

# **Light-Emitting Diodes**

## **3rd edition**

E. Fred Schubert  
Rensselaer Polytechnic Institute  
Troy, New York, USA

ISBN: 978-0-9 863826-6-6

Publisher: E. Fred Schubert

Year: 2018

© E. Fred Schubert, all rights reserved

# Light-Emitting Diodes

**3rd edition**

E. Fred Schubert  
Rensselaer Polytechnic Institute  
Troy, New York, USA

The 1st edition of the book “Light-Emitting Diodes” was published in 2003. The 2nd edition was published in 2006. The current 3rd edition of the book is a substantial expansion of the second edition and has 37 chapters. The book includes a thorough discussion of white light-emitting diodes (LEDs), phosphor materials used in white LEDs, packaging technology, and the various efficiencies and efficacies encountered in the context of LEDs. The background of light, color science, and human vision is provided as well. The fully colored illustrations of the 3rd edition are undoubtedly beneficial given the prominent role of light and color in the field of LEDs. The book is a comprehensive discussion of the LED, particularly its semiconductor physics, electrical, optical, material science, thermal, mechanical, and chemical foundations. The 3rd edition is published in electronic format in order to make the book affordable and easily accessible to a wide readership.

## Table of contents

<b>1</b>	<b>History of SiC light-emitting diodes</b>	<b>1-1</b>
1.1	Silicon carbide (SiC) .....	1-1
1.2	Henry Round's demonstration of the first LED .....	1-2
1.3	Oleg Lossev's research on SiC LEDs .....	1-4
1.4	Kurt Lehovec's explanation of electroluminescence from p-n junctions .....	1-8
1.5	Post 1950s developments in SiC LEDs .....	1-9
1.6	LED centennial in 2007 .....	1-9
	References .....	1-10
<b>2</b>	<b>History of III–V light-emitting diodes</b>	<b>2-1</b>
2.1	Compound semiconductors .....	2-1
2.2	The first III-V compound semiconductor LED .....	2-3
2.3	History of GaAs <sub>y</sub> P <sub>1-y</sub> alloy semiconductors and LEDs .....	2-5
2.4	History of GaAs and AlGaAs infrared and red LEDs .....	2-9
2.5	History of GaP and GaAsP LEDs doped with optically active impurities .....	2-12
2.6	History of AlGaInP visible LEDs .....	2-18
2.7	History of GaN metal–semiconductor emitters .....	2-19
2.8	History of GaInN p-n junction LEDs .....	2-22
	References .....	2-27
<b>3</b>	<b>History of white light-emitting diodes</b>	<b>3-1</b>
3.1	The advent of the white LEDs .....	3-1
3.2	Transition from LEDs to LED-based lighting .....	3-9
3.3	LEDs entering new fields of applications .....	3-15
3.4	LED replacement light bulbs .....	3-18
	References .....	3-19
<b>4</b>	<b>Radiative and non-radiative recombination</b>	<b>4-1</b>
4.1	Radiative electron–hole recombination .....	4-1
4.2	Radiative recombination for low-level excitation .....	4-2
4.3	Radiative recombination for high-level excitation .....	4-6
4.4	Bimolecular rate equations for quantum well structures .....	4-7
4.5	Luminescence decay .....	4-8
4.6	Shockley–Read–Hall non-radiative recombination .....	4-9
4.7	Auger non-radiative recombination .....	4-14
4.8	Non-radiative recombination at surfaces .....	4-17
4.9	Competition between radiative and non-radiative recombination .....	4-21
4.10	Recombination in direct-gap and indirect-gap semiconductors .....	4-23
	References .....	4-25
<b>5</b>	<b>Theory of radiative recombination</b>	<b>5-1</b>
5.1	Quantum mechanical model of recombination .....	5-1
5.2	The van Roosbroeck–Shockley model .....	5-3
5.3	Temperature and doping dependence of recombination .....	5-7
5.4	The Einstein model .....	5-10
	References .....	5-11

<b>6</b>	<b>Recombination modeled by the ABCCD-model</b>	<b>6-1</b>
6.1	Relation between optical and electrical carrier generation .....	6-1
6.2	Free carrier concentrations in the active region .....	6-1
6.3	Recombination expressed in terms of the $A$ , $B$ , and $C$ coefficients and $f(n)$ term .....	6-2
6.4	Determination of the $A$ , $B$ , and $C$ coefficients in absence of carrier leakage .....	6-7
6.5	Carrier leakage and the ABCCD model .....	6-11
	References .....	6-13
<b>7</b>	<b>Current–voltage characteristics</b>	<b>7-1</b>
7.1	Diode current–voltage characteristic based on Shockley equation .....	7-1
7.2	Diode forward voltage .....	7-6
7.3	Diode ideality factor .....	7-9
7.4	Diode parasitic resistances .....	7-11
7.5	Measurement of diode parasitic resistances .....	7-12
7.6	Diagnosis of potential problems in the current-voltage characteristic .....	7-13
7.7	Ohmic contacts .....	7-17
7.8	Physics of ohmic contacts .....	7-19
7.9	Multilayer ohmic contacts .....	7-22
	References .....	7-23
<b>8</b>	<b>Carrier transport effects in the active region</b>	<b>8-1</b>
8.1	Carrier distribution in p-n homojunctions .....	8-1
8.2	Carrier distribution in p-n heterojunctions .....	8-2
8.3	Effect of heterojunctions on device resistance .....	8-3
8.4	Carrier loss in double heterostructures .....	8-7
8.5	Carrier overflow in double heterostructures .....	8-10
8.6	Electron-blocking layers .....	8-14
8.7	Effect of heterojunctions on diode voltage .....	8-15
	References .....	8-17
<b>9</b>	<b>Design of current flow</b>	<b>9-1</b>
9.1	Current-spreading layer .....	9-1
9.2	Theory of current spreading .....	9-7
9.3	Current crowding in LEDs on insulating substrates .....	9-10
9.4	Buried contact design .....	9-15
9.5	Lateral injection schemes .....	9-16
9.6	Current-blocking layers .....	9-17
9.7	Surface-leakage current .....	9-19
	References .....	9-20
<b>10</b>	<b>Alternating-current (AC) and high-voltage (HV) LEDs</b>	<b>10-1</b>
10.1	Simple circuits for AC-driven LEDs .....	10-1
10.2	LED bridge rectifier configurations for AC-driven LEDs .....	10-3
10.3	Analysis of pulsed drive current in AC-driven LEDs .....	10-4
10.4	Challenges associated with AC-driven LEDs .....	10-6
10.5	High-voltage (HV) LEDs .....	10-7
	References .....	10-10

<b>11</b>	<b>Basic optical properties</b>	<b>11-1</b>
11.1	Emission spectrum .....	11-1
11.2	The light escape cone .....	11-4
11.3	Emission pattern .....	11-7
11.4	The lambertian emission pattern .....	11-8
11.5	Encapsulants .....	11-11
11.6	Temperature dependence of emission intensity .....	11-12
	References .....	11-14
<b>12</b>	<b>Reflectors</b>	<b>12-1</b>
12.1	Metallic reflectors, reflective contacts, and transparent contacts .....	12-1
12.2	Total internal reflectors .....	12-6
12.3	Distributed Bragg reflectors .....	12-8
12.4	Omnidirectional reflectors .....	12-19
12.5	Specular, diffuse, and mixed reflectors .....	12-23
	References .....	12-28
<b>13</b>	<b>Definition of Efficiencies</b>	<b>13-1</b>
13.1	Radiative efficiency (RE) of active region .....	13-1
13.2	Injection efficiency (IE) of carriers into active region .....	13-4
13.3	Internal quantum efficiency (IQE) .....	13-5
13.4	Light-extraction efficiency (LEE) .....	13-6
13.5	External quantum efficiency (EQE) .....	13-7
13.6	Forward-voltage efficiency (Electrical efficiency) .....	13-7
13.7	Power efficiency .....	13-8
13.8	Luminous efficacy of radiation (LER) .....	13-9
13.9	Luminous efficacy of a source (LES) .....	13-11
13.10	Efficiency of wavelength-converter materials (phosphors) .....	13-11
	References .....	13-13
<b>14</b>	<b>Designs for high internal quantum efficiency</b>	<b>14-1</b>
14.1	Double heterostructures .....	14-1
14.2	Doping of active region .....	14-4
14.3	p-n junction displacement .....	14-6
14.4	Doping of the confinement regions .....	14-8
14.5	Non-radiative recombination .....	14-11
14.6	Lattice matching .....	14-12
	References .....	14-15
<b>15</b>	<b>Designs for high light-extraction efficiency</b>	<b>15-1</b>
15.1	Absorption of below-bandgap light in semiconductors .....	15-1
15.2	Double heterostructures .....	15-5
15.3	Shaping of LED dies .....	15-6
15.4	Textured semiconductor surfaces .....	15-10
15.5	GaN thin-film LEDs .....	15-12
15.6	Cross-shaped contacts and other contact geometries .....	15-15
15.7	Transparent substrate technology .....	15-15
15.8	Anti-reflection optical coatings .....	15-18
	References .....	15-19

<b>16</b>	<b>Spontaneous emission from resonant cavities</b>	<b>16-1</b>
16.1	Modification of spontaneous emission .....	16-1
16.2	Fabry–Perot resonators .....	16-3
16.3	Optical mode density in a one-dimensional resonator .....	16-7
16.4	Spectral emission enhancement .....	16-12
16.5	Integrated emission enhancement .....	16-14
16.6	Experimental emission enhancement and angular dependence .....	16-15
	References .....	16-18
<b>17</b>	<b>Resonant-cavity light-emitting diodes</b>	<b>17-1</b>
17.1	Introduction and history .....	17-1
17.2	RCLED design rules .....	17-3
17.3	GaInAs/GaAs RCLEDs emitting at 930 nm .....	17-6
17.4	AlGaInP/GaAs RCLEDs emitting at 650 nm .....	17-11
17.5	Newer developments in RCLED devices .....	17-14
	References .....	17-15
<b>18</b>	<b>Photonic crystal light-emitting diodes</b>	<b>18-1</b>
18.1	The photon recycling concept for LEDs .....	18-1
18.2	Thresholdless laser or single-mode LED .....	18-3
18.3	Photonic crystals .....	18-5
18.4	LEDs using photonic crystals .....	18-10
	References .....	18-12
<b>19</b>	<b>Visible-spectrum LEDs</b>	<b>19-1</b>
19.1	The GaAsP, GaP, GaAsP:N, and GaP:N material systems .....	19-1
19.2	The AlGaAs/GaAs material system .....	19-6
19.3	The AlGaInP/GaAs material system .....	19-9
19.4	The GaInN material system .....	19-11
19.5	Optical characteristics of high-brightness LEDs .....	19-13
19.6	Electrical characteristics of high-brightness LEDs .....	19-15
19.7	Wavelength dependence of the efficiency in the visible spectrum .....	19-16
	References .....	19-18
<b>20</b>	<b>The AlGaInN material system</b>	<b>20-1</b>
20.1	The AlGaInN bandgap .....	20-1
20.2	Crystal structure of III–V nitrides and origin of polarization .....	20-2
20.3	Consequences of polarization effects in III–V nitrides .....	20-7
20.4	P-type doping in III–V nitrides .....	20-9
20.5	Epitaxial growth of GaN on sapphire .....	20-13
20.6	Dislocations in III–V nitrides .....	20-15
	References .....	20-19

<b>21</b>	<b>Ultraviolet light emitters</b>	<b>21-1</b>
21.1	The ultraviolet (UV) spectral range .....	21-1
21.2	UV and violet LEDs emitting at wavelengths longer than 360 nm .....	21-2
21.3	UV devices emitting at wavelengths shorter than 360 nm .....	21-4
21.4	Alternative approaches for UV emitters .....	21-8
	References .....	21-9
<b>22</b>	<b>The efficiency droop</b>	<b>22-1</b>
22.1	Introduction to the efficiency droop .....	22-1
22.2	The “ABC” model .....	22-3
22.3	The “ABC + $f(n)$ ” model .....	22-3
22.4	The function $f(n)$ for drift-induced leakage .....	22-4
22.5	Role of “polarization charges and associated electric fields” .....	22-9
22.6	Role of “thermal roll-over” .....	22-10
22.7	Role of “carrier de-localization” .....	22-11
22.8	Role of Auger recombination .....	22-12
22.9	Strategies to overcome the efficiency droop .....	22-14
	References .....	22-18
<b>23</b>	<b>Human eye sensitivity and photometric quantities</b>	<b>23-1</b>
23.1	Light receptors of the human eye .....	23-1
23.2	Basic radiometric and photometric units .....	23-3
23.3	Eye sensitivity function .....	23-6
23.4	Luminous efficacy .....	23-10
23.5	Surface brightness .....	23-12
23.6	Circadian rhythm and circadian sensitivity .....	23-13
	References .....	23-14
<b>24</b>	<b>Colorimetry</b>	<b>24-1</b>
24.1	Colors of near-monochromatic emitters .....	24-2
24.2	Color-matching functions and chromaticity diagram .....	24-2
24.3	Color purity .....	24-10
24.4	LEDs in the chromaticity diagram .....	24-12
24.5	Relationship between chromaticity and color .....	24-13
24.6	The CIE <i>Lab</i> color space .....	24-14
24.7	The CIE <i>UVW</i> and CIE <i>Luv</i> color spaces .....	24-16
	References .....	24-17
<b>25</b>	<b>Black-body radiation and color temperature</b>	<b>25-1</b>
25.1	Incandescence (heat glow) .....	25-1
25.2	The planckian spectrum .....	25-2
25.3	The solar spectrum .....	25-3
25.4	Planckian radiation in the chromaticity diagram .....	25-5
25.5	Color temperature and correlated color temperature .....	25-7
25.6	Standardization of white light by means of color-temperature binning .....	25-10
	References .....	25-12

<b>26</b>	<b>Color mixing</b>	<b>26-1</b>
26.1	Subtractive color mixing .....	26-1
26.2	Additive color mixing .....	26-1
26.3	Calculation of color mixing .....	26-2
26.4	Implementation of color mixing .....	26-5
	References .....	26-9
<b>27</b>	<b>Color rendering</b>	<b>27-1</b>
27.1	Color rendering of physical objects .....	27-1
27.2	CIE uniform color space .....	27-7
27.3	Color-rendering index for planckian-locus illumination sources .....	27-9
27.4	Color-rendering index for non-planckian-locus illumination sources .....	27-10
27.5	Criticism of the CRI and alternative approaches .....	27-13
	References .....	27-15
<b>28</b>	<b>White-light sources based on LED chips</b>	<b>28-1</b>
28.1	Generation of white light with LED chips .....	28-1
28.2	Generation of white light by dichromatic sources .....	28-3
28.3	Generation of white light by trichromatic sources .....	28-7
28.4	Temperature dependence of trichromatic LED-based white-light source .....	28-11
28.5	Generation of white light by tetrachromatic and pentachromatic sources .....	28-14
	References .....	28-14
<b>29</b>	<b>Phosphors</b>	<b>29-1</b>
29.1	Introduction to phosphors .....	29-1
29.2	Types of phosphor materials .....	29-6
29.3	Phosphors used with LED chips .....	29-9
29.4	Phosphor body color .....	29-14
29.5	Phosphor structure and synthesis .....	29-15
29.6	Quenching by temperature and activator concentration .....	29-19
29.7	Phosphor particle size .....	29-22
29.8	Phosphor deposition .....	29-26
29.9	Phosphor sedimentation .....	29-29
29.10	Quantum-splitting phosphors .....	29-30
29.11	Location of phosphors in the CIE chromaticity diagram .....	29-30
	References .....	29-31
<b>30</b>	<b>White LEDs based on phosphors</b>	<b>30-1</b>
30.1	Efficiency of wavelength-converter materials .....	30-2
30.2	Wavelength-converter materials .....	30-4
30.3	White LEDs based on YAG:Ce phosphor .....	30-6
30.4	White LEDs based on phosphor blends .....	30-8
30.5	White LEDs using two LED chips and one phosphor .....	30-10
30.6	White LEDs using violet excitation sources .....	30-11
30.7	White LEDs using UV excitation sources .....	30-13
30.8	White LEDs based on semiconductor converters (PRS-LED) .....	30-15
30.9	White LEDs based on other methods .....	30-17
30.10	Spatial phosphor distributions .....	30-18
	References .....	30-20



<b>31</b>	<b>Packaging: Types of packages for LEDs</b>	<b>31-1</b>
31.1	The 3 mm and 5 mm round LED package .....	31-2
31.2	The SMD LED injection molded package .....	31-3
31.3	The SMD LED package fabricated by using a resin-molded body .....	31-5
31.4	Ceramic-base LED package .....	31-7
31.5	The side-view LED package .....	31-9
31.6	Other examples of LED packages .....	31-11
31.7	Chip-on-board LED packages (COBs) .....	31-13
31.8	Chip-scale LED packages (CSPs) .....	31-13
	References .....	31-14
<b>32</b>	<b>Packaging: Materials used in packaging</b>	<b>32-1</b>
32.1	Resin materials .....	32-1
32.2	Types of resins .....	32-2
32.3	Modification of resins by fillers .....	32-5
32.4	Epoxy resins .....	32-7
32.5	Silicone resins .....	32-10
32.6	Advanced resin structures .....	32-14
32.7	Degradation of resins under harsh operating conditions .....	32-15
	References .....	32-16
<b>33</b>	<b>Packaging: Protection against electrostatic discharge (ESD)</b>	<b>33-1</b>
33.1	The human body model and the IEC 61000-4-2 standard .....	33-1
33.2	The electrostatic discharge process .....	33-2
33.3	ESD-protection circuits .....	33-3
33.4	ESD-protection circuits integrated with the LED .....	33-6
	References .....	33-6
<b>34</b>	<b>Packaging: Junction and carrier temperatures</b>	<b>34-1</b>
34.1	Carrier temperature and high-energy slope of spectrum .....	34-1
34.2	Junction temperature and peak emission wavelength .....	34-3
34.3	Theory of temperature dependence of diode forward voltage .....	34-5
34.4	Measurement of junction temperature using forward voltage .....	34-8
34.5	Thermal considerations for pulsed measurements .....	34-11
34.6	Constant-current and constant-voltage DC drive circuits .....	34-13
	References .....	34-15
<b>35</b>	<b>Communication: Optical communication</b>	<b>35-1</b>
35.1	Types of optical fibers .....	35-1
35.2	Attenuation in silica and plastic optical fibers .....	35-3
35.3	Modal dispersion in fibers .....	35-5
35.4	Material dispersion in fibers .....	35-6
35.5	Numerical aperture of fibers .....	35-9
35.6	Coupling with lenses .....	35-11
35.7	Free-space optical communication .....	35-14
	References .....	35-16

<b>36</b>	<b>Communication: Communication LEDs</b>	<b>36-1</b>
36.1	LEDs for free-space communication .....	36-1
36.2	LEDs for fiber-optic communication .....	36-1
36.3	Surface-emitting Burrus-type communication LEDs emitting at 870 nm .....	36-2
36.4	Surface-emitting communication LEDs emitting at 1300 nm .....	36-3
36.5	Communication LEDs emitting at 650 nm .....	36-5
36.6	Edge-emitting superluminescent diodes (SLDs) .....	36-7
	References .....	36-11
<b>37</b>	<b>Communication: LED modulation characteristics</b>	<b>37-1</b>
37.1	Rise and fall times, 3-dB frequency, and bandwidth in linear circuit theory .....	37-1
37.2	Rise and fall time in the limit of large diode capacitance .....	37-4
37.3	Rise and fall time in the limit of small diode capacitance .....	37-5
37.4	Voltage dependence of the rise and fall times .....	37-6
37.5	Carrier sweep-out of the active region .....	37-7
37.6	Current shaping .....	37-8
37.7	3-dB frequency .....	37-10
37.8	Eye diagram .....	37-10
37.9	Carrier lifetime and 3-dB frequency .....	37-11
	References .....	37-12
	<b>Appendices</b>	<b>A-1</b>
Appendix 1	Frequently used symbols .....	A-1
Appendix 2	Physical constants .....	A-5
Appendix 3	Room temperature properties of III–V arsenides .....	A-6
Appendix 4	Room temperature properties of III–V nitrides .....	A-7
Appendix 5	Room temperature properties of III–V phosphides .....	A-8
Appendix 6	Room temperature properties of Si and Ge .....	A-9
Appendix 7	Periodic system of elements .....	A-10
<b>Index</b>	.....	<b>A-11</b>