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Hisashi Masui

Introduction to the Light-Emitting Diode

Real Applications for Industrial Engineers

Second Edition

Springer

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Dedicated to All My Teachers, to My Dear Wife,
and to My Dearest Parents

Foreword

The practical information you find in this book, you will not find in standard LED textbooks. Dr. Hisashi Masui possesses deep knowledge of device packaging from a standpoint of a graduate student, postdoctoral scholar, and also a leading industry engineer who has worked in the LED Industry both in the US and internationally.

Mr. Masui arrived at the University of California, Santa Barbara as a visiting researcher through an industrial member company supporting our research. Mr. Masui joined the MOCVD research group and pursued his Ph.D. through the Solid-State Lighting & Energy Electronics Center (SSLEEC) at UC Santa Barbara. In the Center we partnered with over a dozen leading LED companies, during which time Mr. Masui's expertise in device packaging technology was developed. The emphasis at UCSB was on the academia-industry collaborations to develop solid-state lighting. SSLEEC maintains the spirit of collaboration, and Dr. Masui carries with him the same spirit throughout his career. After graduate school, Dr. Masui returned to work professionally at several leading LED manufacturing companies. Through his explanations, he offers the reader practical LED-centric knowledge difficult to access on traditional textbooks.

Be sure to check out the first half of the book (Chaps. 1–3) to learn about the LED industry from an insider perspective. The second half (Chaps. 4 and 5) will expose readers to the technical details which semiconductor professionals learn. The appendices contain the basic solid-state physics familiar to most semiconductor engineers and will be useful as a reference for those with non-semiconductor backgrounds.

Winter 2022

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Preface

While working as an experimental scientist at a renowned LED company, I gradually realized two facts. One, not all engineers at the company had LED or solid-state lighting (SSL) backgrounds. Two, there were a lot more people working beyond R&D, in manufacturing and marketing/sales who might not be so interested in LED physics or semiconductor materials science. There are plentiful LED textbooks written by leading researchers and professors of the field, but those advanced textbooks were not quite satisfactory to engineers new to the company. They seemed wanting to learn something else.

Under such circumstances, I was asked by my immediate manager to gather a small class to teach LED basics. You might think the class started on discussing the pn junction; instead we began with how LED products were characterized and why particular methods of characterization were used, what quantities engineers and customers were interested in knowing, and where in the vast field of science those quantities originated from. After a few years my class became a full coverage of LED engineering, from semiconductor physics all the way to product manufacturing. I then came to believe that the class contents were valuable enough to write down.

Years before being familiar with the LED, my first encounter with solid-state luminescence was at my college back in the 1980s. A physics professor, Prof. Tokihisa Nakamura, demonstrated an inorganic electroluminescence (EL) device privately, in the dark after school. The glowing sheet in dim green looked mysterious and fascinating. When I started my first graduate school study, I begged my advisor, Prof. Manabu Takeuchi of materials science, to initiate an organic EL project. It was in 1989, only a year and half after Eastman Kodak's original paper on an organic EL device.

I encountered the LED as a professional in 1991. As I finished my master's thesis, I obtained my first job at Stanley Electric where I was assigned an LED project on epitaxy technology, despite my wish of joining its EL team. Stanley Electric was a well-established public company famous for its LED products. The research group I joined was investigating liquid-phase epitaxy of ZnSe for blue-LED application (this was before GaN emergence—it was a lucky opportunity because I put my hands on a material and growth technique other than GaN and MOCVD), and soon after I branched off to

MOCVD to grow ZnSe. In 1994 I was transferred as a Visiting Scholar to University of California Santa Barbara (UCSB) where I studied GaN epitaxy under Prof. Steven P. DenBaars with his postdoc researchers and graduate students. Young Prof. DenBaars was a renowned researcher in MOCVD technology and had moved from Hewlett-Packard. At his lab GaN publications written in English were apparently insufficient for those eager MOCVD researchers to collect technical information, while Japanese patents were extra sources of technical knowledges. I became busy extracting all growth conditions from Japanese patents to carry out MOCVD GaN growth with the UCSB researchers. If you recall, the mid-1990s was a hot time of GaN technology, with newly explored GaN devices like lasers and white LEDs in addition to fundamental growth and material discoveries. World conferences on nitride semiconductors were full of learnings and fun (often after-hour activities also). Upon completion of the 2-year joint project, I went back to Stanley Electric and worked in a GaN MOCVD group. I also had a chance to work in a product packaging and characterization department at Stanley Electric.

I became attracted by the LED, due largely to its established solid-state physics aspects. At the same time I gradually built up my feeling of lack of knowledge to be a senior professional. It was indeed a thirst and urge for scientific knowledge. I wanted to concentrate on the interest of mine; unfortunately Tokyo was too busy, with too many attractions that would drag me out to the downtown. That was not what I needed. In 2002, I passed exams and entered UCSB's graduate school and started my study as a full-time graduate student under Prof. DenBaars. Next to him already was Prof. Shuji Nakamura, the 2014 Nobel laureate. Professor Nakamura had been known as one of industrial pioneer engineers who contributed to industrialization of InGaN LEDs. Professor Nakamura told me in person some of his breakthroughs made during his industrial career. While taking advanced optoelectronics and MOCVD classes, my assigned research subject was LED packaging technology, which I later extended into LED characterization. Professor DenBaars put me in charge of a newly allocated packaging lab, to which I started gathering packaging equipment and characterization instruments. A few years later it appeared like a small assembly and inspection line that you would find in a startup company, supporting packaging and characterization of LED devices from MOCVD reactors of both Profs. DenBaars and Nakamura. I can emphasize the importance of supplier relations here: In order to customize newly purchased lab instruments, and to receive long-term services on them, maintaining good supplier relations does pay off.

With 5 years and a few more months, I obtained a degree in materials science. After spending a short period as a postdoc, I was hired at Soraa, which was a local startup company started by a few UCSB professors a year earlier. Santa Barbara (and neighboring City of Goleta) was an interesting area where a startup environment had grown. Meaning, professors had experiences of starting companies, small warehouse spaces were always available somewhere in the area, students and postdocs were seeking jobs without relocating, local engineers and techs were mobile to switch to a new company, and so on.

Yet Santa Barbara is a small city for a company to grow big. Soraa was trying to be larger with its novel technology. Silicon Valley is resourceful and accommodates more people. I was transferred to Soraa's brand-new Silicon Valley office to which the company's headquarter functions were also moving. My colleagues and I worked on packaging technologies and phosphor integration combined with characterization to industrialize the novel technology out of UCSB. Given the young company's energy and the time of SSL excitement, we focused on high-end lighting products. All of a sudden, a few years later a group of employees including myself got laid off. Being laid off was not a pleasant experience, but it turned out to be a chance to a new exposure. Soon after I joined Bridgelux, another LED company in the great Silicon Valley area. Bridgelux aimed at general lighting products where cost-effective solutions were sought. I was solely in charge of a new phosphor integration process to implement. About when I made the first demo unit of a cost-effective lighting solution, one of ex-UCSB friends of mine introduced me to a position at Lumileds. Lumileds had lots of optoelectronics history from its Hewlett-Packard time and was under Royal Philips back then. Lumileds was also full of resources. I was first put in charge of a new concept LED chip. A few months later I demonstrated a unique approach to the concept by hand-making an LED device, and in coming years brought that approach to new-product implementation (NPI), where I had opportunities to see and learn manufacturing engineering closely. This exposure to manufacturing made me believe that industrial R&D engineers need to know manufacturing to a certain extent, in addition to various aspects of LED physics and color science. Over these years of my career, "LED" has been always the keyword of my profession, yet every company tried to accomplish something different. Thus working at various LED companies gave me skills of taking various concepts and approaches to tackle a problem. At every place I worked, there were always many teachers who taught me something that I had not learned previously. I wish to thank all my teachers.

As a result of my professional experiences as described above, I came to believe that it was my task to put the learnings in a form of concise book. Therefore, this book has been written for industrial engineers predominantly. This book describes what you need to know to get started at an LED company. Not only that, during your future years in the industry, this book will support you for deeper learning in LEDs, from R&D to manufacturing, wherever your career is headed. Even more, if you are in academia, I hope this book tells you how attractive the world of LED industry is. We have so many interesting problems to solve, or at least to resolve (in fact, one of great things I learned in industry is that any problem can be resolved, if not solved). And we have many people working in various branches, from deep R&D, system designing, manufacturing, all the way to sales and marketing and field engineering. Everybody wants to know more about LED technology, but about various aspects of it in various ways of thinking. That is the reason why this book has come about. While there are many textbooks on LEDs that you can purchase, this book uniquely focuses on industrial engineering, on subjects that industrial engineers confront at their work. I have to admit, nevertheless, that upon writing about industrial aspects of technology things get slightly difficult, because of companies' intellectual properties and confidentiality. This has been a challenge of this book.

Nonetheless, a wide range of engineers in the LED industry should benefit from this book, as the scope spans from the LED physics essence, LED device structure, product ingredients, manufacturing methods, applications, to customer communications from a viewpoint of industrial engineers. After providing a brief chapter of Introduction, the book starts with a discussion on Characterization of LED devices for a reason that this is the first burden that new engineers owe. Chapter 2 describes what quantities the industry is interested in and how they are measured. This chapter provides you knowledge of language and terminology that the LED industry uses. The subsequent Chap. 3 discusses various types of LED devices and how they are fabricated. This somewhat deep knowledge in LEDs will definitely take you further in the industry. You will find various "layers" in the LED: For many people the LED means LED lighting devices or light engines, for others it implies LED light bulbs or lighting fixture, while physics students may envision a pn junction or semiconductor chips. This chapter reveals what is inside an LED product, in order to establish connections between a semiconductor chip and a lighting fixture. Chapter 4 provides a deep dive into physics of each technology in the LED. This chapter should inform you what scientists and engineers of each field are concerned with the most, to help understanding and conversation with them. Because of the deep-dive nature, semiconductor physics of the undergraduate level may be a prerequisite to survive this chapter. Finally, related topics of optics are laid out in Chap. 5. These topics cannot be missed when LED science and engineering are considered.

San Jose, CA, USA
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Hisashi Masui

Contents

Acronyms

1D, 2D, 3D	One-dimensional, Two-dimensional, Three-dimensional
AC	Alternating current
ADB	Adaptive driving beam
AFS	Adaptive front-lighting system
ALD	Atomic layer deposition
AR	Augmented reality, Anti-reflective
AS	Aperture stop
AVI	Automated visual inspection
BAM	BaMgAlO
BEOL	Back end of line
BF	Bright field
BKM	Best known method
BOM	Bill of materials
BOSE	Ba ortho-silicate Eu
BRDF	Bidirectional reflectance distribution function
BTDF	Bidirectional transmittance distribution function
CBCP	Center beam candlepower
CCD	Charge-coupled device
ccp	Cubic close-packed
CCT	Correlated color temperature
CHMSL	Center high-mount stop lamp
CIE	Commission Internationale de l'Eclairage (International Commission on Illumination)
CMP	Chemical-mechanical polishing
COA	Color over angle
COB	Chip on board
CPC	Compound parabolic collector/concentrator
CRI	Color-rendering index
CRT	Cathode ray tube
CSP	Chip-scale package

CTE	Coefficient of thermal expansion
CW	Continuous wave, Cool white
D_{65}	Daylight illuminant (a CIE illuminant standard)
DAP	Donor–acceptor pair
DC	Direct current
DF	Dark field
DH	Double hetero
DMA	Dynamic mechanical analysis
DMM	Digital multimeter
DOE	U.S. Department of Energy, Design of experiments
DOS	Density of states
DRBFM	Design review based on failure mode
DRL	Daytime running lamp
DSP	Double-side polished
DUT	Device under test
EBL	Electron blocking layer
EL	Electroluminescence
EM	Electromagnetic
EPD	Electrophoretic deposition
EQE	External quantum efficiency
ESD	Electrostatic discharge
EXE	Light-extraction efficiency
FA	Failure analysis
FC	Flip chip
FMEA	Failure mode and effect analysis
FOM	Figure of merit
FOV	Field of view
FS	Field stop
FT	Fourier transform
FWHM	Full width at half maximum
GGI	Gold–gold interconnect
GRIN	Graded index
GRR	Gage repeatability and reproducibility
hcp	Hexagonal close-packed
HEMT	High-electron-mobility transistor
HMD	Head-mount display
HT	High temperature
HTOL	High-temperature operation life
ID	Invention disclosure, Identification/identifier
IESNA	The Illuminating Engineering Society of North America
IP	Intellectual property

IQE	Internal quantum efficiency
IR	Infrared
ITO	Indium tin oxide
I–V	Current–Voltage
JEDEC	Joint Electron Device Engineering Council
L0, L1, L2, etc.	Level 0, Level 1, Level 2, etc.
LCD	Liquid-crystal display
LCL	Lower control limit
LD	Laser diode
LED	Light-emitting diode
LEO	Lateral epitaxial overgrowth
LES, LEA	Light-emitting surface, Light-emitting area
LLO	Laser liftoff
LOP	Light output
LPE	Liquid-phase epitaxy
LT	Low temperature
LuAG	Lutetium aluminium garnet
MCPCB	Metal-core printed circuit board
MIL-STD	U.S. Military standard
MOCVD	Metallorganic chemical vapor deposition
MQW	Multiple quantum well
NA	Numerical aperture
NIST	National Institute of Standards and Technology
NPI	New product introduction/implementation
NRR	Nonradiative recombination
NW	Neutral white
ODR	Omni-directional reflector
p&p	Pick and place
PCB	Printed circuit board
PDMS	Polydimethylsiloxane
PEC	Photoelectrochemical
PET	Polyethylene terephthalate
PIG	Phosphor in glass
PL	Photoluminescence
PMT	Photomultiplier tube
POR	Plan of record
PSA	Pressure-sensitive adhesive
PSS	Patterned sapphire substrate
PVC	Polyvinyl chloride
QCSF	Quantum confined Stark effect
QD	Quantum dot

QFN	Quad-flat no-leads
QW	Quantum well
R&D	Research and development
RDL	Redistribution layer
RGB	Red, green, and blue
RH	Relative humidity
RI	Refractive index
RIE	Reactive ion etch
RSS	Root sum squared
RT	Room temperature
R_{th}, Rth	Thermal resistance
SAC	Sn–Ag–Cu solder
SCASN	SrCaAlSiN
SEM	Scanning electron microscopy
SKU	Stock keeping unit
SLD	Super luminescent diode
SLS	Strained-layer superlattice
SMD	Surface-mount device
SMU	Source-measure unit
SQW	Single quantum well
SRH	Shockley–Read–Hall
SSP	Single-side polished
TCS	Test-color sample
TD	Threading dislocation
TDD	Threading dislocation density
TEM	Transverse electromagnetic, Transmission electron microscopy
TFFC	Thin-film flip chip
TIM	Thermal interfacial material
TIR	Total internal reflection
TMCL	Temperature cycle
TMSK	Temperature shock
TSV	Thru-silicon via
TTV	Total thickness variation
TVS	Transient-voltage suppressor
UBM	Under-bump metallization
UCL	Upper control limit
UID	Unintentionally doped
UPH	Units per hour
UV	Ultraviolet
V_f, Vf	Forward voltage
VOC	Volatile organic compound

VPE	Vapor phase epitaxy
VR	Virtual reality
VTF	Vertical thin film
WHTOL	Wet high-temperature operation life
WL	Wavelength
WPE	Wall-plug efficiency
WW	Warm white
XRD	X-ray diffraction
YAG	Yttrium aluminium garnet

1 Introduction

1.1 Definition and the Range of LED

"Oh yes, I have LEDs in my house!" This speaker probably means to say LED light bulbs or LED flashlights, not bare LED chips. In this chapter, we first illustrate how LEDs are widespread today in our lives, where the term "LED" can mean various stages of LED products, from millimeter-sized bare chips to gorgeous building lighting luminaires. Not only do we hear the name everyday and see them everywhere, but many people actually work on them, researching, manufacturing, and selling. At the same time many companies and individuals buy and use/consume LEDs. Because of these various aspects of people interacting with LEDs, the term "LED" has different meanings to different people. While LEDs illuminate offices and houses, physics researchers like university professors and graduate students may be thinking of mm-sized grains of semiconductor and their band diagrams of the pn junction. For device and module packaging engineers, LEDs are to emit light and heat that they want to handle neatly. Optical designers may not care much about electricity while they are dealing with the novel miniature but powerful light engines. Shop owners and employees regard LEDs as little electronic parts that happen to emit light, or emerging light-bulb products that customers recently tend to ask for. A company representative may consider LEDs as his sources of profit that he only sees on financial reports. An LED company manufactures and sells LED chips, while another LED company fabricates the LED lighting luminaire and sells it. End consumers look at modern light bulbs and flash lights that they think a little too expensive as LEDs. An electrician may think LEDs are large lighting fixtures and fancy luminaires that he needs to install in a new building. A car enthusiast may believe the LED makes the coolest-looking headlamps on his high-end car, without noticing traffic lights and street lights are also LEDs. Cellphone photographers may be surprised with knowing their camera flash is an LED. For LED professionals, these above are just various stages of LED products and prevailing applications. The LED can

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today mean anything from a semiconductor chip to lighting fixture in various application fields. That is why, it will not be so surprising to hear that many LED engineers have not seen a bare LED chip.

"LED" is originally an acronym for the light-emitting diode and has become a common noun.[1] It is pronounced "el-ee-dee" in most cases, while a small number of people tend to pronounce "lez" in plural. It was more than 100 years ago that the diode was originally an electrical rectifying device of a vacuum tube. Vacuum tubes have been replaced by the solid-state technology (namely the semiconductor technology); thus the diode means solely a semiconductor-based rectifying device today. The LED is a type of diode that emits light which is visible to humans in most cases, yet in physics light often implies the electromagnetic (EM) wave. Therefore for its wider meaning, a solid-state diode that emits an EM wave can be called an LED. From a viewpoint of electrical devices, an LED is a DC device that is operated at low voltages ($\sim$1.5–4 V). This electrical device has been integrated into various lighting devices and can draw enormous wattage when multiple LED chips are operated together.

Within the scope of this book the meaning of the LED spans from a modern semiconductor device that emits visible light to lighting products that use LED chips. In the language of LED industry, that is L0 and L1 (see Chap. 3), with a little extent to L2. Another keyword in this book is the solid-state lighting (SSL). UV and IR LEDs are only of interest along the natural course of our LED discussions. Organic semiconductors are generally discussed entirely separately, thus excluded from upcoming discussions. In a spirit of "Introduction for Industrial Engineers," the major focus of this book is not only to explain details of LED products but also to describe how LED products are made. Academic interests in physics of semiconductor devices are set as a secondary focus of this book.

1.2 LED in Lighting History

The LED is a hot field today. Why? Because lighting is a big human interest and a need by human nature, thus has become a part of modern industry. In ancient times, lighting was accomplished via flame from wood, candle (wax, solid kerosene), oil (liquid kerosene), then gas in the 19th century. The 20th century saw step-changes in lighting based on vacuum technology: Incandescent filament bulbs, discharge bulbs like the fluorescent tube lamps, and arc lamps. Mankind became able to create artificial light bright like the Sun. Accordingly, many lighting companies thrived during the century and some of them are still in existence today. When the lighting industry encountered the white LED at the end of the century, many found opportunities in it for the approaching 21st century. Today it is considered that the second half of the 20th century was a historical turnover from the vacuum technology to the solid-state technology. Transistors took over vacuum tubes in the 1960–1970s. LCDs

[1] This is similar to "laser" which is no longer spelled in capitals. Furthermore, a verb "lase" has been derived and used in discussions.

took over CRTs in the 1990s. And the LED is the next generation player in lighting, taking over from the vacuum-based light bulbs.

Another large industry counting on SSL technology was the automotive. Headlights equipped on earliest cars utilized oil and gas flames, and stops and turns of a vehicle were signaled by the operator’s hand. Electric light bulbs became popular for both headlights and taillamps in the 1910s as on-vehicle generators improved. High-CCT discharge lamps appeared around 2000, when white LEDs were extending into high-power applications. White LEDs were first employed for auxiliary front lighting of high-end passenger vehicles, and the first LED headlamp was finally launched in 2006. Red LED taillamps were employed in center high-mount stop lamps (CHMSLs) that the US law required in 1985. LED stop lamps first appeared in Europe in 1992 and began to be seen in the US on commercial trucks by the mid-90 s. Once local traffic regulations had certified LED lamps, they spread quickly to various types of automobiles because of LEDs’ high brightness, fast response, mechanical robustness, and design flexibility. Headlight applications are different from general lighting, as they are strictly controlled by local traffic regulations. By contrast, CCT and color rendering requirements are not so demanding. Automotive applications were founded on precedent outdoor-application engineering of transportation signaling (e.g., railroad crossing lights) and signage, which aggressively moved from mechanical message boards (e.g., split-flap displays and rollsigns) to multi-color LED message boards (using discrete emitters) during the 1980–1990s. Emergence of blue and green nitride LEDs enabled full-color outdoor displays, e.g., dynamic digital out-of-home (DOOH) advertising billboards.

A unique but major application that the white LED found was the camera flash. In photography artificial lighting had been sought and it was first attained via flash powders late in the 19th century. Flash powders were burning metal powders. In the 1930s press photographers shifted to portable flash bulbs; that was metal burned in a small glass bulb and thus one-time use per bulb. During the 1960–1980s electronic flashes wiped out flash bulbs. Electronic flashes utilize Xe discharge, hence are bulky and providing only one (or a small range of) CCT. As built-in cameras became popular in mobile phones, the LED happened to be the only possible solution. LEDs are compact, fast response, and readily provide various CCTs.

The LED itself had its own history before meeting the lighting industry. Following the great period of scientific discoveries in solid-state luminescence during the first half of the previous century [1], light emission from semiconductor materials was engineered and industrialized in a small scale during the 1950–1970s. Applications were limited to indoor like circuit-status indicators, because LEDs were small but dim compared to other existing light sources. Those semiconductors were indirect-bandgap materials. Once researchers got access to direct-bandgap materials and bandgap engineering, the 1980s became a decade of brightness improvements that enabled outdoor applications (signboards and automotive stop-lamps). These modern LEDs made the first large step to lighting applications. The second, and final large step was the invention of endurant blue LEDs leading to the down-conversion white LEDs in the 1990s. General lighting was already a large market, hence lighting companies began to invest in LED lighting technology. About 28 years later, the LED industry thrives today in spite of worldwide trade complications.

LED manufacturing became an international operation during the 2000s. In early years of LED industrialization, R&D and manufacturing were largely focused on the synthesis of semiconductor materials that heavily depended on epitaxy equipment development, and were conducted by American companies (followed by Japanese companies during the 1980–1990s. Refer to Sects. 3.1 and 4.1), where manufacturing cost reduction was one of main targets for market penetration. Both for intellectual-property confidentiality and for advanced facilities (e.g., cleanroom engineering), manufacturing stayed within the country where R&D was performed. Triggered by the market demand for high-power LEDs around 2000 (preceded by the emergence of the phosphor-converted white LED in 1996), the international operation took off, especially in low-power product options due to the cost-down competition. Asian countries had experienced electronics and automotive industries since the 1970s; as a result, infrastructure was secured and the labor force was grown. These Asian countries received the back end of line (assembly)[2] first, then followed by the middle of line (device fab), and finally the front end of line (epitaxy) became common towards the end of the 2000s. This movement enabled a worldwide supply of cost-effective LED chips and created opportunities for start-up companies without possession of expensive epitaxy facilities. During the 2010s, the effort of product cost reduction introduced the fabless business model by hiring Asian contract manufacturers (CMs), which was successful in some cases. CMs had limited manufacturing capacities and tended to prioritize high-margin orders, which counteracted the cost-down effort. Today, LED manufacturing is dynamically seeking an optimized operation, while the world economy has been unpredictable.

1.3 Safety Precautions

Before start working on LEDs, one must understand how LEDs may threaten people's lives and health. Light emitted from LEDs is not immediately harmful to human eye or skin; nevertheless, there are a few exceptions. EM waves in the UV-C range (the shortest wavelength range of UV, 100–280 nm) destroy biocells, and there exist LEDs that emit UV-C. They need to be shielded completely when operated to eliminate any harm. Other UVs, UV-A and UV-B, can burn human skin quite badly, like sun tanning. Violet and short-WL blue have similar effects to some degree. All UV can degrade plastic resin, thus shielding equipment may require frequent quality inspection. The rest of visible wavelengths and IR wavelengths (800 nm and beyond) are not of biological harm.

Even if a wavelength is not harmful, concentrated energy of EM waves can burn human tissues. The laser is an immediate example as light emission from a laser is a straight beam and does not spread, thus energy density does not dilute even in a far distance. As for LEDs, emitted light spread in space as the distance from the LED increases. Therefore a chance

[2] See Sect. 3.5 for nomenclature.

of burned eye or skin by an LED is rare, unless in a very vicinity of an LED where the energy density of emitted light is high. As a reference of energy density, solar radiation energy on earth's surface is approximately 1 mW/mm^2 on a bright day. The reader must know how bright the daylight is to the eye. LED light emission easily exceeds this solar level. For example, a 1-mm^2 blue chip can easily exceed 500 mW of light emission (for those who wonder, luminous efficacy of the sunlight is about 100 lm/W). Or, if one uses a little magnifying glass to focus sunlight onto a piece of paper, he can create a burn mark of $\sim$1 mm^2 in a moment. Energy of light can be this strong, therefore exposure of concentrated light to human tissues should be avoided.

LED products contain various chemical elements, and some of which may be toxic. Completed LED chips hardly contain any toxic elements. During epitaxy, GaAs substrates may be used, where As is a toxic element. GaAs substrates may remain in IR LED products. MOCVD uses potentially toxic and flammable chemicals and device processing in cleanrooms utilizes chemicals potentially hazardous, but they do not reside in end products. In a few lighting products quantum-dot (QD) phosphors may be used. QDs contain Cd which is a toxic element. These toxic elements require attention when the LED products get disposed after use. As far as handling those products, there is little danger. Old LED products may have used Pb-containing solder; as of today Pb has been removed from the entire industry.

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Characterization Techniques 2

2.1 Purpose of Characterization

Characterization of LED devices is required for two main reasons. One is to understand properties of LED devices and products in detail for further improvements in R&D. The other is to control production quality. The latter is often called "testing." In this book we do not make rigorous distinction between these two words; use them rather interchangeably.

Characterization is repeatedly performed and data is analyzed by R&D engineers and process engineers for the above purposes. Another important function of characterization is to publish product properties in a form of datasheets, so customers can design their products appropriately with LEDs and communicate with the LED manufacturer and its application engineers when necessary. Presentation of data in datasheets is carefully examined upon publishing, since datasheets may be interpreted by customers from their own viewpoints. Datasheets are also frequently analyzed by competitor companies. Such effort of analyzing competitors' products is called "bench-marking" or "competitive analysis" and is an important operation in a company to assess its products against the competition. In those efforts of bench-marking, terminology used in datasheets is occasionally different between companies. Test conditions are independently defined between companies, hence making the bench-marking difficult and puzzling for customers who try to compare LED products from two or more manufacturers. But this is the reality.

Datasheets often contain binning information. Binning was originally a manufacturing and sales technique of grouping produced devices of a product type in terms of device properties (V_f, LOP, WL, color, etc.) into predetermined "bins." Since the binning technique affects production yields, and therefore production costs and end sales pricing, binning has become an important strategic parameter in modern manufacturing. Binning is also called "sorting."

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