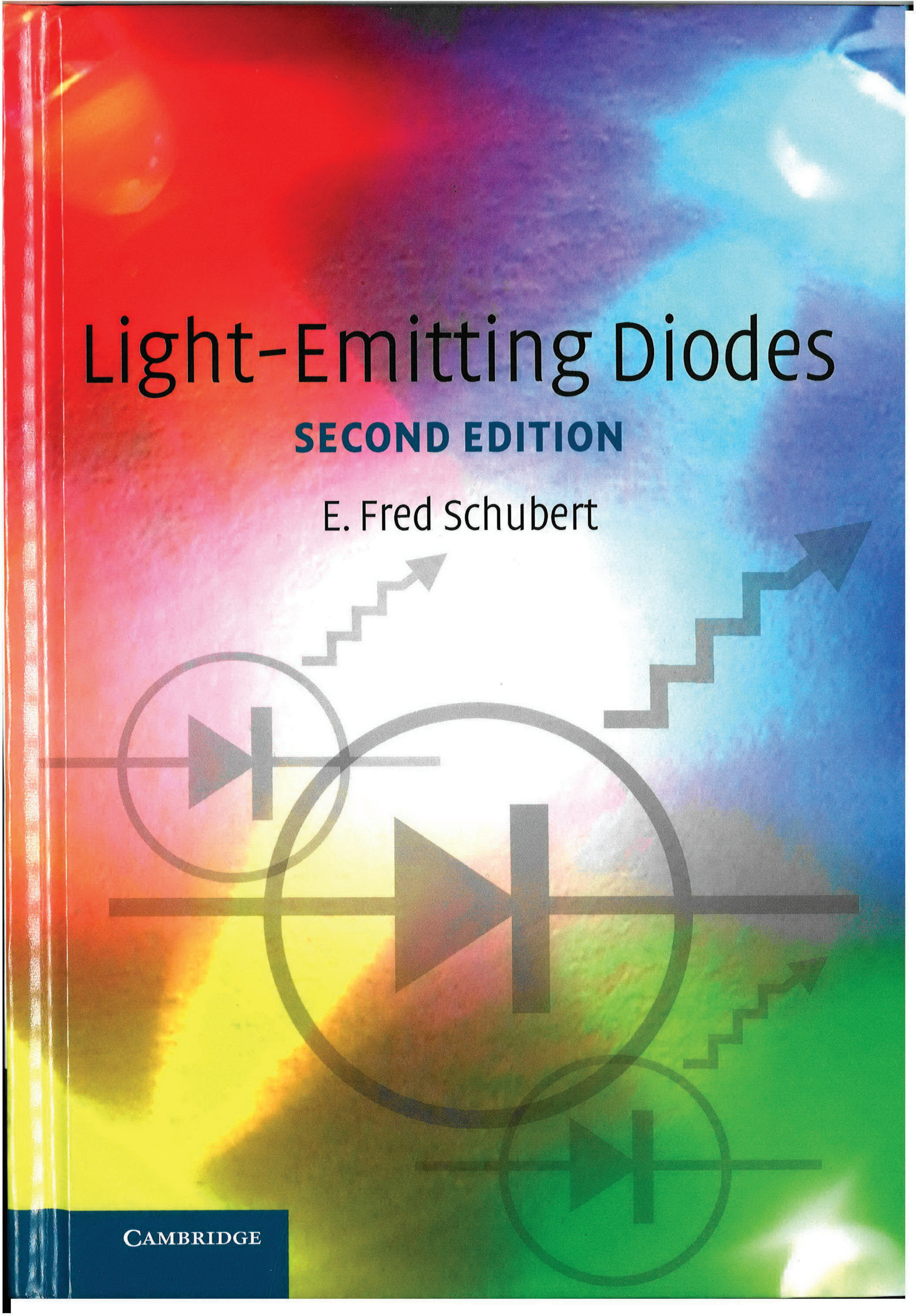
Light-Emitting Diodes
SECOND EDITION
E. Fred Schubert
CAMBRIDGE

LIGHT-EMITTING DIODES
SECOND EDITION

Revised and fully updated, the Second Edition of this textbook offers a comprehensive explanation of the technology and physics of light-emitting diodes (LEDs) such as infrared, visible-spectrum, ultraviolet, and white LEDs made from III–V semiconductors. The elementary properties of LEDs such as electrical and optical characteristics are reviewed, followed by the analysis of advanced device structures.

With nine additional chapters, the treatment of LEDs has been vastly expanded, including new material on device packaging, reflectors, UV LEDs, III–V nitride materials, solid-state sources for illumination applications, and junction temperature. Radiative and non-radiative recombination dynamics, methods for improving light extraction, high-efficiency and high-power device designs, white-light emitters with wavelength-converting phosphor materials, optical reflectors, and spontaneous recombination in resonant-cavity structures, are discussed in detail. Fields related to solid-state lighting such as human vision, photometry, colorimetry, and color rendering are covered beyond the introductory level provided in the first edition. The applications of infrared and visible-spectrum LEDs in silica fiber, plastic fiber, and free-space communication are also discussed. Semiconductor material data, device design data, and analytic formulae governing LED operation are provided.

With exercises, solutions and illustrative examples, this textbook will be of interest to scientists and engineers working on LEDs, and to graduate students in electrical engineering, applied physics, and materials science.

Additional resources for this title are available online at www.cambridge.org/9780521865388.

E. Fred Schubert received his Ph.D. degree with Honors in Electrical Engineering from University of Stuttgart in 1986 and is currently a Wellfleet Senior Constellation Professor of the Future Chips Constellation at Rensselaer Polytechnic Institute. He has made several pioneering contributions to the field of LEDs, including the first demonstration of the resonant-cavity light-emitting diode (RCLED). He has authored or co-authored more than 200 publications including *Doping in III–V Semiconductors* (Cambridge University Press, 1993, 0-521-01784-X) for which he was awarded the VDE Literature Prize. He is inventor or co-inventor of 28 US Patents and a Fellow of the IEEE, APS, OSA, and SPIE. He received the Senior Research Award of the Humboldt Foundation, the Discover Award for Technological Innovation, the RD 100 Award, and Boston University's Provost Innovation Fund Award.

Note: This book contains many figures in which color adds important information. For this reason, all figures are available in color on the Internet at the following websites: <http://www.cambridge.org/9780521865388> and <http://www.LightEmittingDiodes.org>.

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E. FRED SCHUBERT
Rensselaer Polytechnic Institute,
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et al., 2002; Lumileds, 2004). Using one or two Zener diodes or placing several Si diodes in series increases the threshold voltage of the ESD circuit to values beyond the turn-on voltage of the LED. Thus, under normal operating conditions, the current through the ESD circuit is negligibly small.

Sheu (2003) proposed a Schottky diode integrated with the LED on the same chip. The structure, shown in Fig. 11.6 (a), consists of a large-area p-n junction diode and, separated by a deep trench, a small-area Schottky diode. The Schottky diode, fabricated on the n-type buffer layer of a GaInN LED, is forward biased when the LED is biased in the reverse polarity. For reverse electrostatic discharges, the current flows mostly through the Schottky diode, thereby bypassing the p-n junction and preventing damage to the p-n junction. For forward electrostatic discharges, the current flows through the p-n junction. In an alternative structure, shown in Fig. 11.6 (b), the Schottky diode is replaced by a p-n junction diode (Cho, 2005).

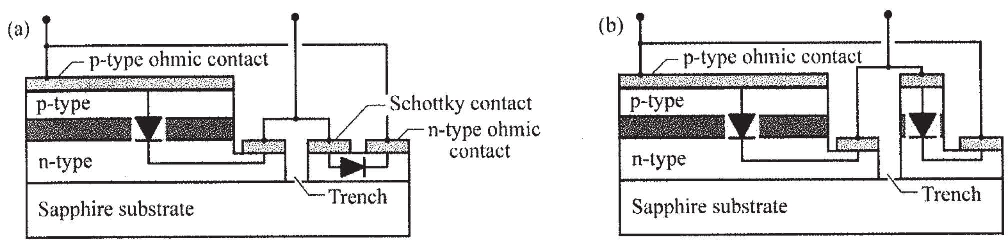

Fig. 11.6. On-chip ESD protection using (a) a small-area Schottky diode on the n-type buffer layer of a GaInN device and (b) a small-area p-n junction diode (Schottky diode circuit after Sheu, 2003).

11.3 Thermal resistance of packages

The thermal resistance of LED packages together with the maximum temperature of operation determines the maximum thermal power that can be dissipated in the package. The maximum temperature of operation may be determined by reliability considerations, by the degradation of the encapsulant, and by internal-quantum-efficiency considerations. Several types of LED packages and their thermal resistance are shown in Fig. 11.7 (Arik *et al.*, 2002). Early LED packages, introduced in the late 1960s and still used for low-power packages at the present time, have a high thermal resistance of about 250 K/W. Packages using ***heatsink slugs*** made of Al or Cu that transfer heat from the chip directly to a printed circuit board (PCB), which in turn spreads the heat, have thermal resistances of 6–12 K/W. It is expected that thermal resistances of

< 5 K/W will be achieved for advanced passively cooled power packages.

Note that the packages shown in Fig. 11.7 do not use ***active cooling***, i.e. fan cooling. Heatsinks with cooling fins and fan are commonly used to cool electronic microchips including Si CMOS microprocessors. They have thermal resistances < 0.5 K/W. The use of active cooling devices would reduce the power efficiency of LED-based lighting systems.

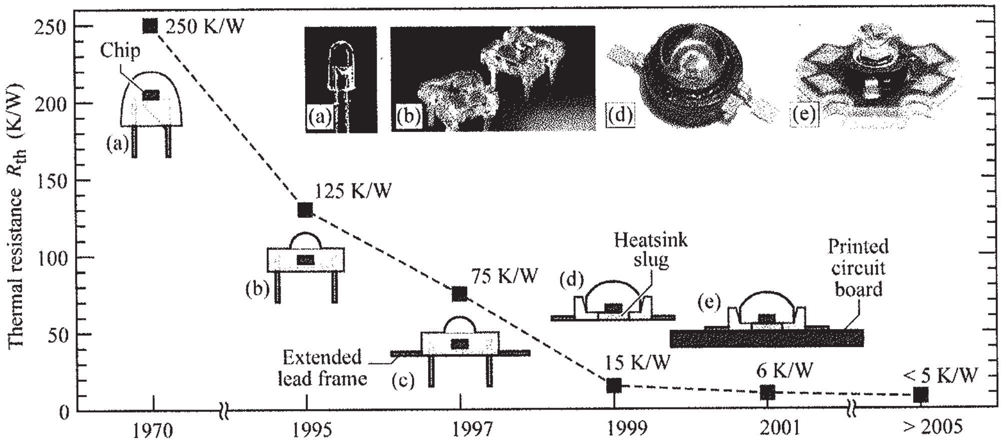

Fig. 11.7. Thermal resistance of LED packages: (a) 5mm (b) low-profile (c) low-profile with extended lead frame (d) heatsink slug (e) heatsink slug mounted on printed circuit board (PCB). Trade names for these packages are "Piranha" (b and c, Hewlett Packard Corp.), "Barracuda" (d and e, Lumileds Corp.), and "Dragon" (d and e, Osram Opto Semiconductors Corp.) (adapted from Arik *et al.*, 2002).

11.4 Chemistry of encapsulants

Encapsulants have several requirements including high transparency, high refractive index, chemical stability, high-temperature stability, and hermeticity. All encapsulants are based on polymers, several of which are shown in Fig. 11.8. A simple polymer molecule consisting of a hydrocarbon chain is shown in Fig. 11.8 (a). Branching and cross linking the polymer molecule results in rubber compounds as shown in Fig. 11.8 (b). Such rubber compounds lack transparency and cannot be used as LED encapsulants. However, it is well known that oxides are frequently transparent. In fact, all encapsulants used for LEDs contain oxygen.

A common encapsulant is ***epoxy resin*** (also called epoxy), which remains transparent and does not show degradation over many years for long-wavelength visible-spectrum and IR LEDs. However, it has been reported that epoxy resins lose transparency in LEDs emitting at shorter