED Television product by white + color filter method[c)]	LG display
2013	P 4KOLED Television prototype[c)]	Sony/Panasonic
2014	D Flexible OLED display product[c)]	LG display
2014	D Flexible OLED lighting product by roll-to-roll manufacturing[c)]	Konica Minolta

a) *Abbreviations in this column*: a-si—amorphous silicon; AMOLED—active-matrix OLED; D—development of; P—publication or presentation/demonstration of; PLED—polymer (O)LED; ppi—pixels per inch; QVGA—quarter videographics array (320 × 240 pixels); SVGA—super videographics array (800 × 600 pixels).

b) SID International Symposium (2003), 40 Years of SID Symposia—Nurturing Progress in EL/OLED Technology, Baltimore, MD. http://sid.org/Portals/sid/Files/DisplayHistory/EL-OLED_History.pdf.

c) By Takatoshi Tsujimura, "Evolution and future of OLED lighting," OLED Forum Japan presentation, Kyushu University 11/12/2015.

A molecule has multiple discrete energy levels, each able to hold two electrons. When electrons fill these levels completely, beginning from the lowest in energy, the system is stable. This is called the ground state.

If an electron is moved to an upper empty energy level, the resulting configuration is called an excited state. The excited state is normally unstable, so the electron tends to release the energy and return to the ground state. In such a transition, the excess energy is released as light (called "luminescence") and/or heat.

Luminescence can be classified depending on how the energy is transferred to the system. Light emission by a firefly is a type of luminescence. Luciferin is oxidized to "oxyluciferin" in an excited state by luciferase enzyme in the presence of adenosine triphosphate. As the oxyluciferin converts to its ground state, the molecule loses energy that it emits as light. If an excited state created by a chemical reaction causes the photon emission as in this case, it is referred to as chemiluminescence.

Fluorescent paint shines when it is illuminated by short-wavelength light. By absorption of this light, an excited state is created and it causes light emission at a longer wavelength, termed photoluminescence (PL).

When energy is transferred to the molecule by an electric field or current, subsequent light emission is called EL.

There are also many other luminescence effects, such as mechanoluminescence, and so on. Many of these phenomena have similar mechanisms, in which excess energy is released as photons and the system relaxes to the ground state, as a result.

2.1.3 Difference Between OLED, LED, and Inorganic ELs

OLED, LED, and inorganic EL devices all emit light electrically, so the distinction between them may be confusing. Here, the features for each technology are summarized.

2.1.3.1 Inorganic EL

An inorganic EL device has a structure similar to an OLED, with emissive layers sandwiched by insulators and two electrodes. However, the emission mechanism is quite different.

An inorganic EL device's emissive layer is a mixture of a semiconductor and a metallic compound. Free electrons in the semiconductor are accelerated by an electric field and their kinetic energy is transferred to emission centers, which are excited by their impact. The excited emission center is unstable and loses its energy by emitting a photon.

If a DC voltage were used for electron acceleration, the emission would stop when the electric field in the semiconductor was sufficiently shielded by the electron movement. Therefore, inorganic EL devices are driven by an AC voltage so that the emission is continued.

2.1.3.2 LED

Normally, inorganic LEDs are simply called "LEDs." Though the materials are different, LEDs and organic LEDs have similar emission mechanisms.

Pure semiconductors normally have very few mobile charge carriers. For electronic purposes, doping of impurities into the semiconductor is frequently used to change its conductivity. The impurities may be of two kinds.

1. "Donor"-type impurities, which supply electrons to semiconductors. Electrons are the major charge carriers in this case and such semiconductors with donor impurities are called "n-type."
2. "Acceptor"-type impurities, which supply holes to semiconductors. (As a "hole" means "lack of an electron," supplying a hole is equivalent to accepting an electron.) Holes are then the major charge carriers and semiconductors with acceptor impurities are called "p-type."

If layers of n-type and p-type semiconductors are stacked together to form a junction with electrodes sandwiching the p/n junction layers, electrons from

the n-type semiconductor and holes from the p-type semiconductor recombine when electric current is applied between the two electrodes. Recombination in the p–n junction creates excited states that emit photons.

Thus, inorganic LEDs have a mechanism similar to that of organic LEDs, which also emit light due to electron–hole recombination. (To be precise, the conduction mechanisms of LEDs and organic LEDs are not the same. Inorganic semiconductor charge carriers are described by a band theory, in which the periodic potential of the semiconductor crystal leads to formation of a Bloch wave. This theory cannot normally be applied to the disordered layers formed by the organic molecules used for OLEDs. So LEDs and OLEDs operate by the same charge recombination route but due to different conduction mechanisms.)

2.2 BASIC DEVICE STRUCTURE

Emission from all OLED devices—whether of the small-molecular or polymer family—can be explained by the same principle. Through electron–hole recombination, a high-energy molecular state is formed. This state is called an *exciton*, as it behaves like a single molecule with high energy. This exciton emits light after an exciton lifetime period (Figure 2.1). (It should be noted that "exciton lifetime" is the exciton decay period and does not refer to the OLED device lifetime.) [Another type of emission, termed *photoluminescent* (PL) emission, is caused by light (e.g., UV)-induced molecular excitation.]

The wavelength of this light emission corresponds to the exciton energy, so it is possible to control the color of the emission by adjusting the molecular design of the color center. This feature is quite advantageous for OLED display applications.

In experiments using tetracene-doped anthracene crystals and materials, OLED emission had been observed before the so-called first OLED paper in 1987 [5] (see Row 1 in Table 2.2 [4]). However, the operating voltage and efficiency levels were insufficient for actual application. The structure depicted in Figure 2.2 and described in the Tang–Van Slyke paper [5] represents advanced concepts that remain valid today:

1. Significant enhancement of the recombination efficiency by using a layered structure using multiple different materials (heterostructure)
2. Fabrication of low-voltage, high-quality devices through evaporation
3. Appropriate choice of electron and hole injection materials and of work-functions for cathode/anode electrodes
4. High electric field obtained by ultrathin-film formation.

OLED devices could emit very dim light before these developments, but high-luminance operation was achieved only after the first OLED paper.