

Light-Emitting Diodes

SECOND EDITION

E. Fred Schubert



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LIGHT-EMITTING DIODES

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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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GaAs substrate, on which the epitaxial layers had been grown, was removed. Si has a higher thermal conductivity than GaAs thus allowing for lower junction temperatures and reducing the joule-heating-induced emission-wavelength shift. The emission from the metal-reflector AlGaInP LEDs exceeded those of reference LEDs with DBRs fabricated on GaAs substrates.

Annealing and alloying forms low-resistance ohmic contacts. Typical annealing temperatures for alloyed contacts are between 375 and 450 °C for III–V arsenides and III–V phosphides and up to 600 °C for III–V nitrides. During the annealing process, the metal surface changes from smooth to rough and a concomitant decrease in the optical reflectivity results.

In contrast, non-alloyed contacts are just deposited on the semiconductor without annealing. Highly doped semiconductor surface layers are needed to obtain good ohmic I – V characteristics for such non-alloyed ohmic contacts. However, even for highly doped semiconductors, the contact resistance of non-alloyed contacts is usually higher than for alloyed contacts.

Thick metallic reflectors and hybrid reflectors are absorbing reflectors that should not be used as light-exit reflectors in LEDs and vertical-cavity surface emitting lasers. Metal contacts become practically opaque for thicknesses > 50 nm. That is, the transmittance of hybrid reflectors is near zero, unless the thickness of the metal is very thin (Tu *et al.*, 1990).

Very thin metal contacts are semi-transparent. Most metal contacts have a transmittance of approximately 50% at a metal film thickness of 5–10 nm. The exact value of the transmittance needs to be calculated by taking into account the real and imaginary part of the refractive index (see, for example, Palik, 1998). However, very thin metallic contacts may form an islanded structure rather than a single continuous film. Furthermore, the electrical resistance of thin metal films can be large, in particular if an islanded structure is formed.

In LEDs with transparent substrates, e.g. AlGaInP LEDs on GaP, light emanating from the active region is incident on the substrate contact. To increase the reflectance of the backside, an ohmic contact geometry covering only a small fraction of the substrate surface can be used, such as a multiple-stripe or a ring-shaped contact. Using Ag-loaded conductive epoxy to attach the LED die to the package provides a high-reflectivity material in the regions not covered by the ohmic contact.

The die-attach epoxy can also serve as a reflector in LEDs grown on a transparent material, e.g. GaInN LEDs grown on sapphire substrates. Conductive Ag-loaded epoxy has a high conductivity as well as high reflectance. Such a highly reflective epoxy can increase the extraction efficiency in LEDs grown on transparent substrates.

There are ohmic contacts that are transparent to visible light. Such *transparent ohmic*

contacts include indium tin oxide, frequently referred to as ITO (Ray *et al.*, 1983; Sheu *et al.*, 1998; Margalith *et al.*, 1999; Mergel *et al.*, 2000; Shin *et al.*, 2001). The material can be considered as a tin oxide semiconductor that is doped with indium. Indium substitutes for tin and therefore acts as an acceptor. Generally the specific contact resistance of ITO contacts is higher than the contact resistance of alloyed metal contacts.

10.2 Total internal reflectors

Total internal reflection is a fascinating phenomenon occurring at the boundary between two dielectric media with different refractive indices. Total internal reflection was first discovered by Johannes Kepler in the early 1600s (Kepler, 1611). Kepler attempted to explain the apparent bending of objects partially submersed in water. Kepler discovered that for rays near normal incidence, the ratio of the angles of incidence and refraction is proportional to the ratio of what are now known as the refractive indices of the media. Kepler's relationship can be expressed as

$$\bar{n}_1 \theta_1 = \bar{n}_2 \theta_2 \quad (10.7)$$

where the angles θ_1 and θ_2 are measured with respect to the surface normal. Comparison with the law discovered between 1621 and 1625 by Cornelius Willebrord Snell (***Snell's law***)

$$\boxed{\bar{n}_1 \sin \theta_1 = \bar{n}_2 \sin \theta_2} \quad (10.8)$$

reveals that Kepler found the small-angle approximation of Snell's law. The angles used in Snell's law are shown in Fig. 10.4.

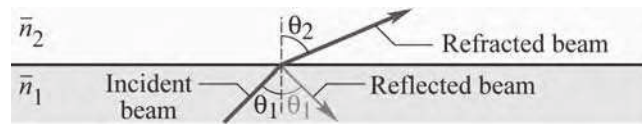


Fig. 10.4. Reflected and refracted light ray at the boundary between two media with refractive indices \bar{n}_1 and \bar{n}_2 , where $\bar{n}_1 > \bar{n}_2$.

Kepler also discovered that, with suitable materials and sufficiently shallow angles of incidence, the refracted angle can be made to exceed 90° , resulting in total internal reflection. The critical angle for total internal reflection can be derived from Snell's law using the condition $\theta_2 = 90^\circ$. Hence

$$\theta_{1,\text{crit}} = \arcsin(\bar{n}_2 / \bar{n}_1) . \quad (10.9)$$